QUANTUM MALTA 2012:
Fundamental Problems in Quantum Physics

and

Black Holes: From Quantum To Gravity

Welcome to Malta!

EUROPEAN SCIENCE FOUNDATION

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Tuesday

	First Joint Session - Chairpersons: Silke Britzen and Angelo Bassi
10:30 (j)	Joe Silk - Cosmological Implications of Black Holes
11:30 (j)	Markus Arndt - Quantum coherence, decoherence and the role of gravity in matter-wave experiments with molecules and nanoparticles
12:30	LUNCH
	First afternoon session - Chairperson: Angelo Bassi
14:00	Tejinder Singh - Removing time from quantum theory : implications for the measurement problem
14:30	Omri Gat - Entangled Schroedinger cats in circuit QED
15:00	COFFEE BREAK
	Second afternoon session - Chairperson: Egidijus Norvaisas
15:30	Nicolas Gisin - Quantum nonlocality based on finite-speed influences leads to signalling
16:00	Catalina Oana Curceanu - A glance into the Pandora Box of quantum mechanics: Pauli Exclusion Principle violation and spontaneous collapse models experimental tests
16:30	Jyrki Piilo - Nonlocal memory effects in the dynamics of open quantum systems
17:00	END of day one

Wednesday

	Second Joint session - Chairpersons: Silke Britzen and Angelo Bassi
10:00 (j)	GianCarlo Ghirardi - Collapse Theories: a viable solutions to the problems of quantum mechanics
11:00 (j)	Greg Landsberg
12:00	LUNCH
	First afternoon session - Chairperson: Bassano Vacchini
13:30	Andreas Buchleitner
14:00	Thomas Durt - Fundamental aspects of Time in Quantum Mechanics and Meson Phenomenology
14:30	COFFEE BREAK
	Second afternoon session - Chairperson: Mario Ziman
15:00	Manfred Niehus - Experimental progress in decoherence studies in free space photonics and optical microfibers
15:30	Christos Efthymiopoulos - Chaos in de Broglie - Bohm dynamics and its physical
16:00	COFFEE BREAK
	Third afternoon session - Chairperson: Sandor Imre
16:30	Jakub Zakrzewski - Extraction of information from dynamics of strongly correlated states
17:00	Daniel Sudarsky - The quantum origin of the seeds of cosmic structure and the need for new physics
17:30	END of day two
18:00	Bus from conference venue to L-Mdina
18:30	Walking tour of L-Mdina (the city is very small, so the distances are not long)
20:00	Conference dinner

Thursday

	Third Joint Session - Chairpersons: Silke Britzen and Angelo Bassi
10:00 (j)	Peter Biermann
11:00 (j)	Jean Bricmont - From the microscopic to the macroscopic world and the origin of irreversibility
12:00	LUNCH
	First afternoon session - Chairperson: Yuji Hasegawa
13:30	Beatrix Hiesmayr - Revealing Bell's Nonlocality in Particle Physics?!
14:00 14:30	Lajos Diósi - Classical-Quantum Coexistence: a 'Free Will' Test COFFEE BREAK
	Second afternoon session - Chairperson: Angel Santiago Sanz
15:00	Giovanni Ciccotti - A pseudo-quantum description of (classical) vacancy diffusion in crystals
15:30	Ward Struyve - Semi-classical approximations based on the de Broglie-Bohm theory
16:00	COFFEE BREAK
	Third afternoon session - Chairperson: Gheorghe-Sorin Paraoanu
16:30	Marco Genovese - Recent experimental progresses in testing Quantum Mechanics
17:00	Spiros Skourtis - Biological electron transport processes
17:30	END of day three

Friday

	First morning session - Chairperson: Beatrix Hiesmayr
10:00	Salvador Miret-Artés - Quantum (Bohmian) Stochastic Trajectories
10:30	Irene Burghardt - Hierarchical effective-mode decomposition for non-Markovian quantum environments
11:00	COFFEE BREAK
	Second Morning session - Chairperson: Petros Wallden
11:30	Yuji Hasegawa - Uncertain relation studied in neutron's successive spin-measurements
12:00	LUNCH
	First afternoon session - Chairperson: Catalina Curceanu
13:30	André Xuereb - Quantum mechanics at the meso-scale
14:00	Adrian Kent - The Quantum Landscape
14:30	COFFEE BREAK
	Second afternoon session - Chairperson: Daniel Braun
15:00	Antonio Di Domenico - The Quantum Mechanics and discrete symmetries of neutral K mesons
15:30	Nikola Buric - Emergence of classical systems from constrained quantum background
	Third afternoon session - Chairperson: Jackson Levi Said
16:30	Thomas Filk - A Chain of Coupled Pendula Leading to Quantum Relativity
17:00	Egidijus Norvaisas - Selfconsistent canonically quantized SU(3) Skyrme Model for Baryons
17:30	Concluding remarks
18:00	END of conference

(j) - Common session with Black Hole conference

Quantum coherence, decoherence and the role of gravity in matter-wave experiments with molecules and nanoparticles

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De Broglie interferometry with macromolecules, clusters and other kinds of nanoparticles explores the boundary between experimentally tested quantum mechanics and classical physics by gradually increasing the size and complexity of objects whose coherent delocalization can still be proven.

We will discuss three recent experiments performed in our group at the University of Vienna and how to extrapolate them to masses where gravity starts becoming influential: far-field diffraction of fluorescent molecules at ultrathin gratings demonstrates the wave-particle duality in a particularly conspicuous and didactical way1,2, as it allows to image the stochastic arrival of single molecules in real-time as well the formation of the deterministic ensemble interferogram in the same image. Near-field interferometry in the Kapitza-Dirac-Talbot-Lau design has led to the current mass record in quantum delocalization experiments3,4 with new results emerging. A novel matter-wave interferometer that operates with pulsed ionization gratings is being discussed, as it is expected to be best adapted for demonstrating translational quantum coherence for the most massive particles5-7. We will discuss the practical complexity limits of matter-wave interferometry, including kinematic effects, phase averaging, decoherence and non-standard models of quantum mechanics.

It turns out that classical gravity and the rotation of the Earth can cause significant dephasing in high-mass interferometry with particle beams of finite velocity dispersion. We discuss the relevance of long coherence times and ways to preserve them in a micro-gravitational environment.

Collaborations: M. Mayor et al. (Univ. Basel), O. Cheshnovsky et al, Tel Aviv University, K. Hornberger (Univ. Duisburg-Essen), A. Bassi (Univ. Trieste), B. v. Issendorff (Univ. Freiburg).

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[1] Juffmann, T. et al. Real-time single-molecule imaging of quantum interference Nature Nanotechn. , , doi:doi:10.1038/nnano.2012.34 (2012).

[2] Arndt, M. et al. Wave-particle duality of C-60 molecules. Nature 401, 680-682 (1999).

[3] Gerlich, S. et al. Quantum interference of large organic molecules. Nature Communs. 2, 263, doi:10.1038/ncomms1263 (2011).

[4] Gerlich, S. et al. A Kapitza-Dirac-Talbot-Lau interferometer for highly polarizable molecules. Nature Phys. 3, 711 - 715 (2007).

[5] Hornberger, K., Gerlich, S., Haslinger, P., Nimmrichter, S. & Arndt, M. Colloquium: Quantum interference of clusters and molecules. Rev. Mod. Phys. 84, 157-173 (2012).

[6] Nimmrichter, S., Haslinger, P., Hornberger, K. & Arndt, M. Concept of an ionizing time-domain matter-wave interferometer. New. J. Phys. 13, 075002 (2011).

[7] Reiger, E., Hackermüller, L., Berninger, M. & Arndt, M. Exploration of gold nanoparticle beams for matter wave interferometry. Opt. Comm. 264, 326-332, doi: (2006).

Removing time from quantum theory : implications for measurement

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Quantum theory depends on a classical time in order to describe evolution. This time is part of a spacetime geometry, whose structure is determined by classical material bodies through the laws of the general theory of relativity. In the absence of these classical objects, it is not possible to assign a physical meaning to the notion of classical time. Yet, one should be able to formulate quantum theory. In other words, there should exist an equivalent reformulation of quantum theory which does not refer to classical time. A consequence of this requirement is that quantum theory is a limiting case of a stochastic nonlinear theory, with the nonlinearity becoming significant on the Planck mass scale. Such a nonlinearity can in principle explain the collapse of the wave-function during a quantum measurement.

We have attempted to construct such a 'Quantum Theory without Classical Time' using the methods of Trace Dynamics [1]. Our starting point is a Non-Commutative Special Relativity [NSR] where a scalar proper time is defined as a Trace over a line-element made from operator space and operator time [1]. A relativistic dynamics can be constructed in the standard manner, for the matrix dynamical variables which live on this operator spacetime. The dynamics possesses a novel conserved charge, having the dimensions of action, and which is equal to the sum of the commutators between position matrices and their corresponding momenta. [The commutators themselves take arbitrary values].

Next, one constructs the statistical thermodynamics for this classical matrix dynamics [2]. A Liouville theorem holds, and the equilibrium probability density is obtained by maximizing the entropy subject to the constraints that there are conserved charges. The invariance of the phase space measure under shifts of dynamical variables leads to an important Ward identity for canonical averages of polynomial functions of the matrix dynamical variables. If one works at scales much below the Planck scale, and ignores statistical fluctuations for the moment, it is shown that canonical averages of dynamical variables obey the standard commutation relations of quantum theory, as well as obeying Heisenberg equations of motion. There is an energy-time commutator as well, and evolution is decsribed with respect to the proper time constructed from the Trace of the line-element. A quantum state can be defined at this emergent level and obeys a functional Schrödinger equation. This is the sought after 'quantum theory without classical time'.

The connection with the measurement problem is through the theory of Trace Dynamics [TD] [1]. TD is a classical matrix dynamics which aims to derive quantum theory from underlying principles, instead of by 'quantizing' a classical Newtonian dynamics. However, TD takes classical spacetime as given. The statistical thermodynamics of TD leads to the emergence of standard quantum theory. Moreover, when statistical fluctuations about equilibrium are taken into account, the non-relativistic Schrödinger equation is modified to a stochastic, non-linear and nonunitary theory, which explains wave-function collapse during a measurement, and the Born rule.

However, TD treats spacetime as having a point structure, while treating matter degrees as operators. Perhaps a more complete treatment would be one where spacetime and matter degrees are treated at par: both as operators, as in our development of 'quantum theory of classical time'. The consideration of stochastic fluctuations leads to the emergence of a classical spacetime geometry produced by classical bodies. On this background classical Universe one can apply TD to select matter operator degrees of freedom, obtain quantum theory for it, and then explain wave-function collapse [3, 4]. Quantum theory without classical spacetime thus provides a backdrop for Trace Dynamics, which in turn provides an explanation for the measurement problem. Gravity possibly plays an important role.

[1] Stephen Adler, *Quantum Theory as an Emergent Phenomenon* Cambridge University Press, 2004

[2] Kinjalk Lochan and T. P. Singh, Phys. Lett. A375 (2011) 3747 [arXiv:1109.0300]

[3] Kinjalk Lochan, Seema Satin and T. P. Singh, arXiv: 1203.6518

[4] T. P. Singh, FQXi Essay, arXiv:1106.0911

[5] Angelo Bassi, Kinjalk Lochan, Seema Satin, T. P. Singh and Hendrik Ulbricht, invited review article in preparation for *Reviews of Modern Physics*

Entangled Schrödinger cats in circuit quantum electrodynamics

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Superconducting circuits process quantum information by coupling Josephson junction qubits with electromagnetic modes, an experimental paradigm known as circuit quantum electrodynamics (CQED). The dynamics of such systems where the field is prepared in highly excited coherent field wave packets is a probe of the onset of classical physics on hand, and generates states with intriguing quantum behavior on the other hand. Single-mode wave packet CQED has been studied thoroughly theoretically [1, 2] and experimentally [3]. A salient feature is the splitting of the initial wave packet into two phase-space localized components, each of which is a squeezed coherent state [4]. The field and qubit are in general entangled, but the system state becomes separable at specific times and then the field state is a pure superposition of classically separate phase-space wave packets—the quantum optics version of Schrödinger's cat.

Recently it has become possible to couple superconducting qubits to more than one electromagnetic mode, and experiments have demonstrated entanglement between two and more field modes [5]. Here we address the question of dynamics and field-entanglement properties of two-mode CQED system prepared in a highly-excited coherent state product state. As in the one-mode case, the original wave packet splits and the field decouples from the qubit at discrete times. The wave packet fragments are phase-space localized, with well-defined quadratures for *both* modes. The superposition of the two fragments is therefore an entangled state $|i\alpha\rangle \otimes |i\alpha\rangle + |-i\alpha\rangle \otimes |-i\alpha\rangle$ where either both mode quadratures are $\frac{q+ip}{\sqrt{2}} = i\alpha$ (up to small uncertainties) or both mode quadratures are $\frac{q+ip}{\sqrt{2}} = -i\alpha$. This state is quantum optical *entangled Schrödinger cats*, where each mode is in either of two classically separate states that is not determined until measured, but are correlated such that measurement of one mode collapses the other mode.

The existence of quantum correlations facilitates Bell-inequality violation, that for an optimized Bell operator $\mathcal{B}$ the expectation value $\langle\mathcal{B}\rangle = 2.45$, more that than the value of 2 allowed by local realism, but less than the maximal possible value $2\sqrt{2}$. This deficiency arises because each wave packet fragment is itself entangled by two-mode squeezing. The purity entanglement (whose negative is an entanglement monotone) of the fragments is 0.78 compared with 1 for separable states and $\frac{1}{2}$ for Bell states.

The CQED field state therefore displays two competing kinds of entanglement, Bell-type entanglement and two-mode squeezing. Nevertheless, this state can be *filtered* to produce maximally entangled Schrödinger cats by weak q-quadrature measurement with recorded value. A complete (von Neumann) q measurement collapses the two-mode squeezing, but the full p uncertainty also destroys the Bell-type entanglement of the state. A weak q measurement is therefore needed so that the resulting p uncertainty is smaller than the phase space separation between the two fragments. Since the separation is classical, in the limit of high photon number, almost full q squeezing is achievable without damaging the Bell-type entanglement, which becomes maximal in the q squeezed state obtained as the result of the weak measurement.

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[1] SM Chumakov, A.B Klimov, and JJ Sanchez-Mondragon, Phys. Rev. A **49**, 4972 (1994)

[2] J. Gea-Banacloche, Phys. Rev. Lett. **65**, 3385 (1990).

[3] A. Auffeves et al. Phys. Rev. Lett. **91**, 230405 (2003); P. Maioli et al., Phys. Rev. Lett. **94**, 113601 (2005).

[4] A. Leshem and O. Gat, Phys. Rev. A **84**, 052303 (2011).

[5] Mariantoni, M. et al, Nature Physics, **7**, 287. (2011).

Quantum nonlocality based on finite-speed influences leads to signalling

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The experimental violation of Bell inequalities using spacelike separated measurements precludes the explanation of quantum correlations through causal influences propagating at subluminal speed [1, 2]. Yet, any such experimental violation could always be explained in principle through models based on hidden influences propagating at a finite speed $v > c$, provided v is large enough [3, 4]. Here, we show that for *any* finite speed v with $c < v < \infty$, such models predict correlations that can be exploited for faster-than-light communication. This superluminal communication does not require access to any hidden physical quantities, but only the manipulation of measurement devices at the level of our present-day description of quantum experiments. Hence, assuming the impossibility of using nonlocal correlations for superluminal communication, we exclude any possible explanation of quantum correlations in terms of influences propagating at any finite speed. Our result uncovers a new aspect of the complex relationship between multipartite quantum nonlocality and the impossibility of signalling [5, 6].

Our result opens a whole new avenue of experimental possibilities for testing these models. It also illustrates the difficulty to modify quantum physics while maintaining no-signalling. If we want to keep no-signalling, it shows that quantum nonlocality must necessarily relate discontinuously parts of the universe that are arbitrarily distant. This gives further weight to the idea that quantum correlations somehow arise from outside spacetime, in the sense that no story in space and time can describe how they occur.

This talk is based on [7].

[1] J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics: Collected papers on quantum philosophy* (Cambridge University Press, Cambridge, 2004).

[2] A. Aspect, Nature **398**, 189 (1999).

[3] D. Salart, A. Baas, C. Branciard, N. Gisin, and H. Zbinden, Nature **454**, 861 (2008).

[4] B. Cocciaro, S. Faetti and L. Fronzoni, Phys. Lett. A **375**, 379 (2011).

[5] M. L. Almeida, J.-D. Bancal, N. Brunner, A. Acín, N. Gisin, S. Pironio, Phys. Rev. Lett. **104**, 230404 (2010).

[6] R. Gallego, L. E. Würflinger, A. Acín, and M. Navascués, arXiv:1107.3738 (2011).

[7] J.-D- Bancal et al., arXiv:110.3795

A glance into the Pandora Box of quantum mechanics:Pauli Exclusion Principle violation and spontaneous collapse models experimental test

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In spite of its enormous success, or maybe exactly for this, Quantum Mechanics still hides many mysteries. We shall explore two: the spin-statistics connection and the collapse of the wave function. Experimental undergoing tests of the Pauli Exclusion Principle violation will be discussed, together with future plans to measure the spontaneous emission of X rays predicted in collapse models (CSL).

We present a method of searching for possible small violations of the Pauli Exclusion Principle (PEP) for electrons, through the search for "anomalous" X-ray transitions in copper atoms, produced by "fresh" electrons (brought inside the copper bar by circulating current) which can have the probability to do the Pauli-forbidden transition to the *1s* level already occupied by two electrons. We describe, then, the VIP (VIolation of PEP) experiment which took data at the Gran Sasso underground laboratories, searching for these Pauli-prohibited transitions. The goal of VIP is to test the PEP for electrons with unprecedented accuracy, down to a limit in the probability that PEP is violated at the level of $10^{-29} - 10^{-30}$, improving the previous limit by 3-4 orders of magnitude. We report achieved experimental results [1] and briefly discuss some of the implications of a possible violation, together with future plans to gain other about 2 orders of magnitude in the estimation of the probability of PEP violation.

We will then present a project to use a similar experimental technique to measure the spontaneously emitted X rays predicted in the framework of collapse models (GRW theory, dynamical reduction models), starting with results obtained [2].

We shall so have a short glimpse into the Pandora's box of Quantum Mechanics, where "apart of Schrodinger cat" other interesting features might still be hiding.

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[1] C. Curceanu *et al.*, International Journal of Quantum Information, **9** (2011) 145.
[2] Q. Fu, Physical Review A **56** (1997) 1806.

Quantifying and controlling non-Markovian quantum dynamics

Bi-Heng Liu,[6] Li Li,[6] Yun-Feng Huang,[6] Chuan-Feng Li,[6] Guang-Can Guo,[6] Elsi-Mari Laine,[7] Heinz-Peter Breuer,[8] and Jyrki Piilo[7]

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Realistic quantum mechanical systems are always exposed to an external environment. The presence of the environment often gives rise to a Markovian process in which the system loses information to its surroundings. However, many quantum systems exhibit a pronounced non-Markovian behavior signifying the presence of quantum memory effects. In this talk, we show how to quantify non-Markovianity of a process based on the concept of information flow [1], and how to control the transition from Markovian to non-Markovian quantum dynamics in an optical system [2]. Moreover, we show that initial correlations in a composite environment can lead to a nonlocal open system dynamics which exhibits strong memory effects although the local dynamics is Markovian [3]. The latter results demonstrate that, contrary to conventional wisdom, enlarging an open system can change the dynamics from Markovian to non-Markovian, and that in an optical setup, one can use the polarization degrees of freedom of photons to probe their frequency correlations.

[1] H.-P. Breuer, E.-M. Laine, and J. Piilo, Phys. Rev. Lett. **103**, 210401 (2009).
[2] B.-H. Liu, L. Li, Y.-F. Huang, C.-F. Li, G.-C. Guo, E.-M. Laine, H.-P. Breuer, and J. Piilo, Nature Physics **7**, 931 (2011).
[3] E.-M. Laine, H.-P. Breuer, J. Piilo, C.-F. Li, and G.-C. Guo, "Nonlocal memory effects in the dynamics of open quantum systems", preprint arXiv:1111.4481(quant-ph).

Fundamental aspects of Time in Quantum Mechanics and Meson Phenomenology

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The role played by Time in the quantum theory is still mysterious by many aspects. In particular it is not clear today whether the distribution of decay times of unstable particles could be described by a Time Operator. As we shall discuss, different approaches to this problem (one could say interpretations) can be found in the literature on the subject. As we shall show, it is possible to conceive crucial experiments aimed at distinguishing the different approaches, by measuring with accuracy the statistical distribution of decay times of entangled particles. In particular, such experiments can be realized in principle with entangled kaon pairs.

Kaons illustrate fundamental quantum properties such as the superposition principle (for instance in kaon oscillations), and their phenomenology also appeared very useful in the past for measuring CP-violation related effects.

More recently, they were also useful for testing decoherence and entanglement related effects.

The aim of our talk is to show that kaons could also be useful for revealing and/or studying fundamental aspects of Time in the quantum theory, such as the existence of a Time Operator [1](and also of the so-called Time Superoperator [1]).

[1] T. Durt, "Correlations of decay times of entangled composite unstable systems", in preparation.

[2] M. Courbage, T. Durt and M. Saberi, "Time decay probability distribution of the neutral meson system", J. Phys. G: Nucl. Part. Phys. 39 (2012) 045008.

The quantum origin of the seeds of cosmic structure and the need for novel physics

Daniel Sudarsky[10]

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Inflation is considered one of the cornerstones of modern cosmology as it supposedly sets the stage, and then gives rise to the seeds of cosmic structure. Looking at the details the story becomes even more remarkable, as the seeds of structure originate in the quantum fluctuations of the vacuum. Galaxies, stars and ultimately human beings, are then, in principle, traceable to those "phantoms" of the quantum world. Furthermore, some the predictions that are made based on these analysis turn out to fit fantastically well with the empirical data.

On the other hand, this aspect of inflation represents the only situation whereby quantum theory and general relativity coalesce in the explanation of something with direct observable signatures. That is, the large scale structure of the universe, and the most ancient observable imprints left by the primordial inhomogeneities and anisotropies which can be accessed by studies of the cosmic microwave background (CMB), correspond to the single opening we have to a realm which has been otherwise beyond our reach.

Perhaps, it is therefore not so surprising that the study of this subject could lead us to confront some of the most problematic aspects of our theoretical understanding of the physical world: Quantum Theory. Our most spectacularly successful theory and, yet, one for which we have, up to date, no truly satisfactory interpretational framework[1]. This fact probably needs no reviewing for most of the colleagues participating in this meeting, and I certainly should not be the person to do that anyway; however, let me just point out that the so called "measurement problem" has not only intrigued generations of some of the most profound thinkers, but has led some distinguished colleagues to propose modifications of the theory, particularly theories that involve a breakdown of the unitary Shroedinger evolution (i.e. dynamical reduction theories) [2–5]. In considering such modifications, enormous care must be taken to ensure that these changes do not lead to conflict with experiments, as no deviations from quantum theory have ever been observed in the laboratory.

Therefore, the inflationary cosmological regime is remarkable once again, because it offers us the only instance of a true closed quantum mechanical system: the universe, thus providing a particularly clean setting for the analysis of some of the fundamental questions about the quantum world. Finally, I will argue that the emergence of the seeds of structure offers us a question to which traditional quantum theory offers no satisfactory answer: *What is the physical mechanism responsible for generating the inhomogeneity and anisotropy of our Universe, starting from the exactly homogeneous and isotropic vacuum state associated with the early inflationary regime?* This is a clear call for a modification of quantum theory, which, albeit imperceptible in most ordinary situations, should lead to dramatic results in the early universe.

We briefly review the shortcomings of the usual answers to this question provided in the standard accounts, and present our evolving proposal to address these shortcomings in terms of a dynamical collapse of the vacuum state of the inflaton field[6, 7]. Moreover, we will discuss how the details of the CMB can be used to constrain the modifications of quantum theory in the regime at hand.

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[1] For a recent review see for instance S. Weinberg "Collapse of the State Vector", UTTG-18-11. arXiv:1109.6462 [quant-ph].

[2] G. C. Ghirardi, A. Rimini, and T. Weber, "A Unified Dynamics For Micro And Macro Systems", Phys. Rev. D **34**, 470 (1986).

[3] L. Diosi, "A universal master equation for the gravitational violation of quantum mechanics", Phys. Lett. A **120**, 377 (1987).

[4] P. Pearle, "Combining stochastic dynamical state-vector reduction with spontaneous localization", Phys. Rev. A **39**, 2277 (1989).

[5] R. Penrose, "The Emperor's New Mind", Oxford University Press, U.K. (1989); "On Gravity's Role in Quantum State Reduction", Gen. Rel. Grav. **28**, 581 (1996).

[6] A. Perez, H. Sahlmann and D. Sudarsky, "On the quantum origin of the seeds of cosmic structure", Class. Quantum Grav. **23**, 2317 (2006).

[7] D. Sudarsky, "Shortcomings in the Understanding of Why Cosmological Perturbations Look Classical", Int. J. Mod. Phys. D **20**, 509 (2011).

Chaos in de Broglie - Bohm dynamics and its physical consequences

C. Efthymiopoulos[11]

[11] *Research Center for Astronomy and Applied Mathematics, Academy of Athens, Greece*

Quantum systems with moving quantum vortices exhibit *chaotic behavior* of their de Broglie - Bohm trajectories [1]. The dynamical mechanisms leading to chaos are studied in [2][3][4][5]. In these works we give many references to works by other authors on the same subject. Our own main results are the following:

The quantum flow near a moving quantum vortex shows a characteristic structure called 'nodal point - X point complex'. The X point is a stationary point of the instantaneous flow vector field, and it possesses a stable and an unstable asymptotic manifold. Chaos is generated by the approach of the quantum trajectories close to the X-point. In [3] we show that the value of the local Lyapunov exponent for a chaotic trajectory approaching an X-point is an inverse function of the velocity of the nodal point and of the distance of the trajectory normal to the stable manifold of the X-point. Chaos can be shown to affect the precision of integration of the de Broglie - Bohm trajectories, and it may influence the precision of numerical schemes of solution of Schrödinger's equation with quantum trajectories (e.g. [7]).

There are also physical consequences of the chaotic quantum trajectories. An important consequence regards the so-called 'quantum relaxation' effect [6], namely the possibility that a quantum system approaches asymptotically in time the Born's rule equality $p = |\psi|^2$, where p is the particles' probability distribution and ψ the wavefunction, even if initially we allowed that $p_0 \neq |\psi_0|^2$. We note that this possibility presents particular interest in the case of small isolated quantum systems, while an alternative statistical mechanical theory for the emergence of Born's rule was developed in [8]. In our works we provide numerical evidence that chaos is a necessary condition for the quantum relaxation to be effective. However, many quantum systems possess also *regular* trajectories. Then, quantum relaxation effects are suppressed. In [2] examples of this phenomenon are given in the case of i) the two-slit experiment, and ii) a quasi-coherent state evolving in a 2D perturbed oscillator model. A detailed study is made in [9], where we consider the superposition of a small number of eigenstates of the 2D harmonic oscillator model.

Finally, in [10] we investigate the role of quantum vortices in diffraction phenomena, taking as an example electron diffraction by thin crystals. In such cases we find that there is a sharp limit, called separator, between the domains of prevalence of the ingoing and outgoing quantum flow. An array of quantum vortices are formed along the separator. The emergence of the whole diffraction pattern can be explained by the deflection of the quantum trajectories at the quantum vortices. An interesting prediction regards the form of the *arrival time distribution* of electrons scattered at different angles, which can be anambiguously computed in the framework of the Bohmian approach. In fact, we can argue how such a prediction could be probed by experiment.

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[1] de Broglie, L.: 1928, in: J. Bordet (ed) *Electrons et Photons: Rapports et Discussions du 5eme Conseil de Physique*, Gauthier-Villars; Bohm, D.: 1952,*Phys. Rev.* **85**, 166; **85** 194. Bohm, D and Hiley, B.J.: 1993, *The Undivided Universe*, Routhledge; Dürr, D and Teufel, S: 2009, *Bohmian mechanics*, Springer.

[2] Efthymiopoulos C., and Contopoulos, G.: 2006, *J. Phys. A* **39**, 1819.

[3] Efthymiopoulos, C., Kalapotharakos, C., and Contopoulos, G.: 2007, *J. Phys. A* **40**, 12945; 2009, Phys. Rev. E **79**, 036203.

[4] Contopoulos, G., and Efthymiopoulos, C.:2008, *Celest. Mech. Dyn. Astron.* **102**, 219.

[5] Contopoulos, G., Efthymiopoulos, C., and Harsoula, M.: 2008, *Nonl. Ph. Com. Sys.* **11**, 107.

[6] Valentini, A: 1991, *Phys. Lett.* **156**, 5; Valentini, A and Westman, H: 2005, *Proc. R. Soc. A* **461** 253; Bennett, A.: 2010, *J. Phys. A* **43**, 5304; Colin, S., and Struyve, W.: 2010, *New J. Phys.* **12**, 3008; Towler, M.D., Russell, N.J., and Valentini, A: 2011, arXiv1103.1589T.

[7] Wyatt, R.: 2005,*Quantum Dynamics with Trajectories*, Springer; Sanz, A.S., Borondo, F., and Miret-Artés, S: 2002, *J. Phys. D* **14**, 6109; Oriols, X: 2007, *Phys. Rev. Lett.* **98**, 066803.

[8] Dürr, D., Goldstein, S., and Zanghi, N.: 1992, J. Stat. Phys. **67**, 843.

[9] Contopoulos, G., Delis, N., and Efthymiopoulos, C.: 2012. J. Phys. A.: Math. Theor. 45, 165301.

[10] Delis, N., Efthymiopoulos, C., and Contopoulos, G: 2011, *Int. J. Bif. Chaos* (in press), arXiv1103.2621D; Efthymiopoulos, C., Delis, N., and Contopoulos, G: 2012. Ann. Phys. **327**, 438.

From the microscopic to the macroscopic world and the origin of irreversibility

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One way to state the problem of irreversibility is to remark that macroscopic or phenomenological laws, like the diffusion equation, are often not time reversible while microscopic laws, like Hamilton's equations, are time reversible. This is sometimes presented as supporting the claim that macroscopic laws cannot be derived from microscopic ones or that such a derivation requires some arbitrary approximation.

After explaining the connection between microscopic laws and macroscopic ones, I shall explain why the derivation of the latter from the former, including the passage from time reversible to time irreversible laws, although very difficult to justify mathematically, is very natural from a physical point of view. This will also explain the increase of entropy, expressed by the second law of thermodynamics. In fact, this explanation goes back to Boltzmann and is closely related to his notion of entropy. I will also explain why mathematical notions like ergodicity, are not relevant for the explanation of irreversibility [1]. All these notions will be illustrated through the simple example of the Kac ring model.

However, this explanation is coherent only if we make some assumptions on the initial conditions of the universe, and those assumptions are not easy to justify. So, even if the problem of irreversibility, as usually stated, is easy to solve, that solution points to another problem, of a cosmological nature, that is quite open.

[1] Jean Bricmont, Science of Chaos or Chaos in Science?, Physicalia Magazine, **17**, 159-208 (1995) available on http://arxiv.org/pdf/chao-dyn/9603009.pdf

Revealing Bell's Nonlocality in Particle Physics?!

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John Stuart Bell was a well renowned particle physicists with an unpopular hobby at that time, namely his interest in foundations of quantum physics. His discovery of a crucial difference between the predictions of quantum mechanics and the implications of locality and realism, nowadays known as Bell inequalities (BIs), has been tested for many physical systems of ordinary matter and light. Entanglement can be found also for systems usually studied in Particle Physics, i.e. those consisting of strange, charm or beauty quarks, thus it is straightforwardly to ask: **Do such systems usually studied in Particle Physics also violate a Bell inequality? Can a conclusive experiment be performed?**

Investigating BIs for neutral kaon pairs being entangled in strangeness, namely being a particle or an antiparticle state, has shown that there are challenging and novel foundational tasks that are revealed only by these systems. For example, the authors of Ref. [1] showed that a set of BIs lead to $\delta = 0$, where δ is the famous $\mathcal{CP}$ violating parameter in mixing ($\mathcal{C}\ldots$charge conjugation, $\mathcal{P}\ldots$parity). Experimentally, the value $\delta \approx 10^{-3}$ is in clear contradiction to the premises of local realistic theories. Herewith, two different concepts, nonlocality and symmetries in Particle Physics, get surprisingly related, clearly, only available for these systems. Unfortunately, this set of BIs cannot be directly experimentally verified due to experimental limitations and other experimentally feasible setups for Bell tests are not violated by the prediction of quantum mechanics mainly due to the decay property [2].

Indeed, the main problem with this kind of systems explored in Particle Physics it the limitation of observables that are allowed for a conclusive Bell test, their decay property, and the experimental limitations concerning the detection and production of entangled states. Only recently the authors of Ref. [3] succeeded in deriving a new BI taking into account the decay property while not spoiling the conclusiveness and, simultaneously, guaranteeing its testability. Moreover, the proposed test is experimentally feasible with current technology, e.g. with the KLOE detector at the accelerator facility DAPHNE in Italy.

In summary, entangled neutral kaons have turned out to be specially suited to test foundations of quantum mechanics in a way only provided by these systems: e.g. they are very sensitive to possible decoherence effects [4, 5] (see Antonio Di Domenico's talk) that could be caused by quantum gravity, possible $\mathcal{CPT}$ violations, $\ldots$; or that the quantum erasure and marking procedure can be proven in a novel way only provided by this kaonic system [6].

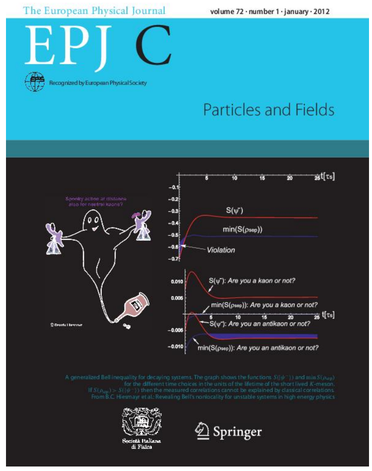

FIG. 1: Frontcover (January 2012) of the Euro. Phys. Journal C [3] highlighting a proposal of a conclusive Bell test in Particle Physics.

[1] R.A. Bertlmann, W. Grimus and B.C. Hiesmayr, Phys. Lett. A 289, 21 (2001).
[2] B.C. Hiesmayr, EPJ C **50**, 73 (2007).
[3] B.C. Hiesmayr, A. Di Domenico, C. Curceanu, A. Gabriel, M. Huber, J.-A. Larsson and P. Moskal, EPJ C 72, 1856 (2012).
[4] R.A. Bertlmann, W. Grimus and B.C. Hiesmayr Phys. Rev. D 60, 114032 (1999).
[5] F. Ambrosino et al., KLOE collaboration, Phys. Lett. B 642, 315 (2006); A. Di Domenico, J. Phys.: Conf. Ser. 171,1 (2008).
[6] Bramon, A. Garbarino, G. & Hiesmayr, B. C. Phys. Rev. Lett. 92, 020405 (2004); ibit, Phys. Rev. A 69, 062111 (2004).

Classical-Quantum Coexistence: a 'Free Will' Test

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Von Neumann's statistical theory of quantum measurement interprets the instantaneous quantum state and derives instantaneous classical variables. In realty, quantum states and classical variables coexist and can influence each other in a time-continuous way. This has been motivating investigations since longtime in quite different fields from quantum cosmology to optics as well as in foundations. Different theories (mean-field, Bohm, decoherence, dynamical collapse, continuous measurement, hybrid dynamics, e.t.c.) emerged for what I call 'coexistence of classical continuum with quantum'. I apply to these theories a sort of 'free will' test to distinguish 'tangible' classical variables useful for causal control from useless ones.

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[1] Diósi L 1999 *Talk at* 'Complexity, Computation and the Physics of Information' (Cambridge, 5-23 July 1999) www.rmki.kfki.hu/~diosi/slides/cambridge.pdf

[2] Diósi L 2004 *Talk at* 'Quantum Theory Without Observers II' (Bielefeld, 2-6 February 2004) www.rmki.kfki.hu/~diosi/slides/bielefeld.pdf

[3] Diósi L 2006 *AIP Conf. Proc.* **844** 133

[4] Diósi L 2011 *Talk at* 'Emergent Quantum Mechanics' (Vienna, 10-13 November 2011) www.rmki.kfki.hu/~diosi/slides/vienna2011.pdf

[5] Diósi L 2012 Classical-Quantum Coexistence: a 'Free Will' Test, arXiv:1202.2472

Semi-classical approximations based on de Broglie-Bohm theory

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Semi-classical gravity is an approximation to the theory of quantum gravity which treats the gravitational field classically and the matter field, say a scalar field, quantum mechanically [1]. The matter is described by a quantum field theory on curved space-time, while the gravitational field is described by Einstein's field equations, with source term given by the expectation value of the energy-momentum tensor operator. It is clear that this approximation can only have a limited domain of validity. For example, it will be valid in cases where the matter behaves approximately classical, but will fail in the case the matter state is a macroscopic superposition.

The purpose of this talk is to consider the possibility of a better semi-classical approach based on the de Broglie-Bohm theory. In the de Broglie-Bohm approach for a quantum field there is also an actual field configuration, whose dynamics depends on the quantum state. The energy-momentum tensor associated to this field may now be considered in the Einstein field equations, instead of the expectation value. However, since this energy-momentum tensor is in general not covariantly conserved, further restrictions or modifications will be necessary to obtain a consistent set of equations.

In order to get a handle on the issues involved, we will mainly focus our attention to the simpler case of scalar quantum electrodynamics. Scalar quantum electrodynamics describes a quantized scalar field interacting with a quantized electromagnetic field. We will consider different formulations of the de Broglie-Bohm approach to scalar electrodynamics (some of which were presented in [2]), discuss how they may naturally lead to semi-classical approximations and identify the conditions under which these approximations are valid. In these approximations, either the scalar field or the electromagnetic field can be treated classically. In the latter case, we have a similar problem as with the energy-momentum tensor in semi-classical gravity if we take the charge current corresponding to the actual scalar field as the source term in the classical Maxwell equations. Namely, due to contributions of quantum mechanical nature, this charge current will in general not be conserved, so that further modifications of Maxwell's equations are required.

Before considering scalar electrodynamics, we will illustrate the key techniques in the context of non-relativistic quantum mechanics. For a system consisting of a light and a heavy particle, there will be situations in which the heavy particle can approximately be described classically. To derive the semi-classical approximation, we will make use of the fact that in the de Broglie-Bohm theory there is a natural definition for the wave function of a subsystem (the *conditional wave function*) and that the classical limit is unambiguous (it arises whenever the motion of the particles is approximately classical). The resulting semi-classical approach has been considered before and was shown to yield better results than the usual semi-classical approach in the case of a simple example [3].

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[1] C. Kiefer, "Quantum Gravity", International Series of Monographs on Physics **124**, Clarendon Press, Oxford (2004).

[2] W. Struyve, "Pilot-wave theory and quantum fields", *Rep. Prog. Phys.* **73**, 106001 (2010) and arXiv:0707.3685v4 [quant-ph].

[3] O.V. Prezhdo and C. Brooksby, "Quantum Backreaction through the Bohmian Particle", *Phys. Rev. Lett.* **86**, 32153219 (2001).

Recent experimental progresses in testing Quantum Mechanics

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Quantum Mechanics is one of the pillars of modern physics: so far a huge amount of theoretical predictions deriving from this theory has been confirmed by very accurate experimental data, while the theory is at the basis of a large spectrum of researches ranging from solid state physics to cosmology, from bio-physics to particle physics. Furthermore, in the last years the possibility of manipulating single quantum states has fostered the development of promising quantum technologies as quantum information (calculus, communication, etc.), quantum metrology, quantum imaging, ...

Nevertheless, even after a pluri-decennial debate many problems related to the foundations of this theory persist [1, 2], like non-local effects of entangled states, wave function reduction and the concept of measurement in Quantum Mechanics, the transition from a microscopic probabilistic world to a macroscopic deterministic world described by classical mechanics (macro-objectivation) and so on. Problems that, beyond their fundamental interest in basic science, now also concern the impact of these developing technologies.

In particular, Bell demonstrated that Local Hidden Variable Theories (LHVT) cannot reproduce all the results of quantum mechanics when dealing with entangled states. Since then many experimental attempts have been made in order to discriminate between these two theoretical frameworks by means of Bell inequalities [1], recently intensified by the application to the emerging field of quantum information. Nevertheless, while a clear space-like separation has been unequivocally achieved, still a conclusive test is missing, because of low detection efficiency and the consequent additional hypothesis that the observed sample is a faithful representation of the whole one, without any anomaly in the hidden variables distribution (the so-called *fair sampling* assumption, leading to the *detection loophole*).
In the last years, relevant progresses for eliminating this loophole have been made [1], both based on improvements of detectors and on the result that for non-maximally entangled states the quantum efficiency limit for the elimination of this problem is lowered from 82% to 66.7% [3, 4]. However, a conclusive experiment is still missing.

Due to this loophole, specific local realistic models (LRM) can still be built. For the most interesting of them specific experimental tests have been proposed [5].

Some of these were realized at INRIM. A first experiment [6] regarded the testing of two specific, restricted local realistic models [7], properly built for experiments with entangled photons; the interesting feature of these models is the fact that they are free from the detection loophole, thus they don't rely on the fair sampling assumption (the quantum efficiency of the system plays a role in the inequalities built for these models). The collected experimental data clearly violated these inequalities, showing instead a perfect agreement with Quantum Mechanics predictions. A second one was a non-classicality test at the single particle level, that excluded a specific restricted class of LRM [8]. Finally, we present some recent results falsifying the model of Ref. [9]

[1] M. Genovese, *Phys. Rep.* **413**/6, 319-398 (2005); Adv. Sci. Lett. 3, 249–258 (2010) and references therein.
[2] S.Adler and A. Bassi, Science 325, 275 (2009);G.Ghirardi,arXiv:0904.0958.
[3] P. H. Eberhard, *Phys. Rev. A* **47**, R747, 2800-2811 (1993).
[4] G. Brida et al., *Phys. Lett. A* **268**, 12-16 (2000).
[5] Dechoum, K., Marshall, T.W., and Santos, E., *Journ. Mod. Opt.*, **47**, 1273 (2000); A. Khrennikov, *Adv. Sci. Lett.* **2** 488 (2009); E. Santos, *Adv. Sci. Lett.* **2** 475 (2009); J. Araujo *et al.*, *Adv. Sci. Lett.* **2** 481 (2009); C. Garola and S. Sozzo, *Europhys. Lett.* **86** 20009 (2009);
[6] G. Brida et al., Eur. Phys. J. D 44, 577–580 (2007).
[7] E. Santos, *Phys. Lett. A* **327**, 33-37 (2004); E. Santos, *Eur. Phys. Journ. D* **42**, 501-509 (2007).
[8] R. Alicki and N. Van Ryn, *J. Phys. A: Math. Theor.* **41**, 062001 (2008);G. Brida et al., *Opt. Expr.* **16**, 11750-11758 (2008); G. Brida et al., *Phys. Rev. A* **79**, 044102 (2009).
[9] M.Richter et al., Journ.Phys.Soc. Japan 81 (2012) 034001.

Uncertain relation studied in neutron's successive spin-measurements

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The uncertainty relation was first proposed by Heisenberg in 1927 as a limitation of simultaneous measurements of canonically conjugate variables owing to the back-action of the measurement[1]: the measurement of the position Q of the electron with the error $\epsilon(Q)$, or 'the mean error', inevitably induces the disturbance $\eta(P)$, or 'the discontinuous change', of the momentum P so that Heisenberg insisted that they always satisfy the relation

$$\epsilon(Q)\eta(P) \sim \frac{\hbar}{2}. \tag{1}$$

Afterwards, Robertson derived another form of uncertainty relation for standard deviations $\sigma(A)$ and $\sigma(B)$ for arbitrary pairs of observables A and B as

$$\sigma(A)\sigma(B) \geq \frac{1}{2}|\langle\psi|[A,B]|\psi\rangle|. \tag{2}$$

This relation has a mathematical basis, but has no immediate implications for limitations on measurements. The proof of the reciprocal relation for the error $\epsilon(A)$ of an A measurement and the disturbance $\eta(B)$ on observable B caused by the measurement is not straightforward. Recently, rigorous and general theoretical treatments of quantum measurements have revealed the failure of Heisenberg's relation (eq.1) and derived a universally valid relation [2, 3] given by

$$\epsilon(A)\eta(B) + \epsilon(A)\sigma(B) + \sigma(A)\eta(B) \geq \frac{1}{2}|\langle\psi|[A,B]|\psi\rangle|. \tag{3}$$

Here, the error $\epsilon(A)$ is defined as the root mean squared (r.m.s.) of the difference between the output operator O_A actually measured and the observable A to be measured, whereas the disturbance $\eta(B)$ is defined as the r.m.s. of the change in observable B during the measurement.

We have experimentally tested the universally valid error-disturbance relation (eq.3) for neutron spin measurements [4]. We determined experimentally the values of error $\epsilon(A)$ and the disturbance $\eta(B)$. A trade-off relation between error and disturbance was clearly observed.

From the experimentally determined values of error $\epsilon(A)$, disturbance $\eta(B)$, and the standard deviations, $\sigma(A)$ and $\sigma(B)$, the Heisenberg error-disturbance product $\epsilon(A)\eta(B)$ and the universally valid expression, that is, the left-hand side of eq.3, are plotted in Fig.1. This figure clearly illustrates the fact that the Heisenberg product is always below the (expected) limit and that the universally valid expression is always larger than the limit in our experiment. This demonstration is the first evidence for the validity of the new relation (eq.3) and the failure of the old naive relation is illustrated. This experiment confirms the solution of a long-standing problem of describing the relation between measurement accuracy and disturbance and sheds light on fundamental limitations of quantum measurements.

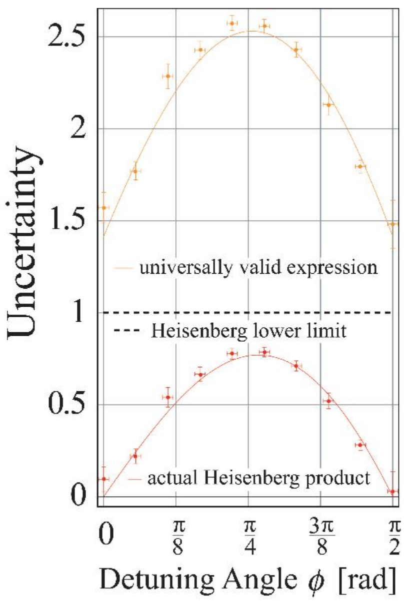

FIG. 1: Experimentally determined values of the Heisenberg product and the three-term sum (eq.3).

[1] J.A. Wheeler and W.H. Zurek (eds) *Quantum Theory and Measurement* (Princeton Univ. Press, 1983).

[2] M. Ozawa, Phys. Rev. A **67**, 042105 (2003).

[3] M. Ozawa, Ann. Phys. **311**, 350–416 (2004).

[4] J. Erhart, S. Sponar, G. Sulyok, G. Badurek, M. Ozawa and Y. Hasegawa, Nature Physics **8**, 185-189 (2012).

Optomechanics: Quantum mechanics at the meso-scale

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The presence of a 'quantum–classical cut' is a familiar enough concept: isolated microscopic objects behave strictly according to the rules of quantum mechanics, whereas the behaviour of larger systems is explained very well by classical physics [1]. Optomechanics [2] is one of the means we have to explore the boundary between these two worlds.

The interaction of light with the motion of massive objects raises the possibility of transferring an engineered non-classical state of the light field to the motional state of a vibrating mirror. A simple example suffices to illustrate this idea. The interaction between light and motion in a Fabry–Pérot cavity with one moving end-mirror can be written [2] as $\hat{H}_{\text{int}} \propto \hat{a}^\dagger \hat{a}\, \hat{x}$, where $\hat{a}$ is the annihilation operator of the cavity field, $\hat{x} = \hat{b} + \hat{b}^\dagger$ the position operator of the mirror, and $\hat{b}$ the annihilation operator of the mirror motion. Under the right conditions, $\hat{H}_{\text{int}} \propto \langle \hat{a} \rangle \big(\hat{a}\, \hat{b}^\dagger + \hat{a}^\dagger \hat{b} \big)$, which is the familiar *beam-splitter Hamiltonian* and can be interpreted physically as mediating the transfer of quantum states between the light and the mechanical motion. By making use of this type of interaction, we will induce strongly non-classical effects in the motion of mesoscopic mechanical systems.

'Non-classicality' in this context has several possible signatures. The relative ease with which, e.g., Fock or Schrödinger cat [3] states of a light field can be prepared, together with the above interaction, hints at the possibility that one might be able to put mechanical oscillators into a non-classical state of this kind. A more intriguing possibility is perhaps to obtain and observe entanglement [4] between optical and the mechanical systems. Beyond entanglement, strongly interacting systems might also demonstrate strongly non-local behaviour, where the shared optical–mechanical state violates Bell's [5] or related inequalities.

Beyond such fundamental applications, optomechanical elements hold promise for quantum information storage and processing. At cryogenic temperatures, coherent storage and manipulation of the state of mechanical oscillators is possible on millisecond timescales. The ease of coupling to such resonators, together with their inherent compatibility with conventional microchip and semiconductor technology makes them a very attractive alternative to cold-atom based quantum memories.

Our recent work touches upon all these considerations. We presented a new configuration for periodic structures interacting with a light field [6] that results in a significant enhancement in the coupling strength, as well as the possibility for observing long-range collective coherent dynamics between physically distant mechanical elements. We are also exploring configurations that make use of non-linear optical processes [7] to generate genuine multi-partite entanglement between multiple light fields and a mechanical oscillator.

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[1] W. H. Zurek, Rev. Mod. Phys. **75**, 715 (2003).

[2] M. Aspelmeyer, S. Gröblacher, K. Hammerer, and N. Kiesel, J. Opt. Soc. Am. B **27**, A189 (2010).

[3] A. Ourjoumtsev, H. Jeong, R. Tualle-Brouri, and P. Grangier, Nature **448**, 784 (2007).

[4] M. Paternostro, *et al.*, Phys. Rev. Lett. **99**, 250401 (2007).

[5] J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, Collected Papers on Quantum Philosophy (Cambridge University Press, 2004)

[6] A. Xuereb, C. Genes, and A. Dantan, *submitted*, pre-print arXiv:1202.0610 (2012).

[7] A. Xuereb, M. Barbieri, and M. Paternostro, *in preparation.*

Quantum mechanics and discrete symmetries of neutral K mesons

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The neutral K meson (kaon) doublet is one of the most intriguing systems in nature. During its time evolution a neutral kaon oscillates between its particle and antiparticle states with a beat frequency $\Delta m \approx 5.3 \times 10^9$ s^{-1}, where Δm is the tiny mass difference between the two physical states K_L and K_S, exponentially decaying with very different lifetimes, $\tau_L \gg \tau_S$. The fortunate coincidence that Δm is about half the decay width of K_S makes possible to observe a variety of intricate quantum interference phenomena in the time evolution and decay of neutral kaons. Such observations, strongly interconnected with the history of particle physics, enabled us to study the interplay of different conservation laws and the validity of various symmetry principles, and also to beautifully test the linear superposition principle of quantum mechanics.

At a ϕ-factory, i.e. an e^+e^- collider running at a center of mass energy corresponding to the ϕ resonance peak, neutral kaon pairs are produced in a pure entangled state, offering new and unique possibilities to study the discrete symmetries and the basic principles of quantum mechanics [1]. For instance a possible violation of the CPT symmetry (where C is charge conjugation, P is parity, and T is time reversal) could manifest in conjunction with tiny modifications of the initial correlation, decoherence effects, or Lorentz symmetry violations, which, in turn, might be justified in a quantum theory of gravity. At a ϕ-factory the sensitivity to some observable effects can reach the level of the interesting Planck's scale region, i.e. $\mathcal{O}(m_K^2/M_{Planck}) \sim 2\times10^{-20}$ GeV, which is a very remarkable level of accuracy, presently unreachable in other similar systems (e.g. the B meson system) [1]. Moreover very recent theoretical studies demonstrated that entangled neutral kaons at a ϕ-factory are suitable to test the foundations of quantum mechanics (see B. Hiesmayr's contribution), such as to test Bell's inequality [2], Bohr's complementarity principle and the quantum erasure and marking concepts [3], the coherence of states over macroscopic distances.

The most recent results on several kinds of possible decoherence and CPT violation mechanisms have been obtained by the KLOE experiment at DAΦNE, the Frascati ϕ-factory [2, 3, 6]. At the moment the results show no deviation from the expectations of quantum mechanics and CPT symmetry, while the precision of the measurements, in some cases, reaches the interesting Planck scale region, and will be further improved with KLOE-2 [4].

[1] A. Di Domenico (ed.) *Handbook on neutral kaon interferometry at a ϕ-factory*, Frascati Physics Series **43**, INFN-LNF, Frascati, 2007.

[2] B.C. Hiesmayr, A. Di Domenico, et al., Eur. Phys. J. C 72 (2012) 1856.

[3] A. Bramon, G. Garbarino, B.C. Hiesmayr, Phys. Rev. Lett. **92** (2004) 020405.

[4] F. Ambrosino et al., KLOE collaboration, Phys. Lett. B **642** (2006) 315.

[5] A. Di Domenico and the KLOE collaboration, Journal of Physics: Conf. Series **171** (2009) 012008.

[6] A. Di Domenico and the KLOE collaboration, Found. Phys. **40** (2010) 852.

[7] G. Amelino-Camelia et al., Eur. Phys. J. C **68** (2010) 619.

Reduction of classical mechanics on quantum physics

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Reduction of classical mechanics onto presumably more fundamental quantum framework necessary involves two clearly distinguished steps. The first step represents some sort of coarse-graining and the second step is a macro-limit corresponding to the particular coarse-graining. In this talk we present a general procedure to formalize the adequate coarse-graining using recently developed [1] description of quantum nonlinear constraints within the framework of Hamiltonian geometric formulation of quantum mechanics. Briefly, a classical system and the corresponding quantum one share the same dynamical algebra g. This algebra determines an equivalence relation on the Hilbert space $\mathcal{H}$ of the quantum system or equivalently on its quantum phase space $\mathcal{M}$. The equivalence classes are parameterized by the points from the submanifold $\Gamma \subset \mathcal{M}$ of the corresponding g-coherent states. In order that the equivalence classes are preserved by the evolution the original Hamiltonian must be constrained on Γ. The constrained Hamiltonian equations preserve minimal the total quantum fluctuations and can be proved to coincide in the macro-limit with the evolution of the classical system. The procedure is illustrated using a system of nonlinear oscillators and a collection of interacting spins [2, 3]. An application of the framework for the nonlinear constraints on hybrid classical-quantum systems is briefly mentioned.

[1] N. Burić, Ann. Phys. (NY), **233** (2008) 17 .
[2] M. Radonjić, S. Prvanović and N. Burić, Phys. Rev. A, **84** (2011) 022103.
[3] M. Radonjić, S. Prvanović and N. Burić, Phys. Rev. A, **85** (2012) 022117.

A Chain of Coupled Pendula Leading to Quantum Relativity

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Any conceptually closed quantum theory which addresses the problem of a quantized space-time structure faces the task of including "rulers" and "clocks" as dynamical subsystems. In view of this challenge, the sine-Gordon theory can serve as a non-trivial toy model.

In addition, the sine-Gordon equation can be formulated as the continuum limit of a classical chain of coupled pendula in a constant gravitational field and, therefore, can be quantized as a nonrelativistic (Newtonian) theory.

The classical equations of motion for the angular variable φ_i of the i-th pendulum in a chain of harmonically coupled pendula (mass m, spring constant D and gravitational constant g) read

$$m\frac{\partial^2\varphi_i(t)}{\partial t^2} = D\Big(\varphi_{i+1}(t) - 2\varphi_i(t) + \varphi_{i-1}(t)\Big) - g\sin\varphi_i(t)\,, \qquad (1)$$

which in the continuum limit becomes

$$\frac{\partial^2\varphi(x,t)}{\partial t^2} = c^2\frac{\partial^2\varphi(x,t)}{\partial x^2} - g\sin\varphi(x,t) \qquad (2)$$

with $c^2 = \frac{Da^2}{m}$ (a being the distance between two neighbored pendula). The continuum limit is valid for $\frac{c}{\sqrt{g}} \gg a$. Equation(2) is Lorentz invariant in the sense that for any solution $\varphi_0(x,t)$ also $\varphi_v(x,t) = \varphi_0(x',t')$ with

$$x' = \gamma(x - vt),\ t' = \gamma(t - \frac{v}{c^2}x),\ \gamma = (1 - \tfrac{v^2}{c^2})^{-\frac{1}{2}} \qquad (3)$$

is a solution. Nevertheless, from an external perspective this is still a Newtonian system.

The sine-Gordon equation has non-trivial solutions [3] — solitons and breathers — which can serve as intrinsic measures for spatial and temporal distances (the width of the solitons and the period of the breathers, respectively). Due to the transformation laws (Eq. 3), the width of a moving soliton shrinks by a factor of $1/\gamma$ and the period of a moving breather increases by a factor of γ. Thus, for an external observer, Lorentz contraction and time dilation are directly observable and measurable. However, "inhabitants" of this (1+1)-dimensional world would experience a relativistic world. The transition from extrinsic to intrinsic measures corresponds to the transition from the Lorentz invariant Newtonian theory to an intrinsically relativistic structure of space and time in the sense of Einstein.

By making the spring constant D position dependent, the theory even allows to discuss the role of dynamical rulers and clocks in the background of a non-trivial geometry.

There are many ways to quantize this theory. Proponents of Bohmian mechanics may want to start from Schrödinger's equation corresponding to (Eq. 1)

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\Psi(\{\varphi_i\},t) = \sum_i\Big(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial\varphi_i^2} + \frac{D}{2}(\varphi_{i+1}-\varphi_i)^2 - g\cos\varphi_i\Big)\Psi(\{\varphi_i\},t)$$

and calculate the quantum potential and the trajectories of the pendula.

The quantum sine-Gordon model is dual to a massive Thirring model ([1, 4])

$$(-\mathrm{i}\hbar\gamma^\mu\partial_\mu - m)\psi(x) = g\gamma^\mu(\bar{\psi}(x)\gamma_m u\psi(x))\psi(x) \qquad (4)$$

(where $\psi = (\psi_1, \psi_2)$ is a two-component spinor, $\mu = 0, 1$, and $\gamma^0 = \sigma_1$ and $\gamma^1 = -\mathrm{i}\sigma_2$ are Pauli matrices). The soliton solutions become the fundamental particles of the Thirring model.

Both, the quantum sine-Gordong equation and the massive quantum Thirring model are integrable by quantum inverse scattering methods [2]. Therefore, the quantum sine-Gordon theory provides an integrable toy model for dynamical quantum rulers and quantum clocks.

[1] Coleman, S.; *Quantum sine-Gordon equation as the massive Thirring model*; Phys.Rev. D 11 (1975) 2088–2097.

[2] Korepin, V.E., Bogoliubov, N.M., Izergin, A.G.; *Quantum inverse scattering method and correlation functions*; Cambridge Monographs on Mathematical Physics, Cambridge University Press (1993).

[3] Lamb Jr., G.L.; *Elements of solition theory*, Wiley, New York, 1980.

[4] Mandelstam, S.; *Soliton operator for the quantized sine-Gordon equation*; Phys.Rev. D 11 (1975) 3026–3030.

Selfconsistent canonically quantized SU(3) Skyrme Model for Baryons

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The SU(3) Skyrme model is traditionally considered as a semiclassical system describing a rigid quantum rotator with the profile function being determined by the classical solution of the SU(2) Skyrme model. In this work we go beyond the semiclassical limit and quantize the model canonically using the formalism of the collective coordinates. The canonical quantization leads to the establishment of purely quantum mass corrections of the model that are absent in the semiclassical approach [1]. These corrections are of a fundamental importance. They are crucial in obtaining stable solitonic solutions of the quantum SU(3) Skyrme model, thus making the model selfconsistent. In contrast, in the semiclassical approach where the quantum corrections are absent, the variation of the energy functional does not lead to a stable solitonic solution.

The canonical quantization realizes the T.H.R. Skyrme's conjecture *that mass (of pion) may arise as a selfcosistent quantal effect* [2]. These quantum mass corrections play an important role in obtaining an exponentially decaying asymptotic profile function which ensures the required exponential decay of the mass density of the quantum soliton. This can be interpreted as the appearance the effective mass for the meson field. Such treatment of the model conversely to the semiclassical case leads to a family of the stable solitons with quantum numbers that correspond to the individual baryons in the baryon octet and decuplet. Interestingly, the stability is preserved even if the Wess-Zumino-Witten and the symmetry breaking terms are not included into the model.

The SU(3) Skyrme model is parametrized by four parameters, f_π, m_0^2, m_8^2 and e, which are of phenomenological origin. The possible input parameters for the model are the nucleon mass $m_N = 939$ MeV, the asymptotic nucleon mass $m_N^{\text{as}} = m_\pi = 137.7$ MeV, the mean nucleon isoscalar (electric) radius $\langle r^2\rangle^{1/2} = 0.78$ fm, and the mass of one of the heavier baryons (e.g. m_Λ or m_Σ). We began the fitting procedure with profile function of the classical SU(2) Skyrme model and found the integrals and parameters of the SU(3) model by requiring to reproduce the physical properties of nucleon and arbitrary heavier baryon. With new parameters we minimized the energy functional and found the first approximation of the quantum profile functions. We repeated the iteration procedure until the convergent solution of profile function, integrals and parameters are obtained. After fitting of the model parameters to the input parameters the selfconsistent stable solitons are found for a wide spectrum of baryons. Our numerical results of the baryon mass spectrum and some other physical parameters are in a good agreement with the experimental data.

[1] D. Jurciukonis, E. Norvaisas, D. O. Riska, J. Math. Phys. **46**, 072103 (2005).
[2] T. H. R. Skyrme, Nucl. Phys. **31**, 556 (1962).

Simulating non-local correlations with local, non-positive models

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In 1964 Bell showed that it was impossible for any reasonable, local theory to agree with the predictions of quantum theory [1]: if quantum theory gives accurate predictions of experimental observation then the universe is undeniably non-local in some sense. This non-locality is one of the more disconcerting phenomena to be found in quantum theory, since it appears to violate at least the spirit of Einstein's theories of Relativity.

However, it remains impossible to transmit information superluminally via quantum operations[2], hence quantum theory satisfies a kind of "non-signaling condition". Whilst this goes some way towards a reconciliation with Relativity, it turns out that there are other conceivable non-signaling physical theories which generate correlations that violate Bell's Theorem to an even greater degree[3].

An experiment involving many systems $A_1, \ldots, A_N$ can be characterized by the distribution $p(a_1, \ldots, a_N | x_1, \ldots, x_N)$, giving the probability of party i obtaining outcome a_i when performing a measurement on system A_i with setting x_i.

The distribution p is said to be *non-signaling* if, for any subset $\{i_1, \ldots, i_k\}$ of the systems, the expression

$$\sum_{a_{i_1}, \ldots, a_{i_k}} p(a_1, \ldots, a_N | x_1, \ldots, x_N) \qquad (1)$$

does not depend on the values of $x_{i_1}, \ldots, x_{i_k}$. We say that p is *quantum* whenever it can be acheived through measurements on quantum systems, i.e. there exists a set of POVM elements $M^{(i)}_{a_i|x_i}$ for each system i and a density matrix ρ such that

$$p(a_1, \ldots, a_N | x_1, \ldots, x_N) = tr\left(\rho \left(M^{(1)}_{a_1|x_1} \otimes \ldots \otimes M^{(1)}_{a_1|x_1}\right)\right). \qquad (2)$$

The set of quantum distributions is strictly smaller than the full set of non-signaling distributions. By understanding how quantum correlations are unique within the full set of non-signaling correlations, one can hope to build intuition about the information theoretic properties of quantum theory. It has recently been shown[4] that a distribution p is non-signaling if, and only if, one can find POVM elements $M^{(i)}_{a_i|x_i}$ for each system i, and a (not necessarily positive) trace-1, Hermitian operator O such that

$$p(a_1, \ldots, a_N | x_1, \ldots, x_N) = tr\left(O \left(M^{(1)}_{a_1|x_1} \otimes \ldots \otimes M^{(1)}_{a_1|x_1}\right)\right). \qquad (3)$$

The set of quantum correlations is then recovered exactly by enforcing the positivity of O. We show[6] that this result can be somewhat strengthened: whenever p is non-signaling, there in fact exists a set of POVM elements and an operator O as before, so that all matrices involved are simultaneously diagonalisable and expression (3) holds. In this setting, all measurements commute and the state is much like a classical mixture of local states, except that some of these states involve "negative probabilities".

Moreover, we also prove a dual statement: p is non-signaling if, and only if, there exists a *quantum* state O and (not necessarily positive) operators $M^{(i)}_{a_i|x_i}$, all diagonal in the same basis, such that $\sum_{a_i} M^{(i)}_{a_i|x_i} = \mathbb{I}$ and (3) holds. In this case O is separable and all measurement operators are local, yet surprisingly non-local distributions can still be simulated.

Locality can therefore be recovered in some sense, by trading off the requirement that the outcomes of unperformed measurements occur with positive probabilities.

[1] J. S. Bell, "On the Einstein-Podolsky-Rosen paradox," *Physics*, vol. 1, pp. 195-200, 1965.

[2] G. C. Ghirardi *et al* "A general argument against superluminal transmission through the quantum mechanical measurement process," *Lettere Al Nuovo Cimento* vol. 27, pp. 293-298, 1980

[3] S. Popescu and D. Rohrlich, "Quantum nonlocality as an axiom," *Foundations of Physics*, vol. 24, pp. 379-385, 1994.

[4] A. Acín *et al*, "Unified framework for correlations in terms of local quantum observables," *Phys. Rev. Lett.*, vol. 104, p. 140404, 2010.

[5] S. W. Al-Safi and A. J. Short, in preparation.

Pilot Qubit Based Quantum Satellite Communications

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From the engineering point of view, the quantum circuits built from different quantum gates give many possibilities to perform computational calculations in a more efficient way than the nowadays used traditional computers [1]. Although quantum computers are still the tools of the future, there are promising quantum based applications, mainly in the field of communication [2].

An interesting question is how an efficient error correction method can be realized over a noisy quantum channel. There are many solutions, e.g., the bit flip code, the Shor code, the Steane code, however, they are redundancy based solutions [3] [4] [5].

Our approach uses pilot qubits for the correction. In classical systems, the pilot bits help in the coherent communication. The two communication parties either agree on the pilot bits, or these bits are well-defined by the protocol. Since these symbols and the specific multiplexing scheme are known for the receiver, the receiver can use them for channel estimation, receiver adaptation and optimal decoding. One example is the GSM system which uses 26 pilot bits in every packet [6].

In our approach, pilot qubits and data qubits are sent over a noisy quantum channel between the two communication parties, Alice and Bob. The protocol consists of two main parts, an initialization process and the communication process. During the initialization process, Alice sends pilot quantum bits through the quantum channel, and Bob receives pilot states. Since the channel performs a unitary transformation on the quantum bit, the error of the channel will be encoded into the quantum state received by Bob. The channel is considered to be constant during the communication, which means Alice must send the pilot qubits only once before the communication. During the communication process, Alice sends data qubit over the quantum channel. Bob receives a damaged qubit from Alice and tries to correct it. In current quantum error correction methods, Bob needs several redundant qubits from Alice to restore the original qubit. In this approximation, Bob does not need redundant qubits from Alice, because he uses pilot qubits to restore the original quantum bit with a given probability. We showed how this probability can be increased using an l-length pilot qubit register, and how Bob can construct the necessary l-length pilot quregister from the single pilot qubits sent by Alice. This error coding technique can be useful in satellite-satellite quantum communications.

As another aspect of the quantum based space communication, we dealt with the theoretical analysis of weak laser signal based satellite communications. We took our current technology into account, and we developed a physical model to describe the quantum communication over space-space, Earth-space and space-Earth links. We analyzed the quantum bit error rate (QBER) of different protocols, i.e., superdense coding, BB84 and B92.

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[1] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information. Cambridge: Cambridge University Press, 2000. ISBN 9780521635035.

[2] S. Imre and B. Ferenc, Quantum Computing and Communications: An Engineering Approach. Wiley, 2005. ISBN 9780470869024.

[3] D. Poulin, Stabilizer formalism for operator quantum error correction, Phys. Rev. Lett., vol. 95, Dec 2005.

[4] P. W. Shor, Scheme for reducing decoherence in quantum computer memory, Phys. Rev. A, vol. 52, pp. 24932496, Oct 1995.

[5] A. R. Calderbank and P. W. Shor, Good quantum error-correcting codes exist, Phys. Rev. A, vol. 54, pp. 10981105, Aug 1996.

[6] J. Eberspacher and H.-J. Vogel, GSM Switching, Services and Protocols. New York, NY, USA: John Wiley & Sons, Inc., 1999.

Testing Quantum Theory with Chiral Molecules

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Although quantum mechanics has obtained many successes since its formulation, it has also generated puzzles that persist to this day. These puzzles, which are clearly manifested in measurement problem, are mainly connected to the linearity of the dynamics and its validity. Coping with these puzzles, some physicists believe one has to modify quantum mechanics by some nonlinear corrections [1]. Recently there is great interest in experiments to create quantum delocalization and the superposition for of many-particle complex systems, with the ultimate aim of testing the validity of quantum linearity and quantum-to-classical transition [2]. Here, we will provide a new approach that can be used as a guide to new experiments in this field.

We study the superposition of molecular structures of chiral molecules, as an example of internal quantum delocalization [3, 4, 6]. These superpositions are conceptually different from the usual macro-molecules superpositions which are delocalized states of center-of-mass of molecules. These are superpositions of internal molecular variables. These superpositions are very sensitive toward environmental perturbations. The destruction of these delocalized internal states of the molecules can also be related to nonlinear quantum effects, e.g. the ones predicted by collapse models [1].

To observe the fundamental nonlinearity, one has to eliminate the environmental decoherence effects as far as possible. Thus, the first challenge is quantification of the environmental decoherence effect. Several attempts have been made to quantify the robustness of superposition of chiral states toward the environmental perturbations [6]. The methods proposed so far usually demands quite heavy numerical calculations.

Using the quantum Brownian motion [6], we first provide a simple and applicable method to compute the dominant contribution to the value of the decoherence effect due to the environmental scattering [3]. We envisage the superposition of chiral states as the spatial superposition of atoms or groups of atoms between two minima of a double-well potential, where the chiral states are given by localized wavepacket in each minima. Thus, we were able to compute the environmental decoherence effect with quantum Brownian motion, and also to compute the fundamental collapse effects with Continuous Spontaneous Localization model [1, 7].

To observe the fundamental collapse effects, we suggest the hybrid of the phase-locked laser pulses with the wavepacket interferometry (in particular nonlinear spectroscopy in a supersonic jet) where one is able, in principle, to observe the decay of quantum coherence of chiral states (i.e., the decay of spatial coherence between two localized wavepackets) due to fundamental collapse effects [7]. We provide the corresponding quantifications and calculations.

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[1] J. A. Leggett Suppl. Prog. Theor. Phys. **69**, 80 (1980); Phys.: Condens. Matter **14**, R415 (2002). S. Weinberg arXiv:1109.6462 (2011). S. L. Adler, and A. Bassi, Science **325**, 275 (2009). A. Bassi and G. C. Ghirardi, Phys. Rept. **379**, 257 (2003).

[2] J. R. Friedman *et al.* Nature (London) **406**, 43 (2000). S. Delglise *et al.* Nature **455**, 510-14 (2008). K. Hammerer *et al.* Rev. Mod. Phys. **82**, 1041-1093 (2010). M. Arndt *et al.*, Nature **401**, 680 (1999). S. Gerlich *et al.*, Nature Comm. **2**, 263 (2011). T. J. Kippenberg and K. J. Vahala, Science **321**, 11726 (2008). Oriol Romero-Isart, Phys. Rev. A **84**, 052121 (2011). S. Nimmrichter *et al.* Phys. Rev. A **83**, 04362 (2011).

[3] M. Bahrami, A. Shafiee, Comput. Theoret. Chem. **978** (2011) 84-87. M. Bahrami, A. Bassi, Phys. Rev. A. **84**, 062115 (2011). M. Bahrami, A. Shafiee, A. Bassi, Phys. Chem. Chem. Phys., DOI:10.1039/C2CP40920H.

[4] J. A. Cina and R. A. Harris, Science **267**, 832 (1995). C. S. Maierle *et al.*, Phys. Rev. Lett. **81**, 5928 (1998). M. Quack, Angew. Chem. Intl. Ed. (Engl.) **41**, 4618 (2002) and references therein.

[5] R. A. Harris, L. Stodolsky, J. Chem. Phys. **74**, 2145 (1981); J. Chem. Phys. **78**, 7330 (1983). J. Trost, K. Hornberger: Phys. Rev.Lett. **103**, 023202 (2009).

[6] B. Vacchini and K. Hornberger, Phys. Rep. **478**, 71-120 (2009).

[7] M. Bahrami, A. Bassi, in preparation.

The projected hidden influence polytope in the tripartite case

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Quantum correlations have very intriguing properties. First and foremost the concept of non-locality that was first demonstrated in [1]. The hope of restoring a continuous picture using local variables was disproved by Bell's original work [2]. The possibility to explain quantum correlations via hidden influences propagating at a speed $v > c$ has acquired a lot of attention recently. The idea was brought forward by V. Scarani and N. Gisin in [3]. However, the paper demonstrated that in such a case and if no local variables are involved, the influence could not remain hidden and would therefore lead to signalling. Very recently the proof could be extended to include the case where local variables are involved too, see [5]. Quantum non-locality played an important role in the argumentation given. More precisely a quantum state that violates a certain Bell inequality was found by studying the hidden influence polytope for 4 parties. For the derivation of the main result, in other words to establish the signalling property of such a model, this inequality was crucial.

To be able to underline this result it would be very favorable to find a quantum state whose preparation is technically less involved and that is more robust to noise in order to conduct a real experiment. The combination of the evidence provided by such an experiment and the work mentioned above excludes a lot of directly conceivable explanations of quantum correlations. It is in the light of this conclusion that the search of a suited quantum state gains its importance.

The starting point of these investigations was given by the urge to find an accomplishable experiment. The most promising approach is believed to be the case where only three parties are involved. Therefore in the work at hand, a more systematic study of the hidden influence polytope in the three partite scenario was undertaken. We conducted the search a long the same lines as given in [5].

For the simplest scenario with binary inputs and outputs, we show that the projection of the non-signalling and the hidden influence polytope coincide. A special case of this can be ruled out by appealing to the monogamy of correlations as was already pointed out in [4]. Here, however, we rule out the possibility of quantum, as well as non-signaling violations in general. In contrast, in certain more general cases, non-signalling violations could be found. We broadened the area of our studies by varying the number of inputs and outputs. First promising results were achieved in the three outputs case; interestingly, this could already be achieved in the case where not all of the parties make use of three outputs. Therefore in the further course of this work the scenarios where the parties do not necessarily have three outputs for each input were scrutinised in more detail. Two of these more general polytopes could be characterised completely. During this procedure we encountered new families of extremal points inequivalent to the local deterministic strategies or the lifted PR box. For the completely solvable cases we could either again demonstrate that the polytope is equal to the non-signalling one or we excluded the possibility of quantum violations. In other words no-go results were achieved. Substantial progress was made in the other scenarios were partial knowledge of the hidden influence polytope could be gained. In particular a list of inequalities could be found that act as a separating hyperplane for the projected hidden influence polytope. The latest development was to extend the generalisation to such an extent that one party possessed four inputs that again were equipped with four outputs each. The analysis of this scenario is still ongoing.

It remains an open question if a quantum state violating the hidden influence constraints can be found that is robust against noise as well as easily producible experimentally.

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[1] A. Aspect *et al.*, Phys. Rev. Let. **49** (25), 1804 (1982).
[2] J. S. Bell, Physics **1** (3), 195 (1964).
[3] V. Scarani and N. Gisin, Brazilian Journal of Physics **35** (2), 328 (2005).
[4] S. Coretti, E. Hänggi and S. Wolf, Phys. Rev. Let. **107** (10), 100402 (2011).
[5] J-D. Bancal *et al.*, arXiv:1110.3795v1 (2011).

Generation and quantum correlations of triple photon states of light

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Triple photon generation (TPG) is a third order nonlinear optical interaction that corresponds to the creation of three highly correlated photons from the annihilation of a photon of higher energy through a nonlinear material. This is the most straightforward way to produce pure triple photon quantum entangled states. Such states are Greenberger-Horne-Zeilinger (GHZ) states, with a statistics going beyond the usual Gaussian statistics of twin states [1]. They are therefore new powerful tools to study the properties of quantum mechanics, and also offer outstanding potential applications in the field of quantum information.

In 2004, our group achieved the pioneer experiment of TPG stimulated by two seeding fields in a phase-matched KTP crystal [2]. In the present analysis, we aim to study the fields created from a sum-frequency generation (SFG) based on the recombination of pairs or triplets of photons in order to exhibit the quantum properties of the triplet states, as the recombination-born field holds information on the correlations of the fields that gave rise to it [3].

Original quantum calculations have been performed for both generation and recombination schemes, following the work of B. Dayan in the case of twin photons [4]. They allow us to know all quantum field operators in any position of the nonlinear crystal. We report both calculations and latest experiments.

In particular, third-order and second-order SFG are considered for triplet photons generated by parametric fluorescence and by stimulated parametric generation. Our calculations show that in the parametric fluorescence generation scheme, the quantum correlations of the triplet photons induce a strong signature in the spectrum of the SFG field, which is absent if classical fields are considered. However, in the stimulated case, the nonclassical signature of triplet photons depends on the optical intensity of the stimulating fields. The SFG fields spectra in the parametric fluorescence or low-injection generation schemes show a very preferential recombination of triplet photons together, leading to a three-photon summed field that is the exact copy of the pump spectrum, and to a two-photon summed field depending on the third nonsummed field, due to energy conservation of each triplet of photons.

These original studies points out the quantum link triple photons share and open the door to new fundamental results in quantum optics.

[1] D.M. Greenberger, M.A. Horne, A. Shimony and A. Zeilinger, Am. J. Phys. **58**, 1131-1143 (1990)

[2] J. Douady and B. Boulanger, Opt. Lett. **29** (23), 2794-2796 (2004)

[3] A. Dot, A. Borne, K. Bencheikh, B. Boulanger, and J.A. Levenson, Phys. Rev. A, under press (2012)

[4] B. Dayan, Phys. Rev. A **76** 043813 (2007)

Quantum cryptography with week randomness

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Quantum physics is a unique source of a valuable property used in most of common cryptography applications - randomness. Whereas any device based on laws of classical physics can provide only pseudorandom outcome (and thus possibly correlated to some adversary), Quantum Random Number Generators (QRNG) relay on the intrinsic quantum randomness originating from measurements in complementary bases. Even though QRNG reached a state where they are commercially available, they partially rely on classical post-processing and are potentially vulnerable against side-channels attacks.

However the intrinsic randomness is not the only advantage of quantum physics if used for cryptography. As we show here, a simple use of a quantum channel in a prepare-measure setting (where pure states of qubits are prepared and they are measured exclusively in their bases) can significantly enhance the security of communication by using a classically (or even quantumly) prepared imperfect random key.

Imagine a following scenario. Alice would like to send a secret bit to Bob, whereas they share a secret random key with its level of randomness expressed via the min-entropy

$$H_\infty(\mathbf{Z}) = \min_{z\in Z}\left(-\log Pr\left(\mathbf{Z}=z\right)\right). \qquad (1)$$

We denote a source as (l, b)-source if it is emitting l-bit strings drawn according to a probability distribution with min-entropy at least b. Notice that for $b = l - c$, the probability of each l-bit string is upper bounded by $2^c \frac{1}{2^{-l}}$ and parameter c is called min-entropy loss.

In the classical scenario, Alice would use the random key to encrypt the bit and send it to Bob. The probability of any adversary to correctly guess the bit is lower bounded by [1]

$$p \geq \begin{cases} 1 & \text{for } 2 \leq c \leq l \\ \frac{1}{2} + \frac{2^c}{8} & \text{for } 2 - \log_2 3 \leq c \leq 2 \\ \frac{2^c}{2} & \text{for } 0 \leq c \leq 2 - \log_2 3. \end{cases} \qquad (2)$$

In quantum scenario with one-qubit channel, Alice would decode the secret bit into one of a set of states of a qubit depending on the random key. Bob, knowing the key, would just measure the state in the correct basis and always decipher correctly. The amount of information accessible to the adversary is limited by his ability to adjust his basis correctly and can be upper bounded by

$$p = 1 - h/4 = 1 - 2^{-c-1}. \qquad (3)$$

In the Figure 1 we show the comparison between the classical and quantum bound. As one can see, the security for the quantum scenario is always higher than in the classical one, moreover, quantum scenario allows for a certain level of security even if only very weak randomness is provided, which deeply contrasts the classical results, where the loss of just two bits of randomness causes complete revealing of the transmitted information. More detailed analysis can be found in [2].

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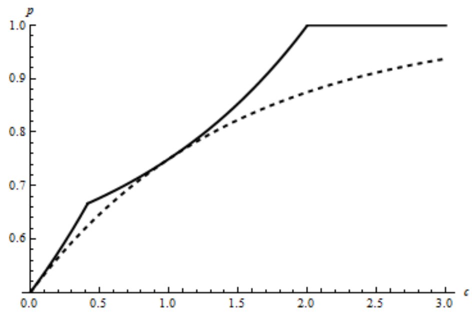

FIG. 1: Comparison of the probability of a successful guess by the attacker, if Alice and Bob use classical channel (full line) and quantum channel (dashed line).

[1] J. L. McInnes and B. Pinkas. On the impossibility of private key cryptography with weakly random keys. In *Crypto'90*, pages 421–435, 1991. LNCS

537.
[2] J. Bouda, M. Pivoluska, and M. Plesch. Encryption with Weakly Random Keys Using Quantum Ciphertext *arXiv:1109.1943v1*, 2011.

Hydrogen Atom in Spaces with Compactified Extra Dimensions and Potential Defined by Gauss' Law

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Unification theories, predicting extra dimensions, have made the study of higher-dimensional models of great importance. One surprisingly simple question, which has not been completely answered yet, is what happens to ordinary atoms when more than the usual three dimensions are present.

Although many existing articles cover the topic of N-dimensional hydrogen atoms, the potential therein is mostly considered to be proportional to $1/r$, irrespective of the the number of spatial dimensions. However, as many authors have pointed out (see e.g. [3–6]), the physically more justified potential is that which corresponds to the solution of Maxwell's equations in N-dimensional space, i.e. $V_N(r) \sim r^{2-N}$. Questions of stability, arising by defining the hydrogen potential in such a manner, are still open.

The present work focuses on the case of four-dimensional spaces. First, we consider the extra space-like dimension to be non-compactified. For charge $Z < 1$ there are no bound states and for $Z > 1$ the continuous spectrum is unbounded from below. The latter fact is also shown by using a trial function. Hence, the hydrogen atom is not stable if the additional dimension is non-compactified (cf. [2, 3]).

However, the main scope of this work is to explore the consequences of one additional compactified dimension for the stability of the non-relativistic hydrogen atom, defined through the potential

$$V(x) := -\sum_{n=-\infty}^{\infty} \frac{Z}{x_1^2 + x_2^2 + x_3^2 + (x_4 - c_n)^2}$$

where $r^2 := x_1^2 + x_2^2 + x_3^2$, $c_n := 2\pi n$, see details in [2].

We have argued that, as a result of compactification, a lower bound is present in the energy spectrum and the four-dimensional hydrogen atom in a compactified universe is stable for $Z < 1$, i.e. with the same critical charge as in the non-compactified version. The rigorous approach using Hardy inequality will be presented in [1]. It uses a local modification of the Hardy inequality and the KLMN theorem.

Finally, we argue that for $Z > 1$, the hydrogen atom is no longer stable. To show this, we employ a trial function to show that the continuous energy spectrum extends to minus infinity. Details will be given in [1].

Acknowledgments

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[1] Bureš, M., Siegl, P. *Stability of the Hydrogen Atom in Spaces with Compactified Extra Dimensions and Potential Defined by Gauss' Law.* Work in progress.

[2] Bureš, M. *Atoms In Compactified Universes.* Master's thesis, Masaryk University Brno (2007).

[3] Gurevich, L., Mostepanenko, V. *On the existence of atoms in n-dimensional space.* Physics letters 35 A, 201-202 (1971).

[4] Andrew, K., Supplee, J. *A hydrogenic atom in d-dimensions.* Amer. J. Phys. 58, 1177 (1990).

[5] Morales, D. A. *Analytical formulas for the eigenvalues and eigenfunctions of a d-dimensional hydrogen atom with a potential defined by Gauss' law.* Int. J. Quantum Chem., 57: 7"15 (1996).

[6] Braga, Nelson R. F., D'Andrea, R. *Bound states for one-electron atoms in higher dimensions.* arXiv:quant-ph/0511078 (2005).

Entanglement, fractional magnetization and long range interactions

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Fractionalization of quantum numbers has attracted a lot of attention in the last years, since it was shown to be connected to most of the fundamental concepts in condensed matter physics, such as conductivity, topological order, degeneracy or criticality. The same applies to *locality*, that is, those properties in quantum many body systems arising from local interactions. Motivated by a Quantum Information perspective, a lot of effort has been devoted lately to understanding the complexity that these systems can generate by showing, on the one hand, that they are simple enough to obey an area law [1] and, on the other, that they still keep enough complexity to make their study intractable [2].

Quantum Information and, in particular, the concept of entanglement, has produced a considerable impact on the understanding of strongly correlated quantum systems, shedding new light on the behavior of quantum phase transitions, topological order and renormalization. Many of these contributions have been made using the so-called Matrix Product States (MPS) [3, 4] and their higher dimensional generalization [5], which have proven to be the exact family of quantum states needed to explain low energy sectors of locally interacting quantum systems.

In this talk, I will explain how using MPS theory we can put on mathematical grounds the belief that a large fractionalization of a quantum number, such as magnetization, or the impossibility of understanding a quantum state as the ground state of a local Hamiltonian, must require large entanglement in the considered system. This shows that MPS are powerful enough to provide formal proofs of believed statements on strongly correlated spin systems that were lacking a mathematical treatment.

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[1] J. Eisert, M. Cramer, M.B. Plenio, Rev. Mod. Phys. 82, 277-306 (2010).

[2] D. Gottesman, S. Irani, arXiv:0905.2419; D. Aharonov, D. Gottesman, S. Irani, J. Kempe, Comm. Math. Physics, vol. 287, no. 1, pp. 41-65 (2009); A. Yu. Kitaev, A. H. Shen, and M. N. Vyalyi. *Classical and quantum computation*, volume 47 of Graduate Studies in Mathematics. AMS, Providence, RI, 2002.

[3] D. Pérez-García, F. Verstraete, M.M. Wolf, J.I. Cirac, Quantum Inf. Comput. 7, 401 (2007).

[4] M. Fannes, B. Nachtergaele and R. F. Werner, Commun. Math. Phys. **144**, 443-490 (1992).

[5] F. Verstraete, J.I. Cirac, arXiv:cond-mat/0407066.

No extension of quantum theory can have improved predictive power

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According to quantum theory, measurements generate random outcomes, in stark contrast with classical mechanics. This raises the question of whether there could exist an extension of the theory which removes this indeterminism, as suspected by Einstein, Podolsky and Rosen [1]. Although this has been shown to be impossible, existing results do not imply that the current theory is maximally informative. Here we ask the more general question of whether any improved predictions can be achieved by any extension of quantum theory.

We make two assumptions:

Assumption QM: quantum theory is correct in the sense that (a) measurement outcomes obey the statistical predictions of quantum theory, and (b) all processes within quantum theory can be considered as unitary evolutions if one takes into account the environment.

Assumption FR: measurement settings can be chosen freely, i.e., to be independent of all variables not in their future lightcones.

Consider then a measurement which depends on a setting A and produces an output X. According to Assumption QM, we can associate a quantum state and measurement operators with this process such that the distribution $P_{X|A}$ is that predicted by quantum theory. An extension of quantum theory would provide us with additional information, Z, that would enable a better prediction of the outcome, X. Conversely, if Z doesn't provide better predictions, we have $P_{X|AZ} = P_{X|A}$.

Main claim: under the above assumptions, no extension of quantum theory can give more information about the outcomes of future measurements than quantum theory itself.

The argument consists of three parts. In the first two, we use a Bell-type setting, involving measurements on a maximally entangled state. We consider two spacelike separated measurements, denoting the measurement choices A and B, and the respective outcomes X and Y and, as above, we introduce some additional information, Z. In Part I of the argument, we show that Assumption FR implies that $P_{X|ABZ} = P_{X|AZ}$ and $P_{Y|ABZ} = P_{Y|BZ}$. In Part II, inspired by a result in quantum cryptography [2], we show that for a particular set of bipartite correlations (the chained Bell correlations [3, 4]), if the above conditions hold, then there cannot exist any Z that gives better predictions about the outcome X. In the final part of the argument, we use the second part of Assumption QM to argue that this conclusion also applies to all measurements on an arbitrary (pure) quantum state. Together, these establish our claim.

We remark that several other attempts to extend quantum theory have been presented in the literature, the de Broglie-Bohm theory [5, 6] being a prominent example (this model recreates the quantum correlations in a deterministic way but uses non-local hidden variables). Our result implies that such theories necessarily come at the expense of violating Assumption FR.

Our result has significance for the foundations of quantum mechanics as well as applications to tasks which exploit the inherent randomness in quantum theory, such as quantum cryptography.

For more details, see the full paper [7], joint work with Renato Renner.

[1] Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of physical reality be considered complete? *Physical Review* **47**, 777–780 (1935).

[2] Barrett, J., Hardy, L. & Kent, A. No signalling and quantum key distribution. *Physical Review Letters* **95**, 010503 (2005).

[3] Pearle, P. M. Hidden-variable example based upon data rejection. *Physical Review D* **2**, 1418–1425 (1970).

[4] Braunstein, S. L. & Caves, C. M. Wringing out better Bell inequalities. *Annals of Physics* **202**, 22–56 (1990).

[5] de Broglie, L. La mécanique ondulatoire et la structure atomique de la matière et du rayonnement. *Journal de Physique, Serie VI* **VIII**, 225–241 (1927).

[6] Bohm, D. A suggested interpretation of the quantum theory in terms of "hidden" variables. I. *Physical Review* **85**, 166–179 (1952).

[7] Colbeck, R. & Renner, R. No extension of quantum theory can have improved predictive power. *Nature Communications* **2**, 411 (2011).

Quantum discord at the quantum-classical boundary

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The boundary between the quantum and the classical world is undoubtedly of fundamental importance to a broad range of disciples from cosmology to quantum and atom optics to quantum measurement theory. Impetus has been provided on some of these fronts by developments in quantum information science, which make available tools for the direct observation of systems that straddle the gap between the quantum and the classical. In that spirit, I will discuss the presence of quantum discord as a signature of quantumness. The classicality of a state induced by quantum discord is defined in terms of its eigenvectors. This is quite different from the distinction between separable and entangled states, which pays no attention to the properties of the joint state's eigenvectors; a state is separable if and only if it has an ensemble decomposition- not an eigendecomposition - in terms of product states. Interestingly, for pure quantum states, these two conditions, based on discord and entanglement, coincide. This reveals that mixedness, or the lack of purity of a quantum state must play a fundamental role in deciding the quantum-classical boundary. This is a facet of the problem that is rarely explored, but I will discuss.

Quantum information science provides us with an operational perspective for exploring the boundary between quantum and classical physics. More concretely, given a particular information processing task, if a system or strategy can perform it better than the best known classical system or strategy, then the system or strategy should be considered non-classical. Evidently, the notion of non-classicality is task dependent. I will discuss instances from computation [1] and communication [4] that flesh these out in detail. The presence of quantum entanglement is often seen as a definitive signature of quantumness or non-classicality in a system. As I will discuss, it now appears that this may not be the whole story, and in fact, certain non-classical advantages can be availed from systems with limited or no entanglement. I will dwell upon some of the possible issues that this raises [3, 4] and the role that more general notions such as quantum discord or other measures play in the demarcation of the quantum classical divide.

[1] Animesh Datta, Anil Shaji, Carlton M. Caves, Phys. Rev. Lett, **100**, 050502 (2008).
[2] Vaibhav Madhok, Animesh Datta, Phys. Rev. A, **83** , 032323 (2011).
[3] Animesh Datta, Anil Shaji, International Journal of Quantum Information, **9**, 1787, (2011).
[4] Vaibhav Madhok, Animesh Datta, arXiv:1107.0994.

Spontaneous radiation emission and particles oscillation in collapse models

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Collapse models are phenomenological models developed to solve the measurement problem in Quantum Mechanics. In these models, one assumes that the wave function undergoes a spontaneous collapse in space. In order to describe this collapse process, one has to modify the Schrödinger equation, by introducing new non linear and stochastic terms [1]. Accordingly, collapse models make different prediction than Quantum Mechanics, so they can be tested. In recent years there was an increasing attention on looking for possible experiments where the collapse effect can be seen [2]. Here we will work with the Continuous Spontaneous Localization (CSL) and the Quantum Mechanics with Universal Position Localizations (QMUPL) models. In this models it is supposed the existence of a noise field that is coupled with every physical system in a non linear and stochastic way. The direct effect of this noise field is to ensure that the wave function associate to a macroscopic system will be always well localized in space. In this way situation like the one described in the Schrödinger cat paradox are forbidden, and the measurement problem is solved. Moreover there are also indirect effects due to this noise field that can be used to test these models, like the spontaneous emission of electromagnetic radiation. The idea is the following one: in quantum mechanics a system in its ground stationary states can't emit radiation. Conversely in these collapse models every system interacts with the noise field and this can induce (if, as in ordinary matter, the system is made of electrically charged particles) radiation emission. The effect was computed with perturbative methods for the CSL model [3, 4] and in the exact way for the QMUPL model [6] and it has been shown to be very small. Anyway these two result, that were expected to be the same, were different by a factor 2. Moreover, when we use more realistic models with colored noise (instead of the white noise) this difference becomes even worse. Here we will show that the origin for this discrepancy is that perturbative computations, in the asymptotic limit $t \to \infty$, can't be used naively. Indeed, using the exact results found with the QMUPL model, it can be show that there are some exponential terms that, in the limit $t \to \infty$, goes to 0. But the same terms, when computed with perturbative methods, give finite contributions even in the asymptotic limit. The physical reason of this behavior is that the noise field interact always with the system and so, even if this interaction is very weak, when we take the asymptotic limit, these effect becomes relevant and treat them as perturbations is not correct anymore.

Another phenomena that could be used to test the collapse models is particles oscillation. This oscillation can be seen for every particles with flavor eigenstates (the one that we found when we perform a measurement) without definite mass. In such case usually it is supposed that the flavour eigenstates are superposition of the mass eigenstates. Since each of the mass eigenstates has different time evolution, there is a non zero probability that an initial flavour eigenstate end up in a different flavour eigenstate after some time t. It has been show that in Quantum Mechanics these probability oscillate in time [6]. Even in collapse models we expect to see this phenomena, but with different probabilities, since the time evolution of the mass eigenstates, due to the interaction with the noise field, will be different. We are still working on a final formula, but some preliminary computation (and also theoretical arguments) suggest that the oscillating term should be dumped by an exponential factor, as it was found in decoherence models [1, 7] and in gravity induced collapse model [4].

[1] A. Bassi and G.C. Ghirardi, Phys. Rept. 379, 257 (2003).
[2] S.L. Adler, A. Bassi, Science 325, page 275 (2009).
[3] Fu Q. Phys. Rev. A 56 1806 (1997).
[4] S.L. Adler and F. M. Ramazanoglu, J. Phys. A 40, 13395, (2007).
[5] A. Bassi D. Duerr, Journ. Phys. A: Math. Theor. 42, 485302 (2009).
[6] M. Beuthe, Phys.Rept. 375, 105-218, (2003).
[7] F. Benatti, R. Floreanini, Phys.Rev. D71, 013003, (2005).
[8] R. A. Bertlmann, K. Durstberger, B. C. Hiesmayr , Phys.Rev. A68, 012111, (2003).
[9] J. Christian, Phys.Rev.Lett. 95, 160403, (2005).

Simulating accelerated atoms coupled to a quantum field

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The study of accelerated atoms interacting with a quantum field is a fundamental problem, which has attracted a great deal of attention in General Relativity. Even though it has been treated extensively in the literature [1], it still poses intriguing questions, as well as experimental challenges for the detection of quantum effects induced by acceleration. Moreover, the emerging field of relativistic quantum information has recently increased the attention drawn to the topic, and in particular the study of correlations and entanglement in non-inertial scenarios [2]. A physical paradigm in this regime is the detection of the Unruh effect [3], which, roughly, implies that an atom accelerated in the vacuum of the field is excited in the same way as an inertial atom in an effective thermal field state.

With this work, we intend to show how simulations in the lab can be implemented for the case of several accelerated emitters, where we face a many-body situation which would require a non-perturbative analysis, very relevant from the point of view of relativistic quantum information, but far beyond the reach of current computational power for a relatively small number of emitters. With that idea in mind, we establish an analogy between static quantum emitters coupled to a single mode of a quantum field and accelerated Unruh-DeWitt detectors. In particular, we show that system of accelerated atoms [4] coupled to a bosonic field in the discrete mode approximation [5, 6], shares interesting analogies to time-dependent problems in quantum optics. Our proposal relies on a periodic driving of single emitters with a time-dependent amplitude. The latter yields an effective time-dependence in the emitter-field coupling which resembles that of an accelerated relativistic particle.

Our work is motivated by the recent experimental progress that has allowed physicists to develop tools to control the dynamics of single emitters coupled to fields in set-ups such as trapped ions [7] or circuit QED [8] . The application of those systems as analog-simulators of accelerated atoms is particularly relevant to many-body non-perturbative regimes, where numerical calculations are difficult. Furthermore, the insight gained by such analogies motivates the study of physical effects that may be relevant to the experimental detection of the Unruh effect. For example, collective phenomena such as superradiance [9, 10] (which are known to amplify the effective coupling of a set of emitters to the field) could be used to increase detection sensitivity of quantum effects in non-inertial scenarios.

We start by presenting the Unruh-DeWitt detector model to characterize an atom coupled to a quantum field. Working in the interaction picture from the comoving atom reference frame, we show how to account for a uniform acceleration in the Hamiltonian. We then proceed to discuss the possible physical implementations in trapped ions and circuit QED. For both cases a model of emitters with controlled time-dependent atom-field couplings is presented, which, after some approximations, yields an identical Hamiltonian. Then, as an illustrative example, we analyze the physics in the case of a single atom to predict the outcome of simple experimental realizations of our ideas. An analogy to a decoupling process is explained in terms of the well-known Landau-Zener formula. Some future research lines on the topic will naturally emerge from our discussion.

[1] L. C. B. Crispino, A. Higuchi, and G. E. A. Matsas, Rev. Mod. Phys. **80**, 787 (2008).

[2] B. Reznik, A. Retzker, and J. Silman, Phys. Rev. A **71**, 042104 (2005).

[3] W. G. Unruh, Phys. Rev. D **14**, 870 (1976).

[4] DeWitt, *General Relativity; an Einstein Centenary Survey* (Cambridge University Press (Cambridge, UK), 1980), ISBN 0521299284.

[5] E. Martin-Martinez, I. Fuentes, and R. B. Mann, Phys. Rev. Lett. **107**, 131301 (2011).

[6] A. Dragan and I. Fuentes, *Probing the spacetime structure of vacuum entanglement*, arXiv.org:1105.1192.

[7] D. Leibfried, R. Blatt, C. Monroe, and D. Wineland, Rev. Mod. Phys. **75**, 281 (2003).

[8] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Kumar, S. M. Girvin, and R. J. Schoelkopf, Nature (London) **431**, 162 (2004).

[9] M. Gross and S. Haroche, Physics Reports (1982).

[10] P. Nataf and C. Ciuti, Nat Commun **1** (2010).

Experimentally feasible set of criteria detecting genuine multipartite entanglement in n-qubit Dicke states and in higher dimensional systems

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The feature of many body entanglement has recently been recognized as a fundamental property of a broad variety of systems. It appears in quantum phase transitions and ionization procedures. Even biological systems have raised questions as to whether multipartite entanglement might be responsible for their astonishing transport efficiency. There are already numerous examples of possible applications of this quantum feature. In quantum information processing it facilitates quantum computation, enables multi-party cryptography and also plays a fundamental role in many popular quantum algorithms.

In contrast to the well studied bipartite case, the structure of multipartite entanglement is far more intricate. Recently, new tools have been developed to find out whether a given quantum state is multipartite entangled. These however have strong limitations (e.g only applicable to pure states or require a full state tomography). In multipartite systems it is of high importance that criteria detecting multipartite entanglement are experimentally accessible without having to resort to a full state tomography, since that would require an unfeasible number of measurements.

At this conference I will present our main result, i.e.: For $1 < m \leq \frac{n}{2}$, the set of inequalities

$$I_m^n[\rho] = \sum_{\{\gamma\}} \left(\underbrace{|\langle d_{\{\alpha\}}|\rho|d_{\{\beta\}}\rangle|}_{O_{\{\alpha\},\{\beta\}}} - \underbrace{\sqrt{\langle d_{\{\alpha\}}| \otimes \langle d_{\{\beta\}}|\Pi_{\{\alpha\}}\rho^{\otimes 2}\Pi_{\{\alpha\}}|d_{\{\alpha\}}\rangle \otimes |d_{\{\beta\}}\rangle}}_{P_{\{\alpha\},\{\beta\}}} \right) - N_D \sum_{\{\alpha\}} \underbrace{\langle d_{\{\alpha\}}|\rho|d_{\{\alpha\}}\rangle}_{D_{\{\alpha\}}} \leq 0 \tag{1}$$

which holds for all biseparable states, where $\Pi_{\{\alpha\}}$ is the cyclic permutation operator acting on the twofold copy Hilbert space, e.g. $\Pi_{\{1\}}|\phi_1\phi_2\rangle \otimes |\psi_1\psi_2\rangle = |\psi_1\phi_2\rangle \otimes |\phi_1\psi_2\rangle$, $\{\gamma\} = \{(\{\alpha\},\{\beta\}) : |\{\alpha\} \cap \{\beta\}| = m-1\}$ and

$$N_D = m \cdot (n - m - 1)\,. \tag{2}$$

The inequality is always maximally violated by the corresponding Dicke state $|D_m^n\rangle$, with the number of excitations m equal to $|\{\alpha\}|$, with a value of

$$I_m^n[|D_m^n\rangle\langle D_m^n|] = m\,. \tag{3}$$

[1] M. Huber, P. Erker, H. Schimpf, A. Gabriel and B.C. Hiesmayr, Phys. Rev. A **83**, 040301(R) (2011)

Gauge: Quantum-Electromagnetic and Gravitational

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Unifying the four fundamental forces is a primary objective of modern theoretical physics. To the extent that all four forces can be described as gauge fields, gauge theory promises to realise such a unification. However, the promise has yet to be entirely fulfilled. In addition to technical differences in the mathematical representations of the four forces as gauge fields (see [1]), there has been criticism of the conceptual foundations of gauge theory. Two main points of criticism concern (i) differences in the empirical statuses of the symmetry transformations associated with each force (ii) the explanatory power of the "gauge principle" which claims to infer the existence of fundamental forces from symmetry requirements. By carefully developing an analogy between non-relativistic quantum-electromagnetism (Q-EM) and general relativity (GR) suggested by 't Hooft in [2], we hope to answer both points of criticism.

In [3], Brading and Brown claim that the external transformations of space-time theories have a different empirical status from the internal transformations of "typical" gauge theories (from which space-time theories of gravitation are excluded). They argue that space-time transformations have a clear active interpretation, whereas gauge transformations do not, in this particular case the phase transformations of Q-EM. We counter that the empirical status of phase (gauge) transformations is obscured by the quantum mechanical characteristics of the electromagnetic four-potential A_μ and the naturally gauge-invariant formulation of classical electromagnetism. By relating a choice of gauge to a choice of "coordinate system" on the internal space, we show that coherent general notions of active and passive transformations can be defined which allow for both active and passive interpretations of gauge transformations. As a result, we hope to revitalize the connection between the Aharonov-Bohm effect and gauge transformations suggested by 't Hooft and attacked by Brown and Brading.

Criticism of the "gauge principle" abounds (see for example [4] and [5]). Dissatisfaction stems from the principle's apparent ability to get something (the existence of a fundamental force) from nothing (a symmetry requirement). We show that the logic of the gauge principle has its roots in Einstein's principle of equivalence. We argue that, when supplemented with a demand for background independence, the logical relation between the geometrization of fundamental forces and symmetry requirements can be demystified. The symmetry requirement necessitates an *a priori* equivalence of coordinate systems (on external and internal space), while the solutions to the field equations (the "force-fields") break this symmetry by determining *de facto* privileged coordinate systems [6]. The equivalence of coordinate systems is understood with respect to the form taken by the laws of physics in the system. We conclude by deepening the analogy between general relativity and quantum-electromagnetism, supporting our argumentation by an appeal to the fiber bundle formulation of gauge theory. First we find an analogue in Q-EM for the inertial coordinate system of GR, which we call the standard gauge. We then apply this notion to show that, just as in GR the local inertial coordinate system is defined by gravitation, in Q-EM the local standard gauge is defined by electromagnetism.

[1] A. Trautman (1980), Fiber Bundles, Gauge Fields and Gravitation, in A. Held (ed.) *General Relativity and Gravitation*, Vol. 1, New York: Plenum Press

[2] G. 't Hooft (1980), Gauge Theories of the Forces between Elementary Particles, *Scientific American*, **242**, pp. 90-166.

[3] K.A. Brading and H. R. Brown (2004), Are Gauge Symmetry Transformations Observable?, *British Journal for the Philosophy of Science*, **55**, pp. 645-665.

[4] M. Redhead (2003), The Interpretation of Gauge Symmetry, in K.A. Brading and E. Castellani (eds.) *Symmetries in Physics: Philosophical Reflections*, Cambridge: Cambridge University Press

[5] C. A. Martin (2002), Gauge Principles, Gauge Arguments and the Logic of Nature, *Philosophy of Science*, **69**, pp. S221-S234

[6] D. Dieks (2006), Another Look at General Covariance and the Equivalence of Reference Frames, *Studies in History and Philosophy of Modern Physics*, **37**, pp. 174-191

Particle Physics in Discrete Space-time: Insights from Quantum Walks and Quantum Cellular Automata

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A single particle evolving in a local, unitary way in discrete space-time is a particular example of a quantum walk, which has been studied in connection with particle dynamics in [1–4]. Surprisingly, not only do these quantum walks display behaviour similar to spin 1/2 particles, such as Zitterbewegung [3], but for some simple cases the continuum limit dynamics have been shown to be identical to particles obeying the Dirac or Weyl equation [1–4].

The Weyl equation in three space dimensions is

$$i\frac{d\psi(t)}{dt} = \vec{\sigma}.\vec{P}\psi(t), \tag{1}$$

where $\psi(t)$ is a two component wavefunction, the three components of $\vec{\sigma}$ are the three Pauli matrices, $\vec{P}$ is the momentum operator, and $\hbar = c = 1$.

Essentially, translationally invariant quantum walks are just quantum particles that live in discrete space-time. So it is interesting that the continuum limit dynamics of quantum walks can have Lorentz symmetry, which poses the question of whether these quantum walks can be used to simulate physical particles. It also hints at the possibility that space-time could be discrete.

One interesting result is that a local translationally invariant quantum walk on a lattice requires an extra degree of freedom [5]; otherwise the evolution shifts everything in the same direction, which is trivial, as it can be undone by a simple change of coordinates. This extra degree of freedom is analogous to spin or chirality.

Surprisingly, it is possible to show that *any* local translationally invariant quantum walk with a two dimensional extra degree of freedom obeys the Weyl equation in the continuum limit (provided the continuum limit exists) in some inertial frame [6].

To be more precise, this result entails embedding the discrete theory into continuous space and then taking a continuum limit. Then, by rotating and rescaling the coordinate axes, and possibly accounting for an overall shift, we see that the evolution is always identical to that of a particle obeying the Weyl equation in *at most* three space dimensions, meaning the dynamics has Lorentz symmetry.

Furthermore, an example showing that there exist quantum walks that have the three dimensional Weyl equation as their continuum limit dynamics (see [1]) has evolution operator given by

$$U = T_x T_y T_z, \tag{2}$$

where $T_a = |\uparrow_a\rangle\langle\uparrow_a| S_a + |\downarrow_a\rangle\langle\downarrow_a| S_a^\dagger$, with $a \in \{x, y, z\}$; $|\uparrow_a\rangle$ and $|\downarrow_a\rangle$ are eigenvectors of the Paul matrix σ_a with eigenvalue $+1$ and -1 respectively; and S_a shifts the state by one lattice site in the positive a direction, while $S_a^\dagger$ shifts the state by one lattice site in the negative a direction.

These results naturally prompt the question of how to study interacting theories of particles or fields in discrete space-time. This problem is considered, for example, in [7] from the viewpoint of Quantum Cellular Automata. This approach is not straightforward, however, as discretizing fermions is highly non-trivial.

[1] Iwo Bialynicki-Birula, *Weyl, Dirac, and Maxwell equations on a lattice as unitary cellular automata*, Phys. Rev. D **49**, 6920, (1994).

[2] A.J. Bracken, D. Ellinas, and I. Smyrnakis, *Free-Dirac-particle evolution as a quantum random walk*, Phys. Rev. A **75**, 022322, (2007).

[3] Frederick W. Strauch, *Relativistic effects and rigorous limits for discrete- and continuous-time quantum walks*, Journal of Mathematical Physics **48**, 8, (2007).

[4] Frederick W. Strauch, *Relativistic quantum walks*, Phys. Rev. A **73**, 054302, (2006).

[5] David A. Meyer, *On the absence of homogeneous scalar unitary cellular automata*, Physics Letters A **5**, 223, (1996).

[6] Terence C. Farrelly, Anthony J. Short, *in preparation.*

[7] Giacomo Mauro D'Ariano, *Physics as Quantum Information Processing: Quantum Fields as Quantum Automata*, Foundations of Probability and Physics **6**, AIP Conf. Proc. 1424 371, (2012)

Stochastic Schrödinger equations and non-Markovian open quantum systems with dissipation

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Stochastic Schrödinger equations (SSEs) are a powerful mathematical formalism which allows for insight into physical systems, like e.g. collapse models [1]. Aim of these models is to give a unique dynamical description, which reproduces both Quantum Mechanics for microscopic objects, and Classical Mechanics for macroscopic ones. This goal is achieved by modifying the Schrödinger equation introducing new stochastic terms. The noise is responsible for the wave function collapse: it kills superpositions and localizes the wave function in a small region of space.

Another interesting field of application of SSEs are open quantum systems (OQSs). It is known indeed that every Markovian master equation allows for a stochastic unraveling, i.e. a SSE whose ensemble of solutions is described by the starting master equation. This means that a SSE can be used to effectively describe the evolution of an OQS, where the noise simulates the environment.

The SSEs approach is very useful because if one assumes the noise term to be non-white (i.e. a noise with a general time correlation function), one can study the behavior of non-Markovian dynamics [2–4]. Furthermore, this is one of the few methods which allow for an analytic treatment of these non-Markovian dynamics. In this regard, some technical difficulties arise since Itô calculus can be exploited to solve only SSEs with white noises. This problem is solved by transforming it into a path-integral problem, which can be exactly solved [4, 6].

In a recent work [6], the problem of the solution of the following non-Markovian dissipative SSE has been addressed:

$$\frac{d}{dt}\phi_t = \left[-\frac{i}{\hbar}\left(H + \frac{\lambda\mu}{2}\{q,p\}\right) + \sqrt{\lambda}\left(q + i\frac{\mu}{\hbar}p\right) w_t - 2\sqrt{\lambda} q \int_0^t ds\, D(t,s) \frac{\delta}{\delta w_s}\right]\phi_t\,, \qquad (1)$$

where H is the Hamiltonian of the system, q, p are respectively the position and momentum operator, w_t is the noise and $D(t,s)$ its correlation function. λ and μ are two coupling constants which set respectively the strength of the interaction with the noise and of the dissipative effects, $\{\cdot,\cdot\}$ denotes the anti-commutator, and $\frac{\delta}{\delta w_s}$ is a functional derivative with respect to the noise at time s. Such SSE describes, on the one hand, the dynamics of a collapse model where the collapsing field has physical features: a colored spectrum (non-Markovian) and finite temperature (dissipative). On the other hand, Eq. (1) describes an OQS interacting with a finite temperature environment, with non-flat spectrum.

We were able to find the general solution of Eq. (1) for an harmonic oscillator. The strategy we adopted is the following: we wrote the solution of Eq. (1) in terms of its Green's function, and we expressed the Green's function itself in terms of a path-integral, which we eventually computed. The one we obtained is a completely analytical result and, as such, a very important achievement. We were able to compare the collapse process of this model with those of previous models, showing that in the non-Markovian dissipative model the collapse is slower. This is mainly due to the fact that the noise is less energetic than in the other models. The reason is twofold: first, since the noise is non-Markovian, high-energy components of the spectrum are suppressed; secondly dissipation makes the interaction with the noise less effective. For further details, the reader can refer to [6].

An explicit expression for the master equation is not available yet. The reason is that, due to the presence of the momentum operator, one cannot exploit standard techniques to derive the master equation from Eq. (1) or from its solution. This problem will be the subject of future research.

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[1] A. Bassi, G.C. Ghirardi, Phys. Rep. **379**, 257 (2003).
[2] L. Diosi, N. Gisin, W. T. Strunz, Phys. Rev. A **58**, 1699 (1998).
[3] S. L. Adler, A. Bassi, Journ. Phys. A **40**, 15083 (2007).
[4] A. Bassi, L. Ferialdi, Phys. Rev. Lett. **103**, 050403 (2009).

[5] A. Bassi, L. Ferialdi, Phys. Rev. A **80**, 012116 (2009).
[6] L. Ferialdi, A. Bassi, arXiv:1112.5065 (2011).

UV Completion by Classicalization and the Quantum N-Portrait of Black-Holes

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We review the idea of "Classicalization" introduced in [1] that provides a novel approach to the UV-Completion of a class of non-renormalizable field theories. In these theories, the high-energy scattering amplitudes get unitarized by production of extended classical configurations that are fully described by the low energy degrees of freedom. In this framework, Einstein's Gravity is self-complete in the deep UV, but not in the Wilsonian sense [2, 3].

Furthermore, it has been recently proposed in [4, 5] that it's possible to establish a measure of classicality in the form of the occupation number, N, of gravitons in a gravitational field. In the large N limit, this provides a complete quantum mechanical description of a black-hole. In this picture, classical background geometries can be viewed as Bose-Einstein condensates of soft gravitons, and the depletion of this condensate gives rise to Hawking radiation, with the thermal spectrum recovered in the limit $N = \left(\frac{M}{M_p}\right)^2 \to \infty$ with $r_s = \sqrt{N} L_p$ fixed. Within this picture, we seek to explain the phenomena of:

Thermality: Hawking radiation emerges as a process in which a single graviton gains an above-threshold energy by scattering off the collective potential. This gives the evaporation rate of a black hole given by

$$\frac{dN}{dt} = -\frac{1}{\sqrt{N} L_p}\left(1 + \mathcal{O}\left(\frac{1}{N}\right)\right)$$

Bekenstein-Hawking Entropy, in which we have a degeneracy of N-graviton states that scale exponentially with N;

UV Self-Completeness by Classicalization, where any few particles state of trans-Planckian center-of-mass scattering at small impact parameter ($b < r_s$) energy will necessarily evolve into an N-graviton state of degeneracy e^N.

[1] G. Dvali, G. F. Giudice, C. Gomez and A. Kehagias, "UV-Completion by Classicalization," JHEP **1108**, 108 (2011) [arXiv:1010.1415 [hep-ph]].

[2] G. Dvali and C. Gomez, "Self-Completeness of Einstein Gravity," arXiv:1005.3497 [hep-th].

[3] G. Dvali, S. Folkerts and C. Germani, "Physics of Trans-Planckian Gravity," Phys. Rev. D **84**, 024039 (2011) [arXiv:1006.0984 [hep-th]].

[4] G. Dvali and C. Gomez, "Black Hole's Quantum N-Portrait," arXiv:1112.3359 [hep-th].

[5] G. Dvali and C. Gomez, "Landau-Ginzburg Limit of Black Hole's Quantum Portrait: Self Similarity and Critical Exponent," arXiv:1203.3372 [hep-th].

Macroscopic Quantum Coherence - starting small

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In considering the validity of quantum theory at macroscopic scales, Leggett and Garg (LG) provided a test for quantum coherence: their celebrated inequality [1]

$$K_{12} + K_{13} + K_{23} + 1 > 0. \quad (1)$$

Applying the inequality involves studying the time evolution of a two level system: $Q(t_i) = \pm 1$ depending on the state of the system at time t_i and $K_{ij} = \langle Q(t_i)Q(t_j)\rangle$ quantifies the degree to which the system correlates with itself over time. If (1) is satisfied, then one can understand the evolution as a classical binary system stochastically flipping from one of its states to the other. If (1) is violated, then one or both of the following assumptions (under which the inequality is derived) is false: *Realism:* the system is in exactly one of its two possibilities at any given time (R), or *Non invasive measurability:* it is possible to measure the state of the system without changing its subsequent evolution (NIM).

The failure of R represents a signature of quantum coherence - the existence of superposition states. The violation of (1), however, is also compatible with a failure of NIM and so may arise from a clumsily measured *classical* system. The nature of the measurements used to determine if (1) is satisfied are therefore very significant. Along with the inequality, LG provided an ingenious measurement scheme involving 'null result' measurements: one uses a measuring device which only interacts with the system if it is in the first of its two possible states, and post-selects runs where the detector does not click. One then uses a complementary device which only interacts with the second possibility, again post-selecting for runs where no interaction was reported.

The true interest here is in testing LG's inequality in macroscopic systems. This is in light of several 'macro-realist' theories which hold that quantum theory (the undisputed champion of the micro-world) breaks down somewhere between the level of atoms and of human observers, e.g. on the mass scale [2] or when the number of particles involved becomes large [3, 4]. The inequality has been applied to many experimental systems. To date only one experiment (involving a superconducting 'transmon' qubit) could claim to be macroscopic [5]. The approach taken in that particular experiment, and in other proof-of-principle experiments in microscopic systems with photons [6, 7] and nuclear spins [8], was deficient. In these cases, null result measurements were foregone in favour of spurious *weak* measurements and/or the additional (and highly restrictive) assumption of 'stationarity' [9].

A demonstration without these shortcomings was reported in [10]. There the inequality was generalised to tolerate a low level of corruption in the null measurement postselection. An isotopically pure Si^{28} crystal impregnated with 10^{10} Phosphorous impurities consists of an ensemble of coupled spin-$\frac{1}{2}$ qubit pairs: the donor P nuclei 'adopt' an electron spin from the bulk, which can act as the measurement ancilla. By Zeemann-splitting the spin-state energies in a static field of 3.4T, and cooling the sample to less than 3K, the corruption in the measurement ancilla was lowered to a level where a falsification of R $\cap$ NIM was possible in principle. High fidelity control techniques were then used to manipulate the nuclear spin (with radio-frequency) and the electron spin (with microwave radiation), and a violation of several standard deviations was extracted. This experiment paves the way for rigorous experiments on more macroscopic objects.

[1] A. J. Leggett and A. Garg, Physical Review Letters **54**, 857 (1985).
[2] R. Penrose, General Relativity and Gravitation **28**, 581 (1996).
[3] G. C. Ghirardi, A. Rimini, and T. Weber, Phys. Rev. D **34**, 470 (1986).
[4] P. Pearle, Phys. Rev. A **39**, 2277 (1989).
[5] A. Palacios-Laloy *et al.*, Nature Physics **6**, 442 (2010).
[6] M. E. Goggin *et al.*, Proceedings of the National Academy of Sciences **108**, 1256 (2011).
[7] J. Dressel *et al.*, Physical Review Letters **106**, 040402 (2011).
[8] G. Waldherr *et al.*, Phys. Rev. Lett. **107**, 090401 (2011).
[9] S. F. Huelga, T. W. Marshall, and E. Santos, Phys. Rev. A **52**, R2497 (1995).
[10] G. C. Knee *et al.*, Nat Commun **3** (2012).

Einstein´s 1935 papers and their relation

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In May of 1935 Albert Einstein published together with Nathan Rosen and Boris Podolsky his famous EPR paper [1]. In July Einstein published together with his assistant Nathan Rosen a paper which became also famous: *The Particle Problem in the General Theory of Relativity* [6]. In this paper Einstein and Rosen found the famous Einstein-Rosen-Bridge solutions of the field equations of general theory of relativity. Einstein intended to explain elementary particles with those solution. It is remarkable that both papers have been published short after each other and both ask for completeness as foundation of a theory. We will discuss the relation between those papers and what it tells us about Einsteins view of reality.

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[1] Einstein, Podolsky, Rosen *Can quantum mechanical description of reality be considered complete*, Physical review, 1935

[2] Bohr *Can quantum mechanical description of reality be considered complete* Physical review, 1935

[3] Heisenberg *The development of the interpretation of quantum theory* in "Niels Bohr and the Development of physics", 1955

[4] Bohm *Wholeness and implicate order*, 1980

[5] Einstein, Rosen *The Particle Problem in the General Theory of Relativity*, Phys. Rev. 48, 73 1935

Foundations of quantum mechanics from superstring theory

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Superstring theory (ST) is an advanced approach toward formulating a theory of quantum gravity, though the 4-d case is still obscure. Highly non-trivial merge of quantum mechanics (QM), quantum field theory, general relativity, geometry, topology and others is realized within ST such that new mathematics is born. This new perspective sheds light also on fundamental questions in QM. We follow this point of view and observe that i) ST teaches us that geometry is usually nontrivially involved in the constructions, ii) non-commutative coordinates appear at some limits, iii) non-trivial B-field is responsible for both, new geometry and the non-commutativity [3]. These indications together with the work on non-standard smoothness on trivial $\mathbb{R}^4$ in ST (see, e.g. [1, 2, 10–12]), shows that there presumably exists a fundamental level of 'quantum' geometry based on exotic $\mathbb{R}^4$. The reason is that exotic $\mathbb{R}^4$'s generate non-trivial classes of B-field and abelian gerbes on S^3. Moreover, the non-commutative geometry is inherently assigned to small exotic $\mathbb{R}^4$'s from fixed radial family, via special codimension-1 foliations of S^3, namely those with non-vanishing Godbillon-Vey class.

On the other hand, QM is usually formulated such that its connection with geometry of spacetime is at best vague. Even though ST may shed light on the relation, our present understanding of this is fragmentary and limited. We propose and discuss the indications how to proceed while working on this problem at very basic level. First, the calculation of the Polyakov path integral in bosonic strings contains miracle expression $1 + 2 + 3 + ... = -\frac{1}{12}$, which is Riemann ζ-function renormalization, i.e. $\zeta(-1) = -\frac{1}{12}$ (see, e.g. [13, 14]). The consistent dealing with this kind of expressions and subsequent derivation of physical predictions from them, can be linked to a shift between models of Peano arithmetic. Such shifts were analyzed some time ago in context of formalism of QM where also set-theoretic forcing became important (see, e.g. [4–6, 8, 9]). Second, one can argue that small exotic $\mathbb{R}^4$'s, as grouped in a radial family, act on modular functions which, in turn, appear as correlation functions of string theory. This is low level impact of 4-geometry on string theory quantum expressions. Finally, set theoretical forcing again appears as a tool for analyzing special model-theoretic structures on manifolds, which were related to exotic $\mathbb{R}^4$'s (see, e.g. [6, 7]). Thus, QM formalism, 4-geometry and string techniques are correlated non-trivially at very basic set theoretic level.

[1] T. Asselmeyer-Maluga, J. Król, Small exotic smooth R^4 and string theory, ICM 2010, Short Communications Abstracts Book (2010).

[2] J. Król, (Quantum) gravity effects via exotic $\mathbb{R}^4$, *Ann. Phys. (Berlin)* **19** No. 3-5, 355-358 (2010)

[3] G. B. Segal, Topological structures in string theory, *Phil. Trans. Roy. Soc. London* **A**359, 1389 (2001).

[4] G. Takeuti, Two applications of logic to mathematics, *Math. Soc. Japan 13*, Kano Memorial Lecture 3 (1978).

[5] P. Benioff, Models of Zermelo-Frankel set theory as carriers for the mathematics of physics I, II, *J. Math. Phys.* **17**(5), 618, 629 (1976).

[6] J. Król, Background Independence in quantum gravity and Forcing constructions, *Found. Phys.* **34**, 361 (2004).

[7] J. Król, Exotic smoothness and non-commutative spaces. The model-theoretic approach, *Found. Phys.* **34**, 843 (2004).

[8] J. Król, A model for spacetime: The role of interpretation in some Grothendieck topoi, *Found. Phys.* **36**, 1070 (2006).

[9] J. Król, A Model for spacetime II. The emergence of higher dimensions and Field theory/Strings dualities, *Found. Phys.* **36**, 1778 (2006).

[10] J. Król, New 4D Results from Superstring Theory, *Acta. Phys. Pol. B* **42**(11), 2343 (2011).

[11] J. Król, Exotic smooth 4-manifolds and gerbes as geometry for quantum gravity, *Acta. Phys. Pol. B* **40**(11), 3079 (2009).

[12] T. Asselmeyer-Maluga, J. Król, Exotic smooth R^4 and certain configurations of NS and D branes in string theory, *Int. J. Mod. Phys. A* **26**, 1375 (2011).

[13] N. Koblitz, *Introduction to Elliptic Curves and Modular Forms*, Springer-Verlag, 1993.

[14] M. B. Green, J. H. Schwarz, E. Witten, *Superstring Theory* Vol. 1, Cambridge University Press, 1987.

Mistaking assumptions in Copenhagen quantum mechanics and consequences

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The Copenhagen quantum mechanics is to be refused on the basis of internal contradictions following from the assumptions added by Bohr. Also the inequalities derived by Bell have been mistakenly interpreted. Consequently, the criticism of Einstein based on ontological approach has been quite justified. And the so called hidden-variable theory being equivalent to standard Schroedinger equation (without adding any deforming assumptions concerning the Hilbert space) may be taken as the common theory of the reality, i.e., of the microscopic as well as macroscopic processes. And the physical picture is practically equivalent to that of classical physics; only the set of physical states being partially limited due to energy quantization. The basic Schroedinger states being determined always by one Hamiltonian eigenfunction are equivalent to solutions of Hamilton equations, while their superpositions correspond to mixtures of corresponding simple classical states [1, 2].

It means that the Schroedinger equation may provide phenomenological description of physical situation only. And the new stage of microscopic physical research should be started that would contribute to explaining physical mechanism of quantum phenomena. E.g., in the case of atom spectra it is not more possible to look only for some phenomenological agreement of Coulomb potential with experimental data. It is necessary to go a step deeper and to try to explain the actual mechanism leading to emergence of quantum states. It is evident that the mere Coulomb potential is quite insufficient to explain it. Some short-range repulsive effect (or force) must exist between electron and proton at small values of kinetic energy. The other questions concern then transition mechanism between quantum states and also correlations between energy and angular momentum. The attention must be devoted to values of spins and rest masses of individual objects and systems, too. However, the physical particles cannot be interpreted as mathematical artifacts, but as realistic ontological objects with given space dimensions and internal structures.

Main attention should be devoted to hydrogen atom. And the important question should concern the problem how the existence of quantum states may be influenced by proton structure. It is necessary to analyze corresponding data from experiments that might help in this direction; mainly elastic collision experiments may be very helpful. However, it is not more possible to look for a phenomenological description of measured values only, but for the interpretation of corresponding processes on ontological basis.

However, it may be also helpful to answer the question how it was possible that the Copenhagen alternative was influencing scientific thinking greater part of the past century. It followed from the fact that two different kinds of quantum physics have existed; one based on the Copenhagen quantum mechanics and looking for the support of quantum paradoxes and the other one solving in principle successfully different physical and technological problems on the basis of standard Schroedinger approach (without mentioning it explicitedly). It is possible to say that it followed from the fact that the scientific thinking in the modern period was fundamentally influenced by mathematical philosophy of Descartes refusing ontological approach. It was also the reason why also Einstein's criticism based on ontological argument has been refused by scientific community. And our main contemporary task consists in devoting more attention to the ontological properties of individual physical objects.

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[1] M. V. Lokajíček: Einstein-Bohr controversy after 75 years, its actual solution and consequences; *Some Applications of Quantum Mechanics* (ed. M. R. Pahlavani), InTech Publisher (February 2012), 409-24

[2] M. V. Lokajíček: The assumption in Bell's inequalities and entanglement problem; J. Comp. Theor. Nanosci. (accepted for publication), /arXiv:1108.0922

Signature of novel possibility for unusual correlations in the CMB spectrum

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The quantum fluctuations of the inflaton are currently considered as the seeds for cosmic structure and their traces are observed in the cosmic radiation background. This idea faces a conceptual difficulty in that the proposal does not contain any mechanism capable of braking the homogeneity and isotropy characterizing the primordial (quantum) state of the Universe. In previous works, it was proposed that a self induced spontaneous collapse of the wavefunction of the inflaton field, would offer a mechanism for the generation of the primordial inhomogeneities. We will present here a novel type of signature in the primordial spectrum, characterizing some unusual statistical aspects that according to these ideas would possibly be associated with the collapse process.

The major success of the inflationary model is to "naturally explain" the origin of the seeds of comic structure. Nevertheless, the standard picture suffers from a conceptual drawback [1]: the Universe is quantum mechanical and, thus, its classical description has to be considered as a collection of imprecise characterizations of complex quantum mechanical states. Our Universe today is certainly well described, at the classical level, by an inhomogeneous and anisotropic classical state. In other words, such description must be regarded as a concise and imperfect description of an equally inhomogeneous and anisotropic quantum state. Therefore, if we want to truly consider a theory, in which the early quantum state of the Universe was perfectly homogeneous and isotropic (i.e symmetric), then we need to provide and explanation of why the quantum state that describes our actual Universe lacks such symmetries. Since there is nothing in the dynamical evolution (as given by the standard inflationary approach) of the quantum state that can break those symmetries, then we are left with an incomplete theory.

In order to address the previous issue, the authors in [1], considered the *self-induced collapse hypothesis*. That is, an auto-collapse of the wave function of the initial quantum state would be responsible for the departure of the original symmetries; they also suggested, inspired by the ideas of Penrose and Diósi, that gravity could be responsible of the self-induced collapse. At this stage of the analysis, the precise physical nature of such collapse mechanism has not been considered, however, the analysis was advanced using phenomenological approach: That is, by characterizing the expectation values of each mode of the inflaton field $\hat{y}_{\vec{k}}$ (and its canonical conjugated momentum $\hat{\pi}_{\vec{k}}$), in the post-collapse state $|\Theta\rangle$, the details of the spectrum can be predicted. Thus writing $\langle \hat{y}^{R,I}_{\vec{k}}(\eta^c_k)\rangle_\Theta = x^{R,I}_{\vec{k},y}\sqrt{(\Delta \hat{y}^{R,I}_{\vec{k}})^2_0}$, $\langle \hat{\pi}^{R,I}_{\vec{k}}(\eta^c_k)\rangle_\Theta = x^{R,I}_{\vec{k},\pi}\sqrt{(\Delta \hat{\pi}^{R,I}_{\vec{k}})^2_0}$, where R, I denotes the real and imaginary parts of the field, respectively; η^c_k is the conformal time of collapse; $(\Delta \hat{y}^{R,I}_{\vec{k}})^2_0$, $(\Delta \hat{\pi}^{R,I}_{\vec{k}})^2_0$ are the uncertainties of each mode of the field momentum operators in the vacuum state; and $x^{R,I}_{\vec{k},y}$, $x^{R,I}_{\vec{k},\pi}$ are random variables with a distribution which in principle might be non-Gaussian, i.e. different modes could be correlated.

In [2] a detailed analysis of the collapse proposal indicated that within each set of random variables, it would be natural that a correlation between the modes $\vec{k}$ and $2\vec{k}$ would emerge (and also of course between $\vec{k}$ and $\vec{k}/2$). This correlation could induce a "small non-Gaussianity" in the probability distribution function of the random variables, where the "smallness" is characterized by the introduction of a parameter ε. Furthermore, in [3], we have shown that the observable quantity O_l, commonly known as the primordial angular power spectrum, that is related to the temperature anisotropies in the CMB, would then be modified to: $O_l \propto 1 + \varepsilon G(l)$, with $G_l \equiv l(l+1)9\sqrt{\pi}\Gamma(l)/[2^{5/2+l}\Gamma(l+3/2)]\ {}_2F_1(l, -1/2; l+3/2, 1/4)$; the function ${}_2F_1(a, b; c, z)$ is known as the Hypergeometric function. This is a deformation from the flat spectrum predicted by the traditional inflationary model. This signature, due to modified statistical correlations between each one of the modes, induced by the collapse mechanism, could be in principle searched for observationally. This shows that the conceptual difficulties in the standard inflationary scenario are not "just philosophy" but are related to observational issues. Thus, confronting those problems, open possible paths to insights about more fundamental aspects of the physical reality, in particular in the uncovering the still unclear aspects of the Quantum Theory.

[1] A. Perez, H. Sahlmann and D. Sudarsky, Class. Quantum Grav. **23**, 2317 (2006)
[2] A. Diez-Tejedor and D. Sudarsky, [arXiv:1108.4928] (2011).
[3] G. Leon and D. Sudarsky, [arXiv:1109.0052] (2011).

Time Measurement without Classical Mechanics

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Time of flight measurements are very commonly performed, for example they are ordinarily used in spectroscopy to determine the mass of unknown analytes. In this kind of applications only the mean value of the arrival time is measured, and the corresponding theoretical description is entirely classical.

In some special cases the whole distribution of arrival times is resolved, but the theoretical description is usually borne from the simpler cases and keeps a semi-classical approach. As an example, consider a free particle that flies from the source towards a detector with an initial spread in position much smaller than the flight path, so that at every run of the experiment the particle travels approximately the same distance, and the distribution of the time of arrival at the detector is entirely due to the initial spread in momentum. Therefore, a measurement of the time distribution is nothing else as a measurement of the initial momentum distribution. This simple reasoning is the standard procedure used for the data analysis of this kind of experiments and gives well confirmed predictions.

The problem arises when quantum interference is relevant. Consider again the previous experimental conditions, but suppose now that the source emits a superposition of two wave packets with slightly different momenta, such that they still overlap when they reach the detector. The detector is therefore inside the interference region, and the probability of finding the particle in its vicinity oscillates in time as the interference fringes pass it. The arrival time distribution should then also have an interference pattern. Despite that, the momentum distribution of the superposition of two freely evolving wave packets with the same initial position does not show any oscillation, and so does not the semiclassical arrival time distribution as well.

To overcome this kind of problems it is needed to abandon the semiclassical approach, in favor of a genuine quantum description. Such a study has been initiated long ago and has produced several proposals for the theoretical prediction of the outcomes of a time measurement, the most noticeable being the one resulting from the application of the *orthodox* Quantum Mechanics [1], and the one coming from Bohmian Mechanics [2, 3]. All of these approaches suffer from some theoretical problems, on which the discussion is still open, therefore an experimental investigation is needed to clarify the situation.

We estimated in which conditions an experiment of the kind described would be able to discern the interference effects, finding them very far from present possibilities. We are current exploring the alternative of using superpositions of spin states instead of superpositions of wave packets as detectable quantum feature in an arrival time measurement. In this regard, we are studying a recent experiment based on a spin echo set-up where the arrival time statistic has been measured and for which the effect of the spin precession is clearly visible [4].

[1] J. Kijowski. On the time operator in quantum mechanics and the Heisenberg uncertainty relation for energy and time. *Reports on Mathematical Physics*, 6(3):361 – 386, 1974.

[2] C.R. Leavens. Arrival time distributions. *Physics Letters A*, 178(1-2):27 – 32, 1993.

[3] M. Daumer, D. Dürr, S. Goldstein, and N. Zanghì. Scattering and the role of operators in Bohmian Mechanics. *The Mathematical Physics of Micro-, Meso-, and MacroPhenomena, NATO ARW*. Plenum, 1994.

[4] F. Jeske, Th. Stöferle, and M. DeKieviet. Massive spin-momentum entanglement measured in an atomic beam spin echo experiment. *The European Physical Journal D*, 63:25–32, 2011.

Guaranteed violation of a Bell inequality without aligned reference frames or calibrated devices

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Bell tests [1] — the experimental demonstration of a Bell inequality violation — are central to understanding the foundations of quantum mechanics and have played an important role in the development of quantum technologies. In a quantum Bell test, two (or more) parties perform local measurements on an entangled quantum state. After accumulating enough data, both parties can compute their joint statistics and assess the presence of quantum nonlocality by checking for the violation of a Bell inequality. Although entanglement is necessary for obtaining nonlocality it is not sufficient. Even for sufficiently entangled states, one needs judiciously chosen measurement settings. Thus although nonlocality reveals the presence of entanglement in a device-independent way, that is, irrespectively of the detailed functioning of the measurement devices, one generally considers carefully calibrated and aligned measuring devices in order to obtain a Bell inequality violation. This in general amounts to having the distant parties share a common reference frame and well calibrated devices.

Although this assumption is typically made implicitly in theoretical works, establishing a common reference frame, as well as aligning and calibrating measurement devices in experimental situations are never trivial issues. For instance, in the context of quantum communications via optical fibers, unavoidable small temperature changes induce strong rotations of the polarization of photons in the fiber. This makes it challenging to maintain a good alignment, which in turn severely hinders the performance of quantum communication protocols in optical fibers [2].

It is therefore an interesting and important question whether the requirements of having a shared reference frame and calibrated devices can be dispensed with in nonlocality tests. Here, we further develop the idea proposed in Ref. [3] and show, both theoretically and experimentally, that neither of these operations are necessary: violation of the Clauser-Horne-Shimony-Holt-Bell inequalities without a shared frame of reference, and even with uncalibrated devices, can be achieved with near-certainty by performing local measurements in randomly chosen bases. We first show that whenever two parties perform three mutually unbiased (but randomly chosen) measurements on a maximally entangled qubit pair, they obtain a Bell inequality violation with certainty—a scheme that requires no common reference frame between the parties, but only a local calibration of each measuring device. We further show that when all measurements are chosen at random (*i.e.*, calibration of the devices is not necessary anymore), although Bell violation is not obtained with certainty, the probability of obtaining nonlocality rapidly increases towards one as the number of different local measurements increases. Our experimental scheme makes use of the singlet state of two photons prepared in a reconfigurable integrated waveguide circuit [4], based on voltage-controlled phase shifters. For further details of our work, see Ref. [5] (see also the related work in Refs. [6, 7]).

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[1] A. Aspect, Nature **398**, 189 (1999).
[2] N. Gisin *et al.*, Rev. Mod. Phys. **74**, 145195 (2002).
[3] Y.-C. Liang *et al.*, Phys. Rev. Lett. **104**, 050401 (2010); J. J. Wallman *et al.*, Phys. Rev. A **83**, 022110 (2011).
[4] P. J. Shadbolt *et al.*, Nature Photon. **6**, 45 (2012).
[5] P. Shadbolt *et al.*, arXiv:1111.1853 (2011).
[6] J. J. Wallman and S. D. Bartlett, Phys. Rev. A **85**, 024101 (2012).
[7] M. S. Palsson *et al.*, arXiv:1203.6692 (2012).

Lorentz invariant quantum dynamics in the multitime formalism

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At the heart of any known quantum theory lies a wave function. In a relativistic setting, one would expect this wave function to live on configuration space $\mathbb{R}^{4N}$ (for N particles). While such a wave function is required by realistic quantum theories such as relativistic Bohmian mechanics [1] and relativistic GRW [2], it is not easily extracted from quantum field theory. The multitime formalism (first developed by Dirac in 1932 [3]) considers a set of N wave equations to determine the wave function, reflecting the energy-momentum relations for each of the N particles. However, such a set of N wave equations has to satisfy severe consistency conditions. So far, explicit multitime wave equations with consistent interactions are only known for two particles [4]. The purpose of the poster is to clarify this situation as well as to emphasise the importance of multitime wave equations for realistic quantum theories.

[1] D. Duerr, S. Goldstein, K. Muench-Berndl, N. Zanghi, Phys. Rev. A 60, 2729 (1999), arXiv:quant-ph/9801070v2

[2] D. Bedingham, D. Duerr, G.C. Ghirardi, S. Goldstein, R. Tumulka, N. Zanghi, arXiv:1111.1425v2 [quant-ph] (2011)

[3] P. A. M. Dirac, Proc. R. Soc. Lond. A 136, 453 (1932)

[4] H. W. Crater, P. van Alstine, Phys. Rev. D. 36, 3007 (1987)

Entangled two-photon state of light through disordered media

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We study transmission of entangled photon pairs through a diffusely scattering random medium. The main state of light we are dealing with is a two-photon state, entangled in frequency, and produced experimentally by parametrical down conversion. We consider a slab of disorder media where light is scattered before reaching two output detectors. Using the scattering matrix theory with independent transmission coefficients, following a gaussian distribution, we study the transmitted light. Its properties are characterized by the coincidence rate of photon detection in two transmitted modes. We perform the statistical analysis of this rate, which is a random quantity, and compare our results to those for a pair of independent photons (separable state) or coherent (classical) state. This allows us to clearly separate quantum and classical phenomena in our results. On the one hand, we show that using entangled photons may be beneficial to probe stationary random media as well as media evolving in time. On the other hand, two-photon speckle patterns contain information about the incident entangled state and can be used to measure its degree of entanglement.

[1] N. Cherroret and A. Buchleitner. Entanglement and thouless times from coincidence measurements across disordered media. Physical Review A, 83 :033827, 2011.

[2] S.E. Skipetrov. Quantum theory of dynamical multiple light scattering in uctuating disordered media. Physical Review A, 75 :053808, 2007.

[3] P. Lodhal, A.P. Mosk, and A. Lagendijk. Spatial quantum correlations in multiple scattered light. Physical Review Letters, 95 :173901, 2005.

[4] W.H. Peeters. Two-photon interference. PhD thesis, Leiden University, 2010.

[5] S.Smolka, A. Huck, U.L. Andersen, A. Lagendijk, and P. Lodahl. Observation of quantum correlations induced by multiple scattering of nonclassical light. Physical Review Letters, 102 :193901, 2009.

[6] J.R. Ott, N.A. Mortensen, and P. Lodaht. Quantum interference and entanglement induced by multiple scattering of light. Physical Review Letters, 105 :090501, 2010.

[7] C.W.J. Beenakker, J.W.F. Venderbos, and M.P. van Exter. Two-photons speckle as a probe of multi-dimensional entanglement. Physical Review Letters, 102 :193601, 2009.

[8] L. Mandel and E. Wolf. Optical coherence and quantum optics. Cambridge University Press, 1995.

[9] W.P. Grice and A. Walmsley. Spectral information and distinguishability in type-II downconversion with a broadband pump). Physical Review A, 56 :1627, 1997.

[10] C.K.Hong, Z.Y.OU, and L.Mandel. Measurement of subpicosecond time intervals between two photons by interference. Physical Review Letters, 59 :2044, 1987.

[11] A. Gatti, E. Brambilla, M. Bache, and L.A. Lugiato. Correlated imaging, quantum and classical. Physical Review A, 70 :013802, 2004.

Maxwell's Equations as Mean Field Equations

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In this poster, we present the work done in [1], where we are interested in the relation between classical and quantum descriptions of the radiation field created by a large system of charged bosons. We consider the "microscopic" model given by the non-relativistic quantum electrodynamics, which means that, in this model, only the radiation field is quantized. The "macroscopic" model is given by the Hartree equation coupled to the classical Maxwell's equations. We apply a new method of mean field analysis (see e.g. [2], [3], [4]) for these two models. First, we define a time-dependent comparing functional, which is a tool to estimate an error made by switching from the microscopic to the macroscopic model. Then, under certain assumptions (some of which are left without proof), we show that initially small errors remain, for relatively small periods of time, small. In this way, the classical Maxwell's equations arise as a mean field limit from the equations of the non-relativistic quantum electrodynamics. To obtain a clean proof for the chosen microscopic and macroscopic models is not that straightforward, but should be possible.

[1] V. Matulevicius. *Maxwell's Equations as Mean Field Equations*. Master thesis, LMU Munich, September 2011.

[2] P. Pickl. *A simple derivation of mean field limits for quantum systems*. Letters in Mathematical Physics (9 March 2011).

[3] P. Pickl. *Derivation of the Time Dependent Gross-Pitaevskii Equation Without Positivity Condition on the Interaction*. Journal of Statistical Physics, (2010) 140: 76-89, DOI: 10.1007/s10955-010-9981-0.

[4] N. Boers. *Derivation of Mean Field Equations for Classical Systems*. Master thesis, LMU Munich, January 2011.

Localised projective measurement of a quantum field in non-inertial frames and in relativistic quantum information

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The usual approach to the problem of carrying out quantum measurements in general relativistic settings has been the use of the so called Unruh-DeWitt particle detector [1]. The problem with this model is that it is very challenging to go beyond the common point-like approximation even in the first order of perturbation theory [2].

We introduce a model of a detector that works in a way similar to the way in which measurements are modelled in quantum optics: by means of localized projective measurements in quantum fields but considering that they are defined in generally curved spacetimes. Our detector can either move inertially or accelerate. This detector does not require perturbative approximations, it gives direct information about a quantum state at the time of measurement and only clicks when particles to which it is sensitive are present [3]. Our model affords the ability to choose the size of the detector while providing non-perturbative results and can be used to solved the locality issues that appeared in the field of relativestic quantum information [4, 5]

This detector model allows us to probe a single, physically realisable state of the field. We show how the model works by studying the simplest case of the Minkowski vacuum state. We investigate the Unruh effect with a single accelerated detector and study how a pair of such detectors can extract nonlocal correlations present in the vacuum. We will also explore the possible implications and outcomes in the field of relativistic quantum information.

Thermal response of accelerated extended detectors.– We consider a uniformly accelerated detector in the presence of the Minkowski vacuum field. In this case the detector is assumed to measure the mode $\psi_{\rm D}(\xi,\tau)$ that is a function of the Rindler coordinates $(c\tau,\xi)$ related to Minkowski coordinates (ct,x), $x>|t|$, by the transformation:$ct=\frac{c^2}{a}e^{a\xi/c^2}\sinh\frac{a\tau}{c}$, $\quad x=\frac{c^2}{a}e^{a\xi/c^2}\cosh\frac{a\tau}{c}$, where $a>0$ is an arbitrary parameter. We wish to interpret a as the proper acceleration of the detector. This requires that the mode $\psi_{\rm D}(\xi,\tau)$ must be spatially localised around $\xi=0$. In addition, the spread must be small such that all the components of the detector will approximatively experience the same proper time, which coincides with Rindler time τ.

We can show that for the Minkowski vacuum state, $|0\rangle_{\rm M}$, and an arbitrary shape of the mode, $\psi_{\rm D}$, the above count statistics is strictly thermal $\mathcal{P}(n)=(\langle\hat{d}^\dagger\hat{d}\rangle^n)/[(1+\langle\hat{d}^\dagger\hat{d}\rangle)^{1+n}]$. For a Gaussian mode of spatial proper length L and with frequency spectrum centred in NL/c we find that

$$kT\approx\frac{\hbar a}{2\pi c}\frac{1}{1-\pi c^2/aLN}. \qquad (1)$$

One observes deviations from the Unruh temperature formula [6] for finite N. This stems from the fact that the energy of the mode is not well-defined due to the finite-sizeness of the detector. Large N, which corresponds to a peaked energy spectrum, we recover the celebrated Unruh result [6].

Vacuum entanglement extraction.– In order to extract entanglement from the vacuum state we consider two identical detectors coupled to localized modes, one moving with proper acceleration $a>0$ in the left wedge of the flat spacetime and the other moving with acceleration $-a$ in the right wedge. Both detectors are causally disconnected. We find that the measurement outcomes carried out by the detectors are correlated The entanglement estimator $\mathcal{E}$ that quantifies the non-local correlations extracted by the detectors [7]: $\mathcal{E}=\log\left|\left\langle\hat{d}_I^\dagger\hat{d}_I\right\rangle+\mathrm{Re}\left\langle\hat{d}_I\hat{d}_{II}\right\rangle\right|+C$ where C is an arbitrary real constant factor. For the modes in the limit of $N\gg\frac{c^2}{aL}\gg1$ the estimator can be approximated by:

$$\mathcal{E}\approx-\frac{\pi c^2}{aL}\left(N-\frac{\pi c^2}{2aL}\right)+C. \qquad (2)$$

We know that the extracted entanglement must vanish ($\mathcal{E}\to-\infty$) as $a\to0$, although for fixed N our approximations are not valid in this limit. We find that the largest amount of entanglement can be extracted from the Minkowski vacuum state when the proper lengths and proper accelerations of the detectors are large and the frequency numbers N are low.

[1] N. D. Birrell, and P. C. W. Davies, *Quantum Fields In Curved Space*, Cambridge, Uk: Univ. Pr. (1982)
[2] S. Schlicht, Class. Quant .Grav. **21**, 4647(2004).
[3] J. R. Letaw and J. D. Pfautsch, Phys. Rev. D **22**, 1345 (1980).; L. Sriramkumar, T. Padmanabhan, Int. J. Mod. Phys. D **11**, 1 (2002).
[4] D. Bruschi, J. Louko, E. Martín-Martínez, A. Dragan, and I. Fuentes, Phys. Rev A **82**, 042332 (2010).
[5] A. Dragan, J. Doukas, and E. Martín-Martínez, in preparation (2012). A. Dragan, J. Doukas, E. Martín-Martínez and D. bruschi, arXiv:1203.0655 [quant-ph]
[6] W. Unruh, Phys. Rev. D **14**, 870 (1976).
[7] L. -M. Duan, G. Giedke, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **84**, 2722 (2000).

A Novel Framework for Interpreting Quantum Mechanics

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Inspired by the mathematical facts that *a*) small objects are not just smaller than larger objects of the same shape but also more 2-dimensional (as indicated by the ratio of surface area to volume), and *b*) in Euclidean Space the representation of an object in a higher-dimensional space takes on in the manner of an actualizable potentiality all possible manifestations that depend on the dimension the object intrinsically lacks, the framework presented here derives the path integral for the simplest possible case, a single free particle, from 5 axioms. This framework, called the Dimensional Theory (DT) [1][2], postulates that there exists a lower limit in which spacetime reduces to a 2+1 version, which for definiteness will be called *areatime*. Objects in this limit are subject to a distinct metric interval and consequently a distinct proper time. The distinctness of their proper times from the proper time of spacetime objects implies that areatime objects do not 'age' in spacetime, and consequently do not have spacetime histories in their proper frames. Such objects are postulated to manifest themselves in terms of all possible histories, while the passage of time for such objects to the passage of time for spacetime observers is related via a certain symmetry that can be mathematically transformed to the standard quantum phase $e^{i\frac{S}{\hbar}}$. Associating each history with a path and each path with the phase factor finally leads to the path integral.

The dimensional theory supplies a geometric underpinning for the Copenhagen interpretation because it provides clearer, geometrically based answers to issues which the under that interpretation remain obscure. For example, according to it, *i*) 'measurements' reflect situations in which objects that actually exist in areatime under certain interactions emerge in spacetime; *ii*) it is not meaningful to assign definite properties to quantum objects prior to a 'measurement' because they do not actually exist in spacetime until they are 'measured' *iii*) the 'cut' between the quantum system and the classical observer reflects the fact that the former is subject to the areatime metric interval whereas the latter is subject to the spacetime metric interval *iv*) the uncertainty principle arises from the fact that in the limit in which space vanishes, spacetime does not vanish as well but reduces to a constant quantity of variable shape of areatime; and *v*) particles described by the same non-separable wavefunction by virtue of being associated with the same phase factor $e^{i\frac{S}{\hbar}}$ are associated with the same proper time, and therefore the same areatime metric interval. This means that they exist in the same region in areatime until a measurement causes them to emerge in different regions of spacetime, giving rise to the well-known correlations between spacelike separated measurement outcomes without violating special relativity.

This framework sharply segregates the domains between quantum theory and general relativity and has significant implications for understanding the relation between quantum theory and special relativity, as well as our most fundamental understanding of dynamic concepts such as mass, energy and momentum. It makes definite testable predictions of phenomena which are so unexpected that researchers are not currently looking for them. In particular, it predicts that radiation in transit does not produce gravitational fields, much in contrast to the predictions of general relativity [3][4][5][6][7][8].

[1] A Nikkhah Shirazi available at http://hdl.handle.net/2027.42/86651 (2011)
[2] A Nikkhah Shirazi available at http://hdl.handle.net/2027.42/83865 (2011)
[3] R Tolman *et. al.* Phys. Rev. 37, 602-615 (1931)
[4] A Peres Phys. Rev. lett. 59, 571-572 (1959)
[5] W Bonnor Commun. Math. Phys. 13, 163-174 (1960)
[6] P Aichelburg *et. al.* Gen. Rel. Grav. 2, 303-312 (1970)
[7] R Mallett Phys. Lett. A, 214-217 (2000)
[8] R Mallett Found. Phys. 33, 1307-1313 (2003)

Entropic Quantum Mechanics in a Relational Set

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Given a probability distribution one can assign probabilities to particular events. But how can we can come up with a distribution in the first place? 1957 Edward T. Jaynes introduced the Maximum Entropy principle as axiom of Bayesian probability theory. It allows to select the distribution which best represents our state of 'knowledge'. Recently Ariel Caticha applied this principle to derive Quantum mechanics. In addition to the particles of interest x extra variables y whose entropy S(x) depends on x are assumed to exist. The Schrödinger equation is derived from the coupled dynamics of the x and y variables. Problems of this approach concern the nature of the hidden variables that also relate to specific probabilistic independence conditions needed for the derivation.

Both the constraints that give rise to the specific distribution and the extra y-variables can be motivated further within a framework of a relational set. This is basically a discrete graph consisting of vertices representing events and edges corresponding to causal relations. In principle the idea is that such a graph might both reflect configurations of particles and also the emerging spacetime. Because its intrinsic non-locality the nature of the hidden y-varibales in the entropic approach to quantum mechanics can be demonstrated. A possible extension of the entropic derivation to relativistic quantum mechanics or quantum gravity can also be discussed within this framework.

In a broader sense the idea of the entropic derivation of quantum mechanics and the given approach is related to a question about the nature of spacetime. It is the question if spacetime is of absolute or relational nature. Of course we already know that it is not absolute in the Newtonian static sense, but it is dynamic and matter can react back on spacetime. But still we make use of spacetime by imagining it being there independently of the matter that it hosts. On the other hand Leibniz, Mach, Sciama and others have promoted the view that spacetime is of purely relational nature, that means that particles have no position in spacetime, but one relative to each other. This approach might solve some inconsistencies regarding the self-interaction of the electron or give a simpler description of Newton's bucket experiment.

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[1] Caticha, A.,"Entropic Dynamics, Time and Quantum Theory", arXiv:1005.2357, 2010.

[2] E.T. Jaynes., "Probability Theory: The Logic of Science", Cambridge University Press, 2003.

[3] Barbour, J., Phister, H. "Mach's Principle", Birkhäuser, 1995.

Universal entanglement witnesses and Schur-Weyl duality

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Entanglement is one of the features of quantum systems that makes them different from their classical counterparts. Even since the invention of this concept there has been an ongoing debate how to precisely define entanglement and quantify entanglement for various physical systems. Entanglement is usually identified with correlations in the composite quantum system that are stronger then any correlations that can be exhibited by any classical system.

In my approach I elaborate the method of entanglement detection that has been already discussed in the papers by Klyachko [1] and Kuś [2]. The general idea is as follows. Consider a Hilbert space $\mathcal{H}$ which describes some physical system. Let K be the symmetry group represented by the representation π as a subgroup of the full unitary group $U(\mathcal{H})$. Because the global phase factor of the wave function is irrelevant one studies the action of K on the projective space $\mathbb{P}\mathcal{H}$ rather then on the Hilbert space itself. Precise forms of $\mathcal{H}$, K and π vary and depend upon a given physical situation. In this context one understands the entanglement in terms of invariants of the action of K in $\mathbb{P}\mathcal{H}$. Usually the group K is a Lie Group (typically semisimple, compact and simply connected) and because of that one can use extensive machinery of the representation theory of Lie groups and Lie algebras [1–4]. In the theory of entanglement one is interested in entanglement witnesses - these are invariants of group action that distinguish between separable (classical) and entangled states [1, 2]. In the presented work I give the construction of a particular class of entanglement witnesses that arise naturally from purely group theoretical considerations. They are constructed from the representation of the second order Casimir $\mathcal{C}_2$ of the group K on the symmetrized tensor product of the Hilbert space $\mathcal{H}$: $\mathcal{H} \vee \mathcal{H}$. In order to compute the representant of $\mathcal{C}_2$ one has to decompose $\mathcal{H} \vee \mathcal{H}$ onto irreducible components with respect to the action of group K. I present this decomposition in three cases: distinguishable particles, bosons and fermions. For bosons and fermions the celebrated Schur-Weyl duality is used to compute the decomposition.

Except for their group theoretical interpretation, obtained entanglement witnesses have also a physical meaning. They can be used to compute a K - invariant variance of a given state $\Psi \in \mathbb{P}\mathcal{H}$ which measures how "classical" the state is. This connection is also discussed. Another interesting feature of proposed entanglement witnesses is that they can be computed from expectation values of certain hermitian and mutually commuting operators on two copies of a physical state Ψ: $\Psi \otimes \Psi$.

Presented work was done in the collaboration with my supervisor prof. Marek Kuś. I gratefully acknowledge support from the National Science Center through the project no. DEC-2011/01/M/ST2/00379.

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[1] A. Klyachko *Dynamic symmetry approach to entanglement, arXiv: 0802.4008* (2007)

[2] M. Kotowski, M. Kotowski, M. Kuś, *Universal nonlinear entanglement witnesses*, Phys. Rev. A 81, 062318 (2010)

[3] A. Sawicki, M. Kuœ *Geometry of the local equivalence of states* J. Phys. A: Math. Theor. 44 495301 (2011)

[4] B. C. Hall, *Lie groups, Lie algebras, and representations: an elementary introduction*, Springer (2003)

Quantum encryption with weak randomness using multi-qubit ciphertexts

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Devices based on measurement of quantum systems are expected to provide uniformly distributed randomness, however, fail to do so in practice. Uniform randomness is a valuable resource and many cryptographic tasks heavily rely on its availability. Nevertheless, real-world random number generators – based on both quantum and classical physics – require post-processing and are potentially vulnerable against side-channel attacks. These facts led to an investigation of the properties of non-uniform randomness in cryptography.

As we have shown in our previous work [2], a simple use of a quantum channel in a prepare-measure setting (where pure states of qubits are prepared and they are measured exclusively in their bases) can significantly enhance the security of communication by using a classically (or even quantumly) prepared imperfect random key. Here we extend the result for use of multi-qubit channels and conjecture a unexpected outcome: with sufficient length of the random key, any entropy loss can be compensated by use of sufficiently large channel to provide arbitrary security.

In our scenario, Alice would like to send a secret bit to Bob, whereas they share a secret random key with its level of randomness expressed via the min-entropy $H_\infty(\mathbf{Z}) = \min_{z \in Z} \left(-\log Pr\left(\mathbf{Z} = z\right)\right)$. We denote a source as (l, b)-source if it is emitting l-bit strings drawn according to a probability distribution with min-entropy at least b. Notice that for $b = l - c$, the probability of each l-bit string is upper bounded by 2^{c-l} and parameter c is called min-entropy loss.

In the classical scenario, Alice would use the random key to encrypt the bit and send it to Bob. The probability of any adversary to correctly guess the bit is lower bounded by [1]

$$p \geq \begin{cases} 1 & \text{for } 2 \leq c \leq l \\ \frac{1}{2} + \frac{2^c}{8} & \text{for } 2 - \log_2 3 \leq c \leq 2 \\ \frac{2^c}{2} & \text{for } 0 \leq c \leq 2 - \log_2 3. \end{cases} \qquad (1)$$

In quantum scenario with one-qubit channel, Alice would decode the secret bit into one of a set of states of a qubit depending on the random key. Bob, knowing the key, would just measure the state in the correct basis and always decipher correctly. The amount of information accessible to the adversary is limited by his ability to adjust his basis correctly and can be upper bounded by $p = 1 - h/4 = 1 - 2^{-c-1}$.

By using more qubit channels, the possibilities of Alice to choose the secret key are far bigger. Here the optimization can be performed only numerically for more than two-qubit channels and the results are shown in Figure 1. Based in these numerical results we conjecture that for any $\varepsilon > 0$ and c there exist n and l such that probability of the attacker to guess correctly the ciphertext is bounded by $p < \frac{1}{2} + \varepsilon$ if n-qubit channel and $(l, l - c)$ random source is used.

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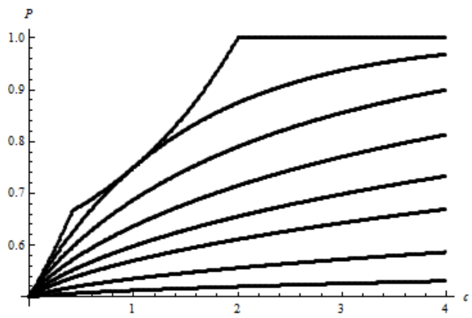

FIG. 1: Comparison of the probability of a successful guess by the attacker, if Alice and Bob use classical channel and quantum channel with increasing number of qubits (from the top to bottom).

[1] J. L. McInnes and B. Pinkas. On the impossibility of private key cryptography with weakly random keys. In *Crypto'90*, pages 421–435, 1991.

[2] J. Bouda, M. Pivoluska, and M. Plesch. Encryption with Weakly Random Keys Using Quantum Ciphertext *arXiv:1109.1943v1*, 2011.

Change of the Pancharatnam phase under unitary transformation and application to a model three-level Γ-type system specified by a pair of dipole-coupled excited states

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Interdependence of total, dynamic and geometric (Pancharatnam) phases of the state vector of a quantum system that are determined in different representations is considered. One finds that the phases calculated using two different bases of the Hilbert space, which are related by a time-dependent unitary transformation, are not invariant under this transformation; rather they are connected by nontrivial and well defined relations. We determine the general relationships between the phases in different representations and then apply, and verify these transformations in the case of the physically interesting model of the three-level Γ-type system specified by a pair of dipole-coupled excited states.

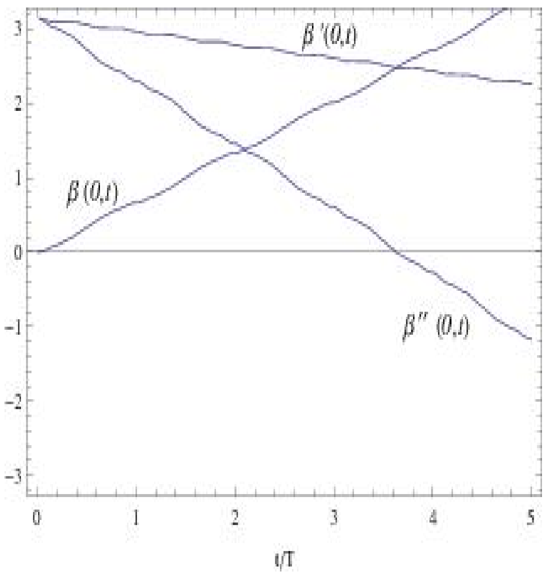

FIG. 1: Comparison of the numerically calculated geometric phases $\beta(0,t)$ and $\beta'(0,t)$, in radians, for two different bases of the Γ-type three-level system, unprimed and primed, respectively. The modifying term $\beta''(0,t)$ as a function of dimensionless time t/T (where $T \equiv 2\pi/\omega_0$ is the optical period) is represented by the curve labeled $\beta''(0,t)$. One finds that the sum $\beta(0,t)+\omega_1 t+\beta''(0,t)$ coincides with $\beta'(0,t)$ testifying to the validity of the relevant equation.

[1] M. Berry, Proc. R. Soc. A **392**, 45 (1984)
[2] Y. Aharonov and J. Anandan, Phys. Rev. Lett. **58** 1593 (1987)
[3] S. Pancharatnam, Proc. Indian Acad. Sci. A **44** 247 (1956)
[4] M. Bernet and R. Parzynski, Phys. Rev. A **82**, 023804 (2010)
[5] H. K. Avetissian, B. R. Avchyan and G. F. Mkrtchain, Phys. Rev. A **77** , 023409 (2008)

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A new experimental upper limit on λ parameter

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The Spontaneous Emission of radiation by free electrons phenomenon arises from the direct interaction of a free electron and a fluctuating scalar field, postulated in the framework of Spontaneous Collapse theories as a trigger to obtain the system wave function collapse and solve the *dualism problem* [1]. The important role played by this new phenomenon in checking such class of theories is easily understandable considering that its cross-section is a function of λ, a fundamental parameter in the Collapse Master Equations.
Nowadays the strongest upper bound on λ is set by the experimental search of spontaneous X-ray emitted by the electrons in a low-energy Ge-based experiment, presented in the work of Q. Fu [2]. In this work we analyze this result and present a new upper limit on λ parameter as a result of the analysis done on data published by the IGEX collaboration [3].

I. THE NEW EXPERIMENTAL UPPER LIMIT ON λ

The IGEX experiment is a low-activity Ge based experiment dedicated to the $\beta\beta 0\nu$ decay research. The apparatus is detailed described in ref. [4]. The IGEX collaboration has released data for a total exposure of 80 kg day in the energy region 4-49 keV [3], used in this wok to reconstruct the histogram to be analyzed with the following formula:

$$R(k) = (2.76 \times 10^{-15}) \times 4 \times (8.29 \times 10^{24}) \times \times (8.6 \times 10^{4}) \times 80 \times \lambda / k \quad (1)$$

The formula gives the number of emitted photons by the 4 external Ge electrons in counts/keV/kg/day for an exposure of 80 kg day. Here k is the emitted photon energy in keV, $2.76 \times 10^{-15} = e^2/4\pi^2 a^2 m_e^2$ where $a = a_{GRW} = 10^{-7} m$ is the correlation length. The new analysis brings the result:

$$\lambda < 1.5 \times 10^{-16} s^{-1} \ (C.L. = 95\%)$$

as the new upper limit on λ.

II. A CRITICAL REVIEW OF THE PREVIOUS ANALYSIS

The simple analysis done in ref.[2] on data coming from a first step of the IGEX experiment [5], consist in the theoretical evaluation of the expected rate R(k) at six different energies compared with the observed data. This ÒpunctualÓ evaluation of the rate at different energies, which could be used to evaluate the order of magnitude of λ and not a reliable upper limit, brings a bias. The choice as the only trustworthy experimental observable the point at 11.1 keV, neglecting the others.

Strictly from the point of view of the analysis, in this way, there is an evaluation of a free parameter (λ) using only one bin of the spectrum. In terms of degree of freedom (d.o.f.) of the analysis, we have d.o.f.=0, so there isn't enough information to evaluate correctly λ. Moreover, in case of systematic error affecting a region or a bin of the spectrum, it will affect the analysis result in a strong way.

Ref.[6], where the experimental history of the two Ge diodes of ref.[2] has been reconstructed, shows that data analyzed by Fu are affected by a Gain Stability problem and have to be corrected (systematic), so the result $\lambda < 0.55 \times 10^{-16} s^{-1}$ is questionable as estimate of the λ order of magnitude, and not reliable as its upper limit.

[1] P Pearle *et al.*, Phis. Rev. A . **39** (1989) 2277.
[2] Q Fu, Phys. Rev. A, **56** (1997) 1806.
[3] A Morales *et al.*, IGEX Collaboration, Phys. Lett. B **532** (2002) 814
[4] C E Aalseth *et al.*, IGEX Collaboration, Phys. Rev. C **59** (1999) 2108.
[5] H S Miley *et al.* Phys. Rev. Lett. **65**, (1990), 3092.
[6] A Rizzo *et al.*, arXiv:1112.1273v1 [quant-ph].

Estimating 2 qubit interaction in memory channel setting

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Let us have a quantum device, which accepts a single quantum input in Hilbert space $\mathcal{H}$ and produces a quantum output in the same Hilbert space. This device is composed of another quantum system, $\mathcal{M}$, which is inaccesible for the experimenter and which interacts with the input system with a unitary interaction $U : \mathcal{M} \otimes \mathcal{H} \mapsto \mathcal{M} \otimes \mathcal{H}$, whenever the input is inserted. The repeated usage of such device is described by a pure memory channel [1], where the inaccesible part is the memory system. Subsequent uses of this device are thus not independent and correlations are mediated via the memory system.

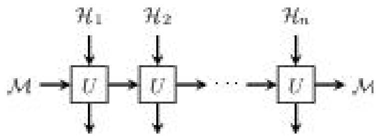

FIG. 1: A concatenation of n uses of a quantum device. The memory system $\mathcal{M}$ is reused in each iteration, and therefore the outputs are dependent on all previous inputs in general, therefore introducing memory effects.

Problem definition: Given these settings, estimate U.

The problem is that the uses of the quantum device are not independent, hence so are the outcomes. Since we have no access to memory, we cannot get rid of these effects. If we would use an naïve estimation scheme where we have some set of testing states ρ_k and testing measurements with outcomes associated to effects E_l and measure the probabilities $p(\rho_k, E_l)$, in order to estimate the local input-output channel

$$\mathcal{E}(\rho) = \mathrm{Tr}_{\mathcal{M}}[U(\xi \otimes \rho)U^\dagger] \quad (1)$$

for some unknown state $\xi \in \mathcal{M}$. The result of the estimation is then dependent on the ordering of the testing states ρ_k. The result doesn't have to be even a channel, the complete positivity can be violated.

The answer to this problem is a simple modification of previous scheme. By randomizing the sequence of testing states and testing measurements one can be sure that the result of such estimation will be channels of form

$$\overline{\mathcal{E}}_{[1,n]}(\rho_{[1,n]}) = \mathrm{Tr}_{\mathcal{M}}[U_{[1,n]}(\overline{\xi} \otimes \rho_{[1,n]})U^\dagger_{[1,n]}], \quad (2)$$

where $\overline{\mathcal{E}}_{[1,n]}$ is an average channel of n uses of the device, the $U_{[1,n]}$ is concatenated interaciton of over n subsequent uses, $\rho_{[1,n]} = \rho_{k_1} \otimes \cdots \otimes \rho_{k_n}$ is a sequence of n randomly chosen testing states, the k_i are randomly chosen from a set and $\overline{\xi}$ is an average state of memory entering the collision. This state is unknown and depends on the chosen probability distribution over testing states and testing measurements.

In the case of two qubit interaction U, the unitary can be fully estimated up to unitary conjugation on memory system, which cannot be known without access to memory system in any dimension. It is enough to estimate parts of the channel $\overline{\mathcal{E}}_{[1,2]}$. No apriory knowledge about the interaction, apart from the unitarity, is needed. Thus we show that estimation of interaction parameters is possible even in memory settings. It might come surprising that one can extract more information about the unitary interaction in this setting, then in memory-less setting, when the memory relaxes to initial state after each use of the device.

[1] D. Kretschmann, and R. Werner, *Quantum channels with memory*, Phys. Rev. A (2005)

Extraction of past-future entanglement in circuit QED

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It has been recently shown [1] that the vacuum of a massless scalar field contains quantum correlations between the future and the past light cones. A theoretical method of extraction by transference to detectors interacting with the field at different times has been proposed [3], using detectors with time-dependent energy gaps whose experimental implementation seems extremely challenging. Another ideal proposal involving cavities transparent to a single mode was provided in [4], although this setting seems even more difficult to tackle experimentally.

In this work [2] we propose a simple experiment to test the extraction of past-future vacuum entanglement by using a pair of qubits interacting with a quantum field at different times. Our setup consists of a circuit QED [5] design, where two superconducting qubits P and F separated by a fixed distance r, interact at different times in a common open transmission line. First, the interaction of P with the vacuum of the field, which is tunable in strength, is on for a time interval T_{on} - the past. Then, P is disconnected from the field during a given T_{off}. Finally, the interaction of F is switched on during T_{on} -the future - while keeping P disconnected. After this procedure, we will show that the qubits end up in a strongly correlated quantum state, in spite of the fact that they have never interacted with the field at the same time. Remarkably, the correlations between different times contained in the vacuum of the quantum field have been transferred to the qubits. The success of this result relies on the ultrastrong nature [6] of light-matter interaction in circuit QED, and its switchable capability [7]. Indeed, the latter has already been exploited to propose a feasible experimental test of the extraction of vacuum entanglement to a pair of spacelike separated qubits [8]. We will finally discuss the relationship of this effect with the spacetime region at which the qubits are placed.

The proposed experiment of past-future entanglement extraction would constitute a fundamental proof for the possibility of using the vacuum state of a field to produce correlations between a qubit in the past and a qubit in the future, but this is not the only interesting aspect. From the quantum technologies point of view, the ability to extract past-future entanglement from the field using a pair of qubits could be used to implement a device which teleports a quantum state in time - as first suggested in [3] -, or in other words, we could use the field in the transmission line for building up a novel kind of quantum memory.

[1] S. J. Olson and T. C. Ralph, Phys. Rev. Lett. **106**, 110404 (2011).

[2] C. Sabín, B. Peropadre, M. del Rey, and E. Martín-Martínez, ArXiv e-prints (2012), 1202.1230.

[3] S. J. Olson and T. C. Ralph, Phys. Rev. A **85**,012306 (2012).

[4] A. Dragan and I. Fuentes, ArXiv e-prints (2011), 1105.1192.

[5] A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, Phys. Rev. A 69, 062320 (2004).

[6] J. Bourassa, J. M. Gambetta, A. A. Abdumalikov, O. Astafiev, and Y. Nakamura, Phys. Rev. A 80, 032109 (2009).

[7] B. Peropadre, P. Forn-Díaz, E. Solano, and J. J. García-Ripoll, Phys. Rev. Lett. 105, 023601 (2010).

[8] C. Sabín, J. J. García-Ripoll, E. Solano, and J. Leóon, Phys. Rev. B **81**, 184501 (2010).

Testing Quantum Foundations with Circuit QED

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Circuit QED provides a framework in which the interaction of two-level systems with a quantum field can be naturally considered. The combination of superconducting qubits with transmission lines implement an artificial 1-D matter-radiation interaction, with the advantage of a large experimental accessibility and tunability of the physical parameters. Using these features, fundamental problems in Quantum Field Theory hitherto considered as ideal are now accessible to experiment, as is the case of the recent first physical realization of the dynamical Casimir effect. [1]

In this talk, we will review some of our experimental proposals for fundamental tests of Quantum Mechanics and Quantum Field Theory with circuit QED setups, ranging from the first experimental test of the long-lasting Fermi problem on the microcausality at the atomic level [2] to the extraction of quantum correlations from the vacuum of a quantum field to a pair of qubits [3], passing through the observation of non-Rotating Wave Approximation phenomena like ground-state qubit self-excitations [4] and their impact in the interpretation of quantum detection at short times [6].

In particular, in this latter work [6] we have shown that for typical circuit QED parameters, a significative amount of time is needed to start trusting the state of a two-level detector as informative regarding an initially excited two-level source. This is due to the breakdown of the RWA in circuit QED. By neglecting the counterrotating terms a total reliability on the information coming out of the detector would be wrongly derived for all time-scales. Our result applies to other setups and quantum detectors, although it is in the case of circuit QED where it might affect the interpretation of coming experimental results.

[1] C. M. Wilson, G. Johansson, A. Pourkabirian, M. Simoen, J. R. Johansson, T. Duty, F. Nori, P. Delsing, Nature **479** 376-379 (2011).

[2] Carlos Sabín, Marco del Rey, Juan José García-Ripoll, Juan León, Phys. Rev. Lett, **107**, 150402 (2011).

[3] Carlos Sabín, Juan José García-Ripoll, Enrique Solano, Juan León, Phys. Rev. B, **81** 184501 (2010).

[4] Carlos Sabín, Juan José García-Ripoll, Enrique Solano, Juan León, Phys. Rev. B, **84** 024516 (2011).

[5] Marco del Rey, Carlos Sabín, Juan León, arXiv: 1108.0672, accepted to Phys. Rev. A.

Decoherence in Loop Quantum Gravity

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Recent developments in operator spin foams (OSF) [1] and the EPRL model [4] have established the correspondence between canonical loop gravity and spin foam models. This allows for a novel perspective on decoherence in quantum gravity.

I. Desiderata for decoherence in LQG

(1) A space of physical states, equipped with the appropriate dynamics (i.e. a space of fine-grained histories);

(2) a background-independent analogue of the decoherent histories formalism (cf. [1]): that is, sequences of projections on a *history space*, corresponding *class operators* C_α, and a *decoherence functional* $D(\alpha, \alpha')$ which satisfies $D(\alpha, \alpha') \approx 0$, for any two incompatible α, α', and a probability measure $p(\alpha)$ on the space of histories.

(3) some physical process instantiating the coarse-graining.

II. Fine-grained histories of spin networks

The state space is given by $\mathcal{H}_{Diff}$, the kinematical diffeomorphism-invariant Hilbert space of spin network states spanned by

$$\psi_{\Gamma, j_l, \mathrm{v}_n}(h_l) = \left(\otimes_l d_{j_l} D^{j_l}(h_l)\right) \cdot (\otimes_n \mathrm{v}_n,) \qquad (1)$$

following the notation in [4].

The fine grained history of a spin network state $\psi_{\Gamma, j_l, \mathrm{v}_n}(h_l)$ is thus given by the amplitude of a spin foam with boundary (see equation 73 in [4]), where the boundary spin network has the quantum numbers $\Gamma, j_l, \mathrm{v}_n$.

III. Coarse graining on spin network states

Generic states of a given geometry are given by linear superpositions of spin network states. Holomorphic coherent states are given by

$$\psi_{H_l}(h_l) = \int_{SU(2)} dg_n \otimes_{l \in \Gamma} K_t(g_{s(l)} H_l g^{-1} h_l^{-1}), \qquad (2)$$

where ψ is holomorphic in H_l, and K_t denotes the analytic continuation to $SL(2, \mathbb{C})$ of the $SU(2)$ heat kernel. The restriction of generic superpositions to holomorphic coherent states and truncation to a finite graph may be regarded as a coarse-graining of a quantum state, the effect of which is peaking the geometry on semiclassical states with particular intrinsic and extrinsic geometry. See procedure in [3].

Transitions between holomorphic coherent states are given by the spin foam amplitude associated with the initial and final states bounding the spin foam. A class operator is then given by a spin foam which is restricted to holomorphic coherent states peaked around particular semiclassical states. This is analogous to the path integral expression for the class operator in the timeless formalism of Hartle, cf. [1].

The probability measure on the collection of such histories is induced by the Ashtekar-Lewandowski-Measure on the space *Cyl* of cylindrical functions (cf. [6]).

IV. Quasiclassical trajectories

Decohered spin networks follow quasiclassical trajectories. This has been shown in [3] for homogenous and isotropic holomorphic coherent states, which reproduce Friedmann dynamics for (i) truncation to a finite graph of the gravitational degrees of freedom; (ii) at first-order in the vertex expansion and (iii) in the large volume limit. More work is needed to extend this result to a more general setting.

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[1] W. Kaminski, M. Kisielowski and J. Lewandowski, Class. Quant. Grav. **27**, 095006 (2010), arXiv:0909.0939

[2] J. Engle, E. Livine, R. Pereira and C. Rovelli, Nucl. Phys. B **799**, 136 (2008), arXiv:0711.0146

[3] J.B. Hartle, *Spacetime Quantum Mechanics and the Quantum Mechanics of Spacetime*, arXiv:gr-qc/9304006

[4] C. Rovelli, *Zakopane Lectures*, arXiv:1102.3660v5

[5] E. Bianchi, C. Rovelli and F. Vidotto, Phys. Rev. D **82**, 084035 (2010), arXiv:1003.3483

[6] A. Ashtekar and J. Lewandowski, *Projective techniques and functional integration*, J. Math. Phys. **36**, 2170 (1995)

Kahler and Hyper-Kahler structures in Quantum Mechanics

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III. INTRODUCTION

Quantum mechanics is standardly formulated as a theory whose states are vectors (or rays) in a *complex* Hilbert space. However, it is also intimately related to theories on complex manifolds, in particular complex manifolds which carry a Kahler or hyper-Kahler structure.

This note discusses two such theories, which I call Geometric Quantum Mechanics (GQM) and A-model Quantum Mechanics (AQM) respectively.

IV. GEOMETRIC QUANTUM MECHANICS

GQM is by far the more familiar of the two (see [1] and [2]). It takes as its starting point the observation that if we quotient out the unphysical $U(1)$ phase freedom in a (let us assume finite-dimensional) Hilbert space $\mathcal{H}^{n+1}$, we obtain a Kahler manifold (M, g, J)as the reduced phase space, specifically $\mathcal{C}P^n$, whose Riemannian metric g is the Fubini-Study metric.

After this quotienting operation, an observable $\mathcal{O}$ on Hilbert space is represented as a real-valued function $f_{\mathcal{O}}$ on M, and unitary evolution is represented as the flow of a Hamiltonian vector field associated to $f_{\mathcal{O}}$. The critical points of this function represent eigenvectors of the observable.(So there is a tantalizing connection to Morse theory.)

Evidently, by quotienting out the $U(1)$ gauge freedom, one can represent a linear algebraic theory (standard Hilbert space QM) as a non-linear, geometric theory, whose phase space resembles a 'classical theory', in the sense that it is also a symplectic manifold (M, w), albeit one that in addition carries an integrable complex structure J, which in conjunction with the symplectic form ω, defines a Riemannian metric g.

This view-point can be used to understand various foundational results in QM. For instance, one proves the no-cloning theorem by showing that a cloning map does not preserve g, as argued in [3]. Furthermore, one can prove the Bell-Gleason theorem by showing that every critical point of $f_{\mathcal{O}}$ is the zero of a Killing vector field. Since these critical points are isolated, there is a non-zero angular separation between them, which can be calculated by means of the metric g.

V. A-MODEL QUANTUM MECHANICS

AQM has only recently been formulated in the work of [4] and [5]. It is based on the insight that one can quantize a $2n$-dimensional classical phase space (i.e. symplectic manifold) M by complexifying it to obtain a $4n$-dimensional phase space $\hat{M}$, and then picking a middle (i.e. $2n$)-dimensional Lagrangian submanifold $L \subset \hat{M}$ as the target space of an A-model QFT. (This particular A-model is the topological 'twisting' of a $(1 + 1)$-dimensional σ-model whose fields are maps from a Riemann surface Σ to $\hat{M}$.) In fact, in order to obtain an A-model with non-vanishing correlation functions, $\hat{M}$ must be chosen to be hyper-Kahler (or almost hyper-Kahler), i.e. it carries three complex structures I, J, K which satisfy a quarternionic relation.

Why does this lead to a valid quantization procedure? Very roughly speaking, the reason is that (i) complexifying M allows one to construct integration cycles (including non-standard integration cycles) for the path-integral via analytic continuation, and (ii) the condition for a middle-dimensional submanifold of $\hat{M}$ to give rise to an integration cycle is just the condition for it to have an A-model interpretation. Thus, in a sense, (But see §3 of [4] for difficulties that arise when one tries to include a non-trivial Hamiltonian.) we have an equivalence between a $(0+1)$-dimensional and a $(1+1)$-dimensional QFT.

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[1] G. Gibbons, Journal of Geometry and Physics 8, 147 (1992), ISSN 0393-0440, http://www.sciencedirect.com/science/article/pii/0393044092900464.
[2] A. Ashtekar and T. A. Schilling (1997), gr-

qc/9706069.
[3] N. Teh, Studies in the History and Philosophy of Modern Physics (2012).
[4] E. Witten (2010), 1009.6032.
[5] S. Gukov and E. Witten (2008), 70 pp, 0809.0305.
[6] So there is a tantalizing connection to Morse theory.
[7] But see x3 of [4] for diffculties that arise when one tries to include a non-trivial Hamiltonian.

Quantum physics and contemporary experimental tests?

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It follows from the poster presented by M. V. Lokajíček to this conference that all solutions of Schrödinger equation correspond to those derived in classical physics (solutions of Hamilton equations and their statistical superpositions); only the set of allowed physical states is smaller. Schrödinger equation may be regarded as valid for the whole physical reality; differences between quantum energy values being unmeasurable in macroscopic region. However, the Schrödinger equation represents phenomenological description only without contributing to understanding actual quantum mechanism.

On the other side, it follows from the given results that it is necessary to return to ontological approach as proposed already by Aristotle, on the basis of which practically the classical physics has been built up. It is not possible to interpret microscopic physical particles as mathematical artifacts only; they must be described as ontological objects of corresponding sizes and having internal realistic structure. It is evident that, e.g., in the case of hydrogen atom the quantum behavior cannot be given by Coulomb interaction only. Very short-range repulsive effect (force) must be surely involved, too. This force (representing practically contact interaction) may be hardly mediated by a potential, at the difference to Coulomb force acting at distance. It means that the given quantum effect will depend also on dimensions and internal structures of interacting objects. It is necessary to look for the corresponding characteristics of theirs.

These characteristics may be obtained by analyzing the experimental data gained in different collision experiments. Some new results have been derived by us from elastic proton-proton collision experiments, when the ontological approach has been respected. Instead of commonly applied description we have made use of the eikonal model where the probability of different processes in the dependence on impact parameter values may be derived [1]. According to our recent preliminary studies the proton is to be regarded as an object existing in diverse internal states exhibiting different external dimensions [2]. The idea of different internal states is similar to that proposed by Good and Walker in predicting diffraction scattering [3].

From the measurements of differential cross section at ISR energies ($53\,GeV$) it has been possible to derive some characteristics of these internal states, as two states exhibiting the greatest dimensions may be taken as responsible for the shape of differential cross section of two-proton elastic collisions corresponding to lowest momentum transfer values (approximately less than 1 GeV in ISR collision experiments).

On the basis of our analysis it has been obtained for these two highest dimensions: $2.15\,fm$ and $2.05\,fm$. They are maximum dimensions of some elongated ellipsoids, while in some perpendicular direction the minimum dimension may be approximately $0.5\,fm$, which might represent hard proton core. It has been also possible to estimate that the corresponding frequency of these two structures are approximately 61% and 16%. The other structures should exhibit lower extreme dimensions, while the minimal dimension should remain practically the same. Our preliminary values are, of course, very rough as some simplifying assumption has been made use of; more realistic analysis is being done at the present. In the course of our analysis it has been also derived that the optical theorem (taken usually as the basic assumption in interpreting elastic scattering data) may hardly hold in the case of strong interactions [4]. It has not been used in our new statistical model described in [2].

They are the correlations between the quantum values of energy and angular momentum (or spins) that should be studied, too; both the quantities being conserved in time evolution according to classical physics.

[1] V. Kundrát, M. V. Lokajíček: High-energy elastic scattering amplitude of unpolarized and charged hadrons; Z. Phys. C 63 (1994), 619-29

[2] M. V. Lokajíček, V. Kundrát: Elastic pp scattering and the internal structure of colliding protons; (2009) /arXiv:0909.3199[hep-ph]

[3] M.L. Good, W.D. Walker: Phys. Rev. 120 (1960), 1857

[4] M.V.Lokajíček, V.Kundrát: /arXiv:0906.3961

Fidelity spectrum, quantum phases and their transitions

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Fidelity between two quantum states characterized by two density operators $\hat{\rho}_1$ and $\hat{\rho}_2$ is defined as the trace of the fidelity operator $\hat{\mathcal{F}}$,

$$F(\hat{\rho}_1, \hat{\rho}_2) = \mathrm{Tr}\hat{\mathcal{F}}(\hat{\rho}_1, \hat{\rho}_2) = \mathrm{Tr}\sqrt{\sqrt{\hat{\rho}_1}\hat{\rho}_2\sqrt{\hat{\rho}_1}}.$$

It is a function that quantifies the distinguishability between two quantum states. Thus, as two quantum states defining different macroscopic phases are expected to have enhanced distinguishability, fidelity arises as a natural candidate for the study of phase transitions (PTs). The fidelity approach to quantum phase transitions (QPTs) was introduced in [1], where the sudden drop of the fidelity along the regions of QPTs was observed in the Dicke and the XY models. The thermal PTs were explored in [2], while the fidelity between partial states was first used to study QPTs in [3]. Recently, we have shown [4] that considering a more refined quantity - fidelity spectrum - could provide even more detailed description of both the critical phenomena and the features of quantum phases, such as which particular modes are responsible for a given transition.

We introduce the spectrum $\{\lambda_i\}$ of the of fidelity operator $\hat{\mathcal{F}}(\hat{\rho}_1, \hat{\rho}_2)$, which we denote the *fidelity operator spectrum*, and the logarithmic spectrum $\{-\ln\lambda_i\}$, which we call the *fidelity spectrum.* We analyze the fidelity spectrum and the fidelity operator spectrum of partial states of different systems: a magnetic impurity in a conventional superconductor, the XX spin-1/2 chain in a transverse magnetic field, and a bulk superconductor at a finite temperature. When the density operators are equal, the fidelity spectrum reduces to the entanglement spectrum, establishing a connection between the two information-theoretic approaches to quantum phase transitions: the fidelity and the entanglement spectrum approaches.

We find that the fidelity spectrum can be a useful tool in giving a detailed characterization of different phases of many-body quantum systems, as well as a more refined description of their phase transitions, providing complementary information to other techniques. Moreover, it allows to identify the modes that have a larger contribution to the distinguishability between the states across a phase transition, and singles out the most divergent contributions to the associated susceptibility.

In the case of a magnetic impurity in a conventional superconductor, we find that only one eigenvalue associated with the charge and one eigenvalue associated with the spin undergo significant changes as the magnetic impurity-induced quantum phase transition occurs: the transition is associated with the capture of one electron by the impurity having a parallel spin. In the case of a bulk superconductor at a finite temperature, we analyze momentum modes, labelled by number k, that block-diagonalize the effective mean-field BCS Hamiltonian (see [2, 4]). For each 4-dimensional block k, we consider the associated *k-fidelity operator* $\hat{\mathcal{F}}_k$ and its eigenvalues. When one density operator represents the normal phase and the other the superconducting phase, we observe a clear change of the eigenvalues (fidelity operator spectrum) whose momentum k numbers are located only around the Fermi surface, identifying the modes responsible for the state distinguishability between different phases.

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[1] P. Zanardi and N. Paunković, Phys. Rev. E **74**, 031123 (2006).

[2] N. Paunković and V.R. Vieira, Phys. Rev. E **77**, 011129 (2008).

[3] N. Paunković, P.D. Sacramento, P. Nogueira, V.R. Vieira and V.K. Dugaev, Phys. Rev. A **77**, 052302 (2008).

[4] P.D. Sacramento, N. Paunković and V.R. Vieira, Phys. Rev. A **84**, 062318 (2011).

Barycentric measure of quantum entanglement

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Majorana representation of quantum states by a constellation of n 'stars' (points on the sphere) can be used to describe any pure state of a simple system of dimension $n+1$ or a permutation symmetric pure state of a composite system consisting of n qubits. We analyze the variance of the distribution of the stars, which can serve as a measure of the degree of non-coherence for simple systems, or an entanglement measure for composed systems. Dynamics of the Majorana points induced by a unitary dynamics of the pure state is investigated.

Non–classical correlations between composite quantum systems became a subject of an intense current research. A particular kind of such correlations, called *quantum entanglement* attracts special attention of theoretical and experimental physicists – see [1] and references therein. One of the key issues is to workout a practical entanglement measure. Although various measures of quantum entanglement are known [1–3], they are usually difficult to compute. An important class of entanglement measures can be formulated within the geometric approach to the problem [2, 4].

We present [5] a homogeneous approach to study the structure of pure quantum states describing two physical problems: a simple system consisting of $n+1$ levels and the class of states of an n–qubit system, symmetric with respect to permutations of all subsystems. Making use of the Majorana–Penrose [6, 7] representation one can find a direct link between these two cases as any constellation of n stars on the sphere determines a quantum state in both setups.

Physical properties of a given pure state can be thus related to the distribution of the corresponding collection of n points on the sphere. The variance of this distribution, related to the radius of the barycenter inside the ball, can be used to characterize the degree of non spin coherence of the states of a simple system or the degree of entanglement for the composite systems. The proposed barycentric measure of quantum entanglement achieves its maximum for these states, for which the barycenter of the corresponding Majorana points is located at the center of the ball. This class of states includes the Bell state of a two-qubit system, the GHZ state of a three qubit system and several states distinguished by being most distant from the set of separable states and called 'Queen of Quantum' [8]. In the case of four–qubit states we have explicitly described a two-parameter class of extremal symmetric states for which the barycentric measure achieves the maximal value, $E_B = 1$. All these states are also highly entangled with respect to the geometric measure E_G, which for them belongs to the interval $[1, \log_2 3]$.

Any unitary dynamics acting on the n–qubit system is described by a matrix U of order 2^n. Under assumption that the dynamics does not break the permutation symmetry, the matrix U is reducible and can be written as a direct sum of two unitary matrices, $U = V \oplus W$. The matrix V or order $n+1$ describes the unitary dynamics in the subspace of symmetric states of the composed system or the corresponding unitary dynamics in the space of all states of the $(n+1)$–level system. A unitary dynamics of a quantum pure state leads to a non-linear dynamics of the corresponding stars of its Majorana representation. In a simple model evolution investigated for a two qubit system the velocity of stars is small if they are far apart, what corresponds to the highly entangled states, and it increases as the stars get together and the state is close to be separable.

[1] R. Horodecki, P. Horodecki, M. Horodecki and K. Horodecki, *Rev. Mod. Phys.* **81**, 865 (2009).
[2] I. Bengtsson and K. Życzkowski, *Geometry of quantum states* (Cambridge University Press, Cambridge, 2006).
[3] M. B. Plenio, S. Virmani, *Quant. Inf. Comp.* **7**, 1 (2007).
[4] M. Kuś and K. Życzkowski, *Phys. Rev.* **A 63**, 032307-13 (2001).
[5] W. Ganczarek, M. Kuś, K. Życzkowski, *Phys. Rev. A* **85**, 032314 (2012).
[6] E. Majorana, Nuovo Cimento **9**, 43 (1932).
[7] R. Penrose, *The Emperor's New Mind* (Oxford University Press, Oxford, 1989)
[8] O. Giraud, P. Braun and D. Braun, *NJP* **12**, 063005 (2010).