Journées de Broglie 2023

100 years of matter waves

International conference, Paris, 3-5 July 2023

Campus des Cordeliers, Sorbonne Université

Book of Abstracts

A quantum bouncing ball gravity resonance spectrometer

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Abstract

Inspired by DeBroglie's now famous *Recherches sur la théorie des quanta*, Erwin Schrödinger set-up an equation for matter waves. For a reflected neutron falling in the gravity potential of the earth, the solutions are so-called Airy functions, which Sir George Airy used to explain the interference pattern in connection with a rainbow.

The coherent superposition of such Airy functions describes the time and space evolution of the quantum bouncing ball measured by neutron detectors with spatial resolution. Such matter wave interference is still good for a surprise.

The discrete eigen-energy spectrum of a neutron on a reflector allows to develop a gravity resonance spectroscopy (GRS) technique for ultra-cold neutrons. The application of Ramsey spectroscopy to GRS permits to test basic symmetries and questions about the origin of gravity at different levels.

Plasma-like description for quantum particles

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Abstract

Schrödinger noticed in 1952 [1] that a scalar complex wave function can be made real by a gauge transformation. It was shown recently that one real function is also enough to describe matter in more realistic theories, such as the Dirac equation in an arbitrary electromagnetic [2] or Yang-Mills [3, 4] field. As these results suggest some "symmetry" between positive and negative frequencies and, therefore, particles and antiparticles, the author previously considered a description of one-particle wave functions as plasma-like collections of a large number of particles and antiparticles [5, 6]. The similarity of the dispersion relations for the Klein-Gordon equation and a simple plasma model provides another motivation for the plasma-like description of quantum particles. In this description, the frequency of the "periodic phenomenon" related to the particle mass [7] appears as a natural frequency (plasma frequency), rather than a frequency of some "internal clock".

A criterion is offered [4, 8] for approximation of continuous charge density distributions by discrete ones with quantized charge based on the equality of partial Fourier sums. It is proven for the one-dimensional case that such approximation can be arbitrarily precise as defined by this criterion. An example of such approximation is computed using the homotopy continuation method. An example mathematical model of the interpretation is proposed. A modification of the interpretation for composite particles, such as nucleons or large molecules, describes them as collections including a composite particle and a large number of pairs of elementary particles and antiparticles. In the case of composite particles, the plasma-like description has more similarities with the de Broglie-Bohm interpretation and the de Broglie's double solution program [9].

While it is not clear if there is some reality behind such a description, it can become a basis of an interesting model of quantum mechanics. For example, it can offer an intuitive picture of the double-slit experiment. It also seems to enable simulation of quantum phase-space distribution functions, such as the Wigner distribution function, which are not necessarily non-negative, whereas, according to Feynman [10], "The only difference between a probabilistic classical world and the equations of the quantum world is that somehow or other it appears as if the probabilities would have to go negative, and that we do not know, as far as I know, how to simulate."

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Space-time resolved quantum field approach to Klein tunneling dynamics of fermions and bosons

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Abstract

We investigate Klein tunneling with space-time resolved solutions to relativistic quantum field equations with background potential barriers. We show in particular that no particle actually tunnels through a finite supercritical barrier, even in the case of resonant tunneling. The transmission is instead mediated by modulations in pair production at each edge of the barrier caused by the incoming particle which decreases (increases) the number density of anti-particles in the case of fermions (bosons). This decrease (increase) undergoes multiple reflections inside the barrier modulating pair production rate at its edges and forming the reflected and transmitted wave packets. We further examine the effect of the barrier?s width on the numbers of produced pairs in the fermionic case (characterized by saturation) and in the bosonic case (characterized by exponential superradiance). We compare the results qualitatively and quantitatively to the first-quantized account of Klein tunneling.

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From observer-dependent facts to frame-dependent measurement records in Wigner friend scenarios

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Abstract

In Wigner-Friend Scenarios, the description by a super-observer (Wigner) of the state evolution of a lab containing a friend which performs a quantum measurement is still controversial. Many recent works assume that the lab's state evolves unitarily after the friend measures. We present a protocol showing that this assumption, in the context of relativistic considerations, can lead to frame-dependent outcomes. Specifically, a distant agent sharing an entangled pair with the friend and performing a space-like separated measurement can steer the state of the lab, causing super-observers in different inertial frames to disagree about their observation of measurement records issued by the friend.

Towards models of wave-particle duality and quantum measurement based on stochastic fields with future-input dependence

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The ideas of de Broglie (1923) lead within a few years to a clear set of rules for quantum mechanics, providing predictions for a full range of possible experiments, albeit without supplying a corresponding model of physical reality. In 1964, Bell showed that such a model must violate local causality, but he took causality for granted, emphasizing locality. Indeed, it is now standard to state that although quantum physics is nonlocal in Bell's sense, i.e., it involves nonlocal variables such as many-body wavefunctions, it does not entail nonlocal signaling. While the alternative "retrocausal" view was promoted all along, including by Costa de Beauregard (a student of de Broglie), explicit mathematical models of this type were constructed only very recently; see [1] for a review. In these models, internal variables associated with a specific point in space and time may depend, through additional mediating variables, on input variables in their future. In agreement with standard quantum mechanics, such models do not entail any retrocausal signaling (just as with the standard statement on nonlocality above). The mediating variables allow the models to conform to a generalized "no action at a distance" locality condition which, unlike Bell locality, does not assume a predefined arrow of time.

Developing a future-input-dependent model reproducing the full range of quantum phenomena, while retaining this generalized locality, represents a grand challenge. The models discussed in [1] are toy models, describing only a single pair of fully entangled particles. A generalization to three-particle GHZ correlations was given in [2], and the implications for quantum computing were discussed in [3]. Going further requires confronting wave-particle duality, i.e., devising an alternative to the resolution reached by the physics community in the 1920s.

The present work considers stochastic fields in spacetime (cf. Parisi-Wu stochastic quantization), subject to time-reversal symmetric rules, with initial conditions imposed to break the time symmetry. Measurement apparatuses consisting of additional stochastic degrees of freedom are invoked. These are initialized in a metastable state, enabling modeling of an irreversible "click" — falling out of the metastable state — with dissipation introduced via a heat bath. The wave-like properties emerge from the field itself, while "particle-like" properties correspond to the clicks, each of which occurs stochastically and acts back on the field when it does ("dark counts" — clicks in the absence of a source — may occur). The clicks represent macroscopically available information, which can be copied.

In this approach, the Schroedinger equation is analogous not to Newton's equation but to the Liouville equation which follows the evolution of classical phase-space probability densities (the Liouville and Schroedinger equations are both universally linear, and are both exponentially complex for many degrees of freedom). However, the wavefunction at time t encodes just the information available from earlier times, and can produce probabilities for detector clicks only when combined with information regarding which measurements are performed later. In this type of model, wavefunction collapse occurs in the appropriate double limit in which the heat bath consists of many degrees of freedom, and dark counts are minimized. The distinction between the state of the stochastic field, or its probability distribution, and the state of knowledge — the wavefunction — is dramatic. A broad discussion of such models will be presented, and avenues for the development of detailed models will be sketched.

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Universal Matter-Wave Interferometry

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Abstract

When Louis de Broglie proposed his idea on matter waves in 1923, he claimed that this idea was likely to ‘solve all problems related to quanta’.

His idea inspired Schrödinger’s wave equation and became the basis for a century of many quantum technologies. However, the fundamental nature of the quantum wave has remained a matter of debate throughout the century, as there is no well-defined cut between the coherent quantum evolution and our classical experience.

This has motivated a series of quantum experiments in Vienna throughout with different types of atoms, polyaromatic hydrocarbons, clusters of organic molecules, vitamins, neurotransmitters and polypeptides in meanwhile half a dozen of different types of matter-wave interferometers. All these experiments confirm quantum mechanics to be correct and even to apply to objects that were deemed too complex or too agitated to show quantum wave behavior, still thirty years ago.

I will describe ongoing explorations to expand these studies to objects of increasing mass and complexity. We will discuss measures of macroscopicity and experiments to probe potential deviations from quantum theory.

Given the universality of de Broglie’s ideas, we will discuss how to exploit the matter-wave nature of large molecules to gain new insight into materials science and biophysical chemistry.

Quantum force and space-time topology in the Aharonov-Bohm effect

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Abstract

Zeilinger's dispersivity theorem predicts the absence of force, while Shelankov and Berry predict the presence of a force for Aharonov-Bohm effect. We investigated this conundrum both by experiment and theory [1]. An experiment is presented that supports Shelankov and Berry's prediction, while theory is presented to encompass both predictions thus resolving this confusing problem. Even if we feel that this issue is now resolved others remain. We will present a theoretical argument that questions the idea that one has to enclose a magnetic flux to observe the Aharonov-Bohm effect [2]. The idea is offered that spatial topology that is relevant for the Aharonov-Bohm effect is part of a space-time topology that may be used to escape the requirement that one has to enclose a magnetic flux, while still preserving gauge invariance.

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Quantum trajectories, quantum potential, superoscillations: Bohm, Madelung, de Broglie, Newton

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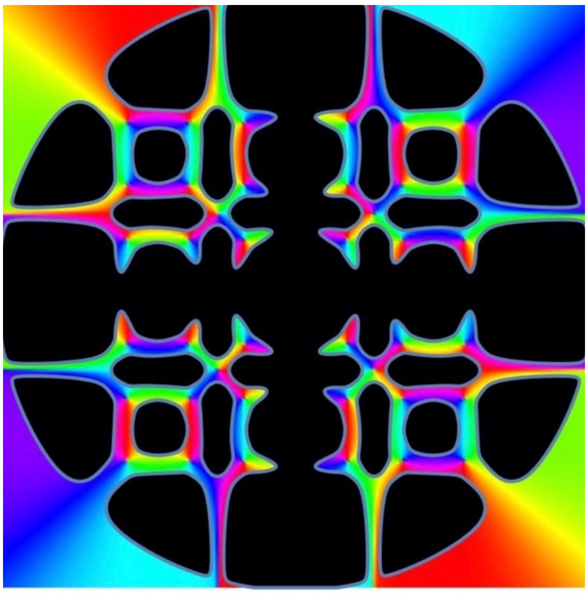
Abstract

Trajectories modified by the quantum potential are the wave counterparts of the classical paths of material particles and the rays of geometrical optics. As envisaged by Isaac Newton in his attempts to understand diffraction, such trajectories can undulate. They are strongly influenced by phase singularities. The local quantum velocity (proportional to the phase gradient, i.e. weak value of momentum with position postseelected), can be faster than the classically allowed speed. This happens in regions of superoscillation, containing the phase singularities; outside these regions, the quantum velocity is slower. The two regions are separated by manifolds where the quantum potential is zero. The quantum potential suggests a generalisation of quantum mechanics, applicable to classical curl forces, which are not derivable from a potential.



Poster abstract:
Obtaining entanglement by particle indistinguishability

Ewa Borsuk

The poster presents a novel method of generating arbitrary entanglement of three qubits in no-touching scenario as well as multipartite W state. The key idea behind the no-touching scenario is that particles do not have to "interact" with each other in order to create entangled state. Let us precise what is meant by the interaction here. The common intuition behind the interaction is that particles need to be present at a given location at the same time. In this sense creating entanglement is on some kind of a dynamical event represented by mixing terms in the Hamiltonian which correlates modes of the system, as it happens to be the case in the SPDC. One can also think of a more kinematical-like example of interaction such as the interference of identical particles on a beam splitter where bosons show the bunching effect and fermionsshow the anti-bunching effect due to Pauli exclusion principle. Hence the correlation between particles arises as a consequence of the particles' statistics and the commutation relations at the touching point.

Alternative approach is taken in the *no-touching* scenario where the particles do not meet at any point of the entire protocol yet the entanglement arises due to interference and particle indistinguishability. The optical realization of this scenario can be implemented by the coincidence injection of k independent particles into the circuit that has spatially separated paths (without any crossing) and a proper post-selection procedure. The first implementation of the no-touching scenario was interferometer of Yurke and Stoler [1] where the authors were able to produce Bell state.

The poster presents two optical circuits in the no-touching scenario: the first one generating arbitrary entanglement of three qubits [2], the second one generating multipartite W state [3]. The results show that entanglement can be generated solely thanks to interference effects as well as particle indistinguishability.

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A bridge between Schrödinger equation and Schrödinger Bridge process *by Léon Brenig and Marc Vincke.* Université Libre de Bruxelles.

Summary *: The unitary evolution described by the Schrödinger equation and the non-unitary evolution governed by the Schrödinger Bridge random process are shown to be mathematically related. Indeed, these two types of evolution mix under nonlinear gauge transformations of the wavefunctions introduced in this work. After such a transformation the new wavefunction appears to obey again to both the above unitary and non-unitary evolutions. The interpretation of this result is discussed but remains an open question.*

Nonlinear gauge transformations of the wavefunction are introduced in the non-relativistic description of a free spinless particle of mass m. These transformations constitute a one-parameter Lie group. For wavefunctions $\psi(x) = \rho(x)^{1/2}e^{\frac{i}{\hbar}s(x)}$ normed to one, they only act on the argument $s : s \to s(\alpha) = e^{-\alpha}s$; $\alpha \in \mathbb{R}$. These transformations conserve the product $\psi\psi^*$ and keep invariant the following system of equations for the wavefunction :

$$i\partial_t\psi = -\frac{\hbar}{2m}\nabla^2\psi \tag{0.1}$$

$$i\partial_\tau\psi = -\frac{\hbar}{2m}\nabla^2\psi + \frac{\hbar}{m}\psi\frac{\nabla^2 \mid \psi \mid}{\mid \psi \mid} \tag{0.2}$$

The first equation is the Schrödinger equation which describes the unitary evolution in time t. The second equation is nonlinear and describes the evolution of ψ in a parameter τ that has temporal physical dimension but, a priori, is different from time t. The invariance of the system (0.1), (0.2) under the nonlinear gauge transformations is ensured provided the couple (t, τ) transforms in a hyperbolic rotation :

$$t(\alpha) = \cosh(\alpha)t + \sinh(\alpha)\tau \tag{0.3}$$

$$\tau(\alpha) = \sinh(\alpha)t + \cosh(\alpha)\tau \tag{0.4}$$

Remarkably, the equation (0.2) can exactly be transformed into the so-called Schrödinger Bridge random process that E.Schrödinger studied in 1931-1932 [1][2] :

$$\partial_\tau\varphi = \frac{\hbar}{2m}\nabla^2\varphi \tag{0.5}$$

$$\partial_\tau\phi = -\frac{\hbar}{2m}\nabla^2\phi \tag{0.6}$$

These two equations, respectively, describe the forward and backward diffusive evolution of a Brownian particle whose probability density is prescribed both at the initial and final time. The functions of position and time φ and ϕ are not themselves probabilities but their product $\varphi\phi$ is the probability density that interpolates at intermediate times between the initial and final distributions. In his 1931 and 1932 papers, E.Schrödinger introduced this problem in an effort to understand the origin of the Born rule in quantum mechanics. He, however, called his attempt a fiasco because he did not find any connection between quantum mechanics and the classical random process he had defined and studied. Here, we show that this is not the case : the two types of evolutions are tightly bound by the nonlinear gauge transformations defined above. We also show that this mathematical relation can be extended to interacting particles and, even, to quantum fields. A question that remains open is its physical interpretation. Some arguments could relate the Schrödinger Bridge evolution to the reduction of the wavefunction induced by a measurement. However, this hypothesis remains to be substantiated.

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Fast Atom Diffraction from crystalline surfaces at femtometer wavelengths: where is the quantum limit?

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Since the physical intuition by Louis de Broglie in 1923, diffraction has been the most direct demonstration of the wave nature of matter. Electrons in 1927, light atoms and molecules in 1930, neutrons in 1934, all these exhibited diffraction by scattering from crystalline materials. Incidentally, each of these diffraction regimes have produced a standard technique or a commercial instrument for material structure analysis. In practice, these particles are characterized by a de Broglie wavelength from a few Å (electrons at energies below 100 eV, thermal neutrons) to few pm (electrons at 100-200 keV in transmission mode). Diffraction of atoms (H, rare gases) and molecules (H_2) was typically performed at thermal energies, i.e. with de Broglie wavelengths close to 1 Å. The diffraction signal typically vanishes at energies above 200 to 400 meV, depending on experimental conditions (surface material and temperature), due to thermal decoherence. Nowadays, observations tend to push the limits of diffraction to ever-smaller wavelengths. This can be done by increasing the mass or the velocity of the diffracting object. The former case leads to the study of macromolecules diffraction, where energy stored in the internal degrees of freedom eventually lead to decoherence [1]. We will rather focus on the latter case, where high energy (up to 10 keV) light atoms are scattered form crystalline surfaces. Here, decoherence proceeds by entanglement with the surface though inelastic processes. As an illustration, Figure 1 shows the diffraction pattern from the quantum scattering of 5 keV He from LiF(100) at the grazing incidence angle of 0.72°. This new regime of diffraction [2,3], called GIFAD for *Grazing Incidence Fast Atom Diffraction*, appears to be well suited for observing matter waves at the smallest wavelengths, with values down to 160 fm [4]. The level of inelasticity in the He-surface interaction, and thus the coherent fraction, can be adjusted through the incidence angle. GIFAD has essentially been operated for surface structure analysis and interaction potential refinement. Alternatively, the crystalline surface can also only be used as (i) a reflection grating for the production of wave packets whose subsequent decoherence can be explored by e.g. interaction with a surrounding gas; (ii) a beam splitter for fast atom interferometry but also (iii) as a source of entangled atomic pairs.

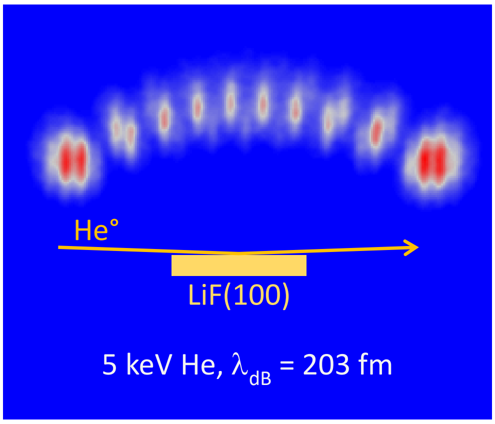

Figure 1. Diffraction pattern form 5 keV He° scattering from a LiF(100) surface at a grazing angle of 0.72°.

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On a possible Wave-memory interpretation for Quantum Mechanics

An attempt to unify pilot-wave theory with standard QM formalism

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In the 1927 Solvay Conference two views about quantum phenomena were proposed. One was Bohr's complementarity view, founded on Heisenberg's uncertainty relations, leading to the Copenhagen interpretation and to Hilbert space formalism. The other was de Broglie's double solution hypothesis, implying the existence of a Pilot-wave effect along the corpuscle's trajectory. Bohr's view would prevail given the implications of the Heisenberg relations, state superposition and the existence of non-locality, disproving so far, the pilot-wave approach. On the other hand, although presenting high predictability describing quantum phenomena, the Copenhagen Interpretation carries a heavy load on the epistemological limits of human knowledge, while giving no explicit relation between indeterministic and deterministic behaviors in Nature. Over the last years the Hydrodynamic Quantum Analogs (HQA) field has been developed showing a set of surprising features in the kinematic behaviors of what can be called macroscopic particles [1]. It so happens that a droplet can be put to bounce on an oil bath, creating a quasi-monochromatic wave field, that guides the former along a non-classical trajectory [2]. Using this macroscopic pilot-wave effect, several quantum situations have hence been modeled by these analog experiments. It seems quite sensical that HQA cannot provide an empirical picture of the quantum world, or even a mathematical complete description of what happens at the quantum level. However, it does indicate a conceptual framework favoring a realism-based approach, while keeping the standard formalism of quantum mechanics. A most striking feature in HQA is that the field encodes information about the droplet's path [3], thus being a memory carrier structure about the droplet possible future behaviors. In my talk I wish to extend this idea to quantum phenomena description. Adopting de Broglie's realism, where wave and corpuscle coexist at all times, I will propose that a quantum wave acts as a physical memory for the corpuscle behavior, encoding the probability density of all its positions and acquirable momentum values within the wave. I will further suggest that a complete description of quantum phenomena involves both a pilot-wave dynamics describing the particle behavior in four-dimensional spacetime and the standard QM formalism, describing the dynamics of the information encoded in the quantum wave [4]. Providing further motivation to this line of thought, I will present a generalized version of the Heisenberg uncertainty relations [5], holding the later as a special case, and that can be interpretated as a mathematical measurement of the degree of order in a system, depending on the information encoded in the wave.

Keywords: Hydrodynamic Quantum Analogs (HQA), Pilot-wave theory, physical memory, standard Quantum Mechanics formalism, Quantum Physics foundations.

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Structure de l'Onde et Paramètres Libres.

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One hundred years after de Broglie, the data accumulated in the form of free parameters, and their precision, allow to find a form of coherence in their numerical values. Returning to the source, with the plane wave [1], the first object is to obtain the equivalent of Balmer formulas for each type ; the results show an intrinsic coherence of this data set through these formulas. We first extend and generalize de Broglie's hypothesis :

There is one and only one resonant phenomenon defining the entire physical world where pulsations, wavenumbers, and rotations refer to the same quantum and compare as lengths.

and show an intricate wave, a system of resonances based on harmonics 1, 2, 3, their cube differences 7 and 19, and π - with all available precision at all levels. This result addresses :

- Particles mass (electrons, quarks, and bosons) [3] where, through two mass equations, the harmonic system appears. The sum of all known resonances is 137 on one axis - which explains the Sommerfeld constant and implies an origin - and 274 on the other axis, the ratio of which can correspond to spin 1/2 and/or spin 2.
- An estimate of the neutrino mass [3] in agreement with experiment and the three electrons resonances.
- The lifetimes of the three bosons [3].
- Sommerfeld's constant [2] from the Bohr-de Broglie model of the hydrogen atom, because the hypothesis allows to separate the components of the electron wave resonance around the proton, and thus to count the quanta ; then *alpha* is the inverse of the total number of quanta on one turn.
- The formulation of the two other couplings [3] involved in the masses equations, using the pattern provided by the Sommerfeld constant. It appears then that those three couplings are composite of the particle resonances - a mirror effect.
- The formulation of the three couplings let appear a fourth one [3], in hollow, transparent to the particles mass calculations, which logically corresponds to gravitation ; it allows to compute the mass of the supposed Planck particle as the basis of the harmonic system.
- The origin of the resonances [3], through a defect of the Planck mass, which 1) gives an origin to the particles resonances and to the number 137, 2) allows to calculate the Planck length as a pure number, and 3) explains quantitative relation between the constants intervening in the mass equations.
- The accuracy of the results is checked by calculating Planck's constant from the calculated values of Planck's mass and length, then Newton's constant is calculated.

The harmonic system is then complete, the complete spectrum of resonances is known (most probably also the particles spectrum). The calculus of the Planck length as a pure number shows that our systems of units are redoundant, the only surviving are mass and velocity.

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De Broglie
Causal Research Realistic Program
and the
Lisbon School

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Abstract

Andrade e Silva a disciple of de Broglie came to the University of Lisbon in 1972 with the main purpose of spreading his master's realistic causal ideas, thus initiating Lisbon School.

In cooperation with Fanco Selleri's Italian group and Jean Pierre Vigier, in the spirit of de Broglie realistic program, were able, for the first time, to propose experiments that could decide on the ontic nature of the quantum waves. That is, deciding by praxis whether quantum waves are mere probabilistic waves devoid of any physical meaning, as claimed by the usual interpretation of quantum Mechanics, or, on the contrary, just as electromagnetic waves, seek to represent real physical entities.

A brief history of the development of de Broglie causal realistic program by Lisbon School shall be presented.

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Louis de Broglie's discovery of matter waves

Olivier Darrigol
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Abstract

Wave properties of matter were completely unheard of when, in the fall of 1923, Louis de Broglie predicted their existence in a series of three notes in the Comptes rendus of the French Academy of Science. Coming from a young theorist heretofore dedicated to applications of received quantum theory, this innovation was a case of extreme audacity. Yet, after closely analyzing de Broglie's itinerary, we can identify multiple resources and ways of reasoning that help us to understand the steps he took toward his stunning proposal.

Mass-independent test of quantumness of a massive object

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A cutting-edge research enterprise in contemporary physics is to explore realizable schemes towards empirically checking the validity of the quantum mechanical principle of superposition of states in the macroscopic regime, together with demonstrating its incompatibility with the world view based on the pivotal classical notion of macrorealism (MR). The goal is to expand as much possible the macroscopic domain of evidencing nonclassicality. This has also potentiality in providing useful empirical constraints on suggested modifications of quantum dynamical evolution in the macroscopic limit (such as the models of spontaneous wave function collapse), which suppress superposition of states at the macrolevel. Nonclassical massive matter states are also a resource for witnessing nonclassical gravity. Though a variety of "macroscopicity" measures have been invoked for testing MR in different contexts, there is not yet any practical scheme which can evidence the irreducible quantumness of an arbitrarily large mass. Motivated by this, we investigate the quantum violation of MR for arbitrary masses in a harmonic potential.

While testing MR, and through it nonclassicality, can be, in principle, much easier than creating highly nonclassical states, in practice it imposes very high demands on the initial control of parameters, as well as extremely precise measurements. To this end, we use standard tools for probing quantum violation of MR, but incorporate crucial modifications: while usual tests use the same measurement arrangement at successive times, here we use two different measurement arrangements. This yields a striking result: a *mass-independent* violation of MR is possible. In fact, our adaptation enables probing quantum violations for literally any mass, momentum, and frequency. Moreover, our proposal only requires measurements on macroscopic oscillators to the accuracy of the standard quantum limit, as well as only knowing parameters to this precision without requiring them to be tuned. These should drastically reduce the experimental effort in testing the nonclassicality of massive objects ranging from atomic ions to mirrors in LIGO.

Author Contributions:– D.D., D.H., H.U., S.B.: Conceived the idea. D.D., D.H., S.B.: Developed the theoretical model. D.D.: Performed the theoretical calculations. S.B., H.U.: Proposed the experimental realizations. All authors discussed results and contributed to writing the paper.

Double-slit experiment remastered

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(Dated: April 16, 2023)

In [1], Peter Holland remarks that the de Broglie-Bohm (dBB) particle trajectories for the double-slit experiment—which feature invariably in expositions of the dBB pilot-wave theory—*"remain among the most striking illustrations so far of the insight provided by this theory into quantum phenomena."*

My presentation aims to argue that these trajectories serve not only to anchor one's intuition but also to provide theoretical resources for understanding/interpreting arrival-time or Time-of-Flight (ToF) experiments—one of the last areas where experts disagree about what quantum mechanics should predict. While a cornucopia of different ToF distributions exists in the literature, so far none of the suggestions have been benchmarked against experiment. To my knowledge, [2] is the first comparison of this sort.

This work presents numerical evidence showing that the statistics of impact positions *and* arrival times of He atoms in a double-slit experiment (reported in [3]) can be reproduced by a straightforward, pragmatic application of the dBB theory. I will outline the findings of [2] in my presentation. That the dBB theory offers a distinct conceptual advantage with regards to ToF measurements owing to the well-defined concepts of point particles and trajectories embedded in this theory, has long been recognized.

Time permitting, I would like to close by describing the spin-dependent dBBian arrival-time distributions predicted in [4, 5]. (Here, the set-up consists of spin-polarized electrons accelerating down a cylindrical waveguide and arriving at a distance L downstream.) These unexpected and very well-articulated arrival-time distributions appear as a direct consequence of a rare wave phenomenon called "quantum backflow" (loosely understood as the flow of probability current against the direction of propagation), which is an area of considerable recent activity. However, as it happens, *steady* backflow is extremely difficult to induce, therefore most examples display this effect for fleeting moments of time and preclude experimental inspection FAPP. In view of this, the *stable-in-time*, even *controllable* backflow observable in this waveguide set-up is one-of-its-kind and experimentally very promising. The observed backflow—consequently, the spin-dependent ToF statistics—manifests even in relativistic regimes, regardless of the initial wave function [6]. In the foreseeable future, the suggested experiment would be well-amenable to the single-electron-in-microwave-Paul-trap technology currently being developed by a few research groups [7, 8].

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On Schrödingerist Quantum Thermodynamics

L. De Carlo[1] and W. David Wick[2]

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We recasted thermodynamics in terms of spin-wavefunction ensembles, rather than classical particle configurations or "found" values of Copenaghen Quantum Mechanics. This asks a completely new mathematical treatment. In these ensembles magnetic phase transitions are possible if and only if we consider indistinguishable particles jointly with a macroscopic non-linearity which blocks macroscopic dispersion (i.e. macroscopic superpositions) by energy conservation (preserving norm and energy). This non-linearity (we dubbed "*Wavefunction Energy*") becomes significant only at the macroscopic level, and hence it is of possible interest for the Measurement Problem. Once indistinguishable particles are introduced, in these new ensembles the symmetry exchange of the wavefunction arguments does not seem to allow a description of magnetism in terms of nearest neighbors and a deep thinking seems will be necessary to define models beyond the mean field case we treated.

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Atomic diffraction through a material grating

Gabriel Dutier
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Abstract

What a better textbook experiment in quantum mechanics than Young's slits with matter wave? I will present such an experiment with a cold metastable argon beam crossing homemade material nano gratings. The novelty of our experiment is based on an appropriate ratio between slits depth and atomic velocity to enhance the quantum matter wave properties. First, the diffraction picture is strongly enlarged due to attractive atom surface Casimir-Polder interaction. And second, the theoretical model must use Schrödinger equation rather than semi classical approach. The good control of both experiment and theoretical model leads to one of the most rigorous Casimir-Polder potential measurement opening the path to different research fields like e.g. collective effect mediated by surface, dynamical effect, heat transfer and fifth force constraint.

The association of wave and particle aspects in the works of Louis de Broglie and his collaborators, and novel developments

Daniel Fargue & Claude Daviau
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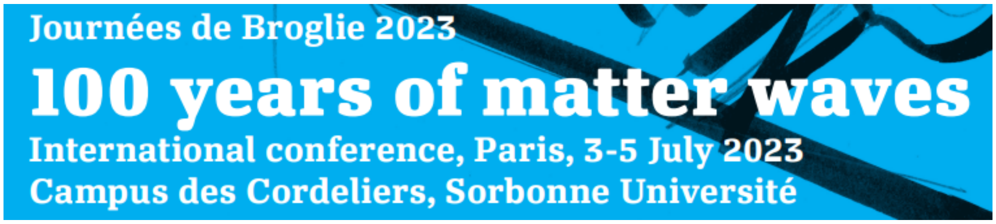
Abstract

Because he believed, following Einstein, that light was at the same time an actual corpuscle and a wave closely bound together, L. de Broglie extended this twofold property to any matter and founded quantum wave mechanics.

He never gave up his hope of a clear description of this association. Since the link between wave and corpuscle was a relativistic property, he extended relativistic wave mechanics starting from Dirac's electron to light and higher spin particles together with his co-workers. He later developped the "double solution theory": extending the dynamics of the wave to the relativistic case, looking for a nonlinear wave equation for particles, and avoiding configuration space.

Most of these ideas are now conforted by the extension of relativistic and gauge invariances and a generalization of electromagnetism including the four kinds of interactions and all kinds of particles.

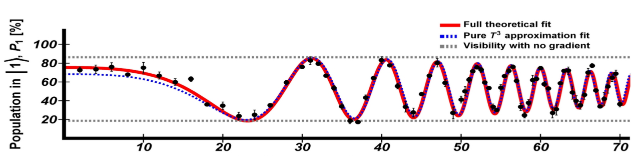


Stern-Gerlach Splitting and Wave-Particle Duality, Recombined

R. Folman, and the Atom Chip Group
Ben-Gurion University of the Negev

In this talk I will present in detail how De-Broglie's Particle-Wave Duality plays a key role in Stern-Gerlach (SG) interferometry. The Stern-Gerlach effect, found a century ago, has become a paradigm of quantum mechanics. Unexpectedly, until recently, there has been little evidence that the original scheme with freely propagating atoms exposed to gradients from macroscopic magnets is a fully coherent quantum process, or in other words, that the atoms indeed behave as waves which can be in a state of spatial superposition. Several theoretical studies have explained why coherence in a Stern-Gerlach interferometer is a formidable challenge. Here, we provide a detailed account of the realization of a half- [1-3] and full- [4-5] loop Stern-Gerlach interferometer for single atoms [6] and use the acquired understanding to show how this setup may be used to realize an interferometer for macroscopic objects doped with a single spin [5], namely, to show that even rocks may be shown to be waves. I will also describe unique decoherence channels such as those relating to phonons [7,8] and rotation [9], which must be considered in such a challenging experiment. The realization of such an experiment would open the door to a new era of fundamental probes, including the realization of previously inaccessible tests of the foundations of quantum theory and the interface of quantum mechanics and gravity, including the probing of exotic theories such as the Diosi-Penrose gravitationally induced collapse. Time permitting, I will also briefly present our recent work on Bohmian mechanics, which is an extension of De-Broglie's ideas concerning the pilot wave [10].

Fig 1. Spin population oscillations due to interference in a full-loop Stern-Gerlach interferometer at BGU [4].



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Macroscopic scale matter wave interferometers for exploring quantum physics

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Abstract

Seminal experiments with electrons, neutrons, atoms and now with molecules have shown that matter wave interferometers provide remarkable tools for exploring quantum physics, until then limited to thought-experiments. In Toulouse, we demonstrated atom interferometry experiments operating with a large spatial separation between the interferometer’s arms. This specificity allows to shape electromagnetic and gravitational potentials, opening the way to new measurements in fundamental physics.

In a first period (1998-2014), we developed a lithium atom interferometer using a supersonic beam of lithium and Bragg diffraction on a laser standing wave at a 671 nm wavelength. We mostly used diffraction of order 1. In this Mach-Zehnder interferometer, the maximum separation of the two atomic paths was near 100 micrometers, sufficient to introduce a septum (a thin sheet of aluminized mylar or an aluminum foil) between the two atomic paths. We were thus able to apply different electric fields on the two paths or to put a small gas pressure on one atomic path. These possibilities were used for a series of experiments with metrological interest such as the measurement of the lithium electric polarizability, the index of refraction of argon, krypton and xenon for a lithium atomic wave, the atom-surface interaction. This interferometer was also used for exploring quantum curiosities such as the He-McKellar-Wilkens and Aharonov-Casher geometrical phases, or the phase modulation of lithium atomic waves.

Since 2016, we are developing a new atom interferometer using rubidium Bose-Einstein condensates manipulated with a vertical optical lattice. A very appealing solution to enlarge the arms separation is the so-called Large Momentum Transfer (LMT)-interferometer, in which the interferometer’s arms separation is increased by the transfer of a large number of photons momentum () during the beam-splitting process. Various configurations for an LMT-interferometer have been demonstrated. We will present a promising technic based on a sequence of optical lattice

pulses in the quasi-Bragg diffraction regime. In particular, we will show interferometric measurements with a total momentum transfer of 200 , improving upon the previous record of 112 . This work has applications in high-precision sensing. In addition, such interferometers with macroscopic spatial separations pave the way for the new LMT-interferometers proposed in various tests of fundamental physics for example in dark matter searches, atom neutrality tests, gravitation tests.

Antimatter Quantum Interferometry

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Abstract

Matter-antimatter asymmetry is one of the key ingredients of our Universe, making the very existence of life possible. The prediction of antimatter following the Dirac equation played a decisive role in the construction of a relativistic quantum theory, together with the experimental discovery of several antiparticles. Understanding antimatter properties nowadays is linked to the still open problem of violation of fundamental laws to explain matter-antimatter asymmetry in the first picosecond of Cosmic Time.

In this talk I will present the first demonstration of antimatter particle interference, obtained with positrons; the experiment was performed in the one-particle-at-a-time mode, in analogy with the Merli-Missiroli-Pozzi 1976 work for the electron and is the first step towards the study of Positronium gravitation.

Une expérience pour mieux comprendre les ondes de phase et de matière de Louis de Broglie

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Avril 2023

Résumé

Dans ces trois articles de 1923 [1, 2, 3], Louis de Broglie associe à tout mobile de masse m se mouvant à une vitesse v, deux ondes : ***"l'onde de phase"***, qui est une onde *"fictive"* et *"non matérielle"*, ayant v comme *"vitesse de groupe"* et ***"une onde matérielle"*** correspondant au mobile. Ces deux ondes sont reliées (en résonance) par un accord de phase.

Pour expliquer les expériences d'interférence par deux fentes, de Broglie fait l'hypothèse que, lors de la préparation du faisceau, tous les atomes ont la même onde de phase et qu'ils se diffractent en suivant la portion d'onde de phase qui les entoure.

Ainsi, dès 1923, de Broglie pense que l'onde de phase passe par les deux fentes et guide la particule massive représentée par l'onde matérielle correspondant à la densité du corpuscule étendue. Cette onde de matière passe, elle, par une seule des deux fentes et son impact sur l'écran correspond au résultat de la mesure.

Nous avons repris cette interprétation dans la théorie de la double échelle que nous avons développé [4]. Nous proposons de tester dans cet article cette hypothèse qui distingue les deux ondes. Pour tenir compte de la taille des corpuscules, c'est-à-dire de la taille de l'onde de matière, nous proposons des expériences d'interférence avec des fentes de différentes tailles : une grande fente *"laissant passer"* les corpuscules (l'onde de matière) et une grille de petites fentes *"ne les laissant pas passer"* (mais laissant passer une partie de l'onde de phase).

Nous présentons les résultats de simulations numériques des densités de transmission (de l'onde de phase) réalisées avec des fullerenes ou des atomes de Rydberg pour l'interprétation standard de la mécanique quantique et l'interprétation de la double échelle. Nous montrons que ces résultats sont très différents [5] : le nombre de franges d'interférence diffère d'un cas à l'autre. Une réalisation expérimentale serait donc un test crucial entre ces deux interprétations et permettrait une meilleure compréhension de l'interaction de ces deux ondes.

Abstract

In three articles from 1923 [1, 2, 3], Louis de Broglie associates to any mobile of mass m moving at a speed v, two waves : ***"a phase wave"***, which is a *"fictional"* and *"non-material"* wave, having v as its *"group velocity"* and ***"a matter wave"*** corresponding to the mobile. These two waves are linked (in resonance) by a phase agreement.

To explain the double-slit experiment, de Broglie made the assumption that, during the preparation of the beam, all the atoms would have the same phase wave and that they would diffract by following the portion of phase wave which surrounds them.

Thus, as early as 1923, de Broglie thinks that the phase wave passes through the two slits and guides the massive particle represented by the material wave and corresponding to the density of

the extended corpuscle. This material wave passes through only one of the two slits and its impact on the screen corresponds to the result of the measurement.

We have deal with this interpretation in depth in the double scale theory [4]. In this paper, we propose to test this assumption which distinguishes the two waves. To take into account the size of the corpuscles, i.e. the size of the matter wave, we propose interference experiments with slits of different sizes : a large slit "letting through" the corpuscles (the matter wave) and a grid of small slits "not letting them through" (but letting through part of the phase wave).

We present the results of numerical simulations of transmission densities (of the phase wave) considering fullerenes or Rydberg atoms for the standard quantum mechanical interpretation and the double scale interpretation. We show that these results are very different : the number of interference fringes differs from one case to another. An experimental realization would thus be a crucial test between these two interpretations and would give a better understanding of the interaction of these two waves.

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Testing the standard model using atom interferometry

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Abstract

Quantum sensors based on light-pulse atom interferometry enable precise measurement of a variety of physical quantities. They have a huge potential for testing the fundamental laws of modern physics and for the accurate determination of fundamental constants. Among them is the fine structure constant. This constant is ubiquitous in physics and the accurate knowledge of its value is crucial to test some predictions of the Standard Model of particle physics.

In this talk, I will focus on the determination of the fine structure constant from the measurement of the recoil velocity of an atom that absorbs a photon. I will present the most recent results of the Paris experiment and I will conclude my talk by discussing their impact on the test of the Standard Model, which relies on the comparison between experimental and theoretical values of the electron's magnetic moment.

Abstract

Vincent Hardel

May 2023

Nelson's stochastic quantum mechanics provides an ideal arena to test how the Born rule is established from an initial probability distribution that is not identical to the square modulus of the wavefunction. Here, we investigate numerically this problem for three relevant cases: a double-slit interference setup, a harmonic oscillator, and a quantum particle in a uniform gravitational field. For all cases, Nelson's stochastic trajectories are initially localized at a definite position, thereby violating the Born rule. For the double slit and harmonic oscillator, typical quantum phenomena, such as interferences, always occur well after the establishment of the Born rule. In contrast, for the case of quantum particles free-falling in the gravity field of the Earth, an interference pattern is observed before the completion of the quantum relaxation. This finding may pave the way to experiments able to discriminate standard quantum mechanics, where the Born rule is always satisfied, from Nelson's theory, for which an early subquantum dynamics may be present before full quantum relaxation has occurred.

Inertial mass, rest mass and the quantum potential:de Broglie's pioneering work on the geometry of conformal rescaling

Basil Hiley
(UCL & Birkbeck, University of London)

Abstract

De Broglie is well known for his pilot wave approach, an approach he later remarked was a mistake because it did not do what he hoped it would achieve. It did not make a sharp separation between the subjective and objective elements that are fused in the wave function. With his double solution, he had hoped to achieve this distinction by attempting what Penrose now calls the 'geometrization of QM'. He already set out the generalisation of QM to relativistic Riemannian geometry, an approach explored by DeWitt who showed that by using the principle of general covariance an extra quality of energy must be added to the quantum Hamiltonian. DeWitt also referred to this extra energy term as the 'quantum potential energy'. Remarkably his paper appeared in the same volume of Physical Review as did Bohm's original hidden variable paper. This geometric approach formed the basis of de Broglie's 'double solution' which has since been developed further by Hiley and Callaghan using Clifford's geometric algebra. This enables the de Broglie-Bohm approach to be generalised to include spin and the Dirac relativistic approach. This opens up a geometric approach to quantum physics.

Free-Electron Quantum Optics

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Until recently, work in quantum optics focused on light interacting with *bound-electron* systems such as atoms, quantum dots, and nonlinear optical crystals. In contrast, *free-electron* systems enable fundamentally different physical phenomena, as their energy distribution is continuous and not discrete, allowing for tunable transitions and selection rules.

Recent theoretical and experimental breakthroughs involving quantum interactions of free electrons spawned an exciting new field: *free-electron quantum optics*. We developed a platform for exploring free-electron quantum optics at the nanoscale, and used it to demonstrate the first coherent interaction of a free electron with a photonic cavity and with the quantum statistics of photons.

These capabilities open new paths toward using free electrons as carriers of quantum information. Free electrons emerge as quantum optical sources for desired photonics states used in fault-tolerant quantum computation and communication such as Schrodinger cat states and GKP states.

Concepts of quantum optics with free electrons also promote new modalities in electron microscopy. We demonstrated the first instance of *coherent amplification* in electron microscopy. Our vision is to develop a microscope that can *image coherence*, going beyond conventional imaging of matter to also image the coherent quantum state of matter and probe quantum correlations between individual quantum systems.

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Influence of Louis de Broglie’s Matter Wave Theory on Japanese physicists

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Abstract

Louis de Broglie (1892-1987), a French physicist who proposed the conception of matter waves, kept away from the Copenhagen school that drove the formation of quantum mechanics and took a different position in the interpretation of it This study analyzes how de Broglie’s theory, which stands out for its unique idea in the history of quantum mechanics, was accepted in Japan.

1. Tokio TAKEUCHI (1893-1944)

Japanese physicists began to translate papers on quantum mechanics vigorously including de Broglie’s matter waves theory from around 1927. Among them, Tokio Takeuchi, who published abridged translation of de Broglie’s dissertation for the first time in Japan, was especially impressed by de Broglie’s way of thinking which deduced matter waves using Einstein’s relativity. Because he had been waiting for integrating the theory of relativity with the quantum theory since 1922 and that’s one of the reasons why Takeuchi introduced de Broglie’s original thought spending 10 pages in the first part of his book Shinrikigaku oyobi hadourikigaku sousho (New mechanics and wave mechanics) published in 1927.

2. Satoshi WATANABE (1910-1993)

Satoshi Watanabe who had read Takeukchi’s book in his high school days, left for France in 1933 after graduating from Tokyo university, and he studied under de Broglie till 1937. He translated de Broglie’s book, Introduction à l’étude de la Mécanique ondulatoire and published Hadourikigaku kenkyu josetsu (Introduction to wave mechanics) in 1934. In the translator’s notes, Watanabe stated that there seemed to be a disproportionate bias towards Germen physics in Japanese physics to date and that the simplicity of French physics had been forgotten. According to Watanabe, the national character of Japanese was probably more inclined inspirational and leaping French physics, so he translated de Broglie’s book to compensate for a lack of French esprit.

3. Takehiko TAKABAYASHI (1919-1999)

De Broglie developed his matter waves theory to his pilot waves theory at the fifth Solvay International Conference in 1927, but few scientists approved it and he also gave it up until 1951 when he returned to his original idea. From 1956 to 1959, Takehiko Takabayashi joined de Broglie's seminar at Institut Henri Poincaré and had a heated discussion with D.Bohm (1917-1992), N.P. Vigier (1920-2004) and others. In 1970, he translated de Broglie's pupils' book, J.L. Andrade e Silva (1928-2017) and G. Lochak (1930-2021) Quanta, grains et champs (Quanta, grains and field) published in 1969 and introduced their research as a new interpretation of wave mechanics, which contributed to a better understanding of their view in Japan.

Atomic interferometry based inertial sensors

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Abstract

Atomic interferometry is based on the principle of wave-matter duality, stated by Louis de Broglie. In practice, most atomic interferometers are based on the manipulation of atomic wave packets (separation and deflection) by light. Since the pioneering experiments of 1991, atomic interferometry has established itself as a unique tool for the precise measurement of fundamental constants and gravito-inertial effects. It covers multiple applications in metrology, inertial navigation, geophysics, fundamental physics tests, and has been proposed for the detection of gravitational waves. Indeed, atomic interferometry combines both a high intrinsic sensitivity and a high accuracy thanks to the high level of control of the atom-laser interaction.

In particular, interferometers with free-falling atoms have shown state-of-the-art performances as gravimeters and gyroscopes, and very promising performances as gradiometers. Important efforts are being made to improve their accuracy and sensitivity by using more coherent atomic sources and more complex atomic manipulation on the one hand, and to make them more robust to parasitic vibrations and to extend their fields of application on the other hand. Behind these developments, trapped or guided interferometers are more prospective and open to new applications such as local force measurements. In particular, they could benefit from quantum engineering protocols to improve the sensitivity below the quantum standard detection limit.

Quantum sensing for gravity cartography

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Abstract

The sensing of gravity has emerged as a tool in geophysics applications such as engineering and climate research, including the monitoring of temporal variations in aquifers and geodesy. However, it is impractical to use gravity cartography to resolve metre-scale underground features because of the long measurement times needed for the removal of vibrational noise. Here we overcome this limitation by realizing a practical quantum gravity gradient sensor. Our design suppresses the effects of micro-seismic and laser noise, thermal and magnetic field variations, and instrument tilt. The instrument achieves a statistical uncertainty of 20 x 10^{-9} s^{-2} and is used to perform a 0.5-metre-spatial-resolution survey across an 8.5-metre-long line, detecting a 2-metre tunnel with a signal-to-noise ratio of 8. The sensor parameters are compatible with applications in mapping aquifers and evaluating impacts on the water table, archaeology, determination of soil properties and water content, and reducing the risk of unforeseen ground conditions in the construction of critical energy, transport and utilities infrastructure, providing a new window into the underground.

Attosecond scattering delays in photo-ionized molecules

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Abstract

Electrons are very accurate probes of matter at the fundamental level. In electron microscopy, their quantum nature and short De Broglie wavelength permits to obtain high spatial resolution. In photoionization spectroscopy, the electron momentum allows us to determine the electronic structure of bulk matter, molecules and atoms. In this context, attosecond experiments, which aim at studying electron dynamics on the angstrom length scale, have opened up a wide variety of novel opportunities to study dynamical properties of matter such as ionization.

Photoionization as a half-scattering process is not instantaneous. Usually, ionization delays are of the order of few tens of attoseconds (1 as = 10 −18 s). Attosecond technology allows to measure the phase and related time delays associated to this electron scattering process. While it has been applied to the case of isolated atoms, the case of polyatomic systems offer new experimental and theoretical challenges. Here, we have studied how quantum scattering phase can be measured and interpreted in terms of attosecond delays, in the case of three dimensional and planar molecular systems. We find that the time delays in 2D molecules can significantly be smaller than those of the corresponding 3D counterparts. These findings are supported by first-principles calculations based on static-exchange density functional theory and offer new perspectives in terms of attosecond measurements in complex objects.

TOWARDS A HIGH DATA RATE ATOM INTERFEROMETRIC GRAVIMETER (HIDRAG) FOR GRAVITY MAP MATCHING NAVIGATION

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Although satellite navigation (SATNAV) has been prevailing in the past few decades, the inertial navigation system (INS) keeps attracting interest from people because of the limitations of the SATNAV technology, e.g. jamming, spoofing and signal reception in harsh environments including underground and underwater. The INS uses dead reckoning for positioning, and consequently, it is susceptible to the sensitivity and drift of inertial sensors. The state-of-art inertial sensors can reach the sensitivity below [1], but the drift is still a significant issue. Several auxiliary aiding techniques combined with low-drift high-sensitivity quantum sensors are considered promising candidates to remedy the deficiencies, and the gravity map-matching technique combined with a quantum gravimeter is one of them. Further developments of such systems will potentially allow absolute positioning to accuracy at meter-scale in all weather and environmental conditions without any communication or satellite navigation. Other applications include urban infrastructure mapping to provide feedback on the conditions of, e.g. water pipes and other infrastructure items.

A high data rate quantum gravimeter for gravity map-matching navigation is currently being developed at the University of Birmingham. It uses the technique of atom interferometry and similar design concepts [2] to provide low-drift high-precision local gravity measurement. Its targets are to provide a sensitivity of $10^{-7}\ g/\sqrt{Hz}$ with a data rate of 100 Hz and absolute stability of $1\ ng/month$. We will show the progress of our quantum gravimeter at the conference.

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Observation of Fractional Elementary Charges in a Periodic Many-body Quantum System

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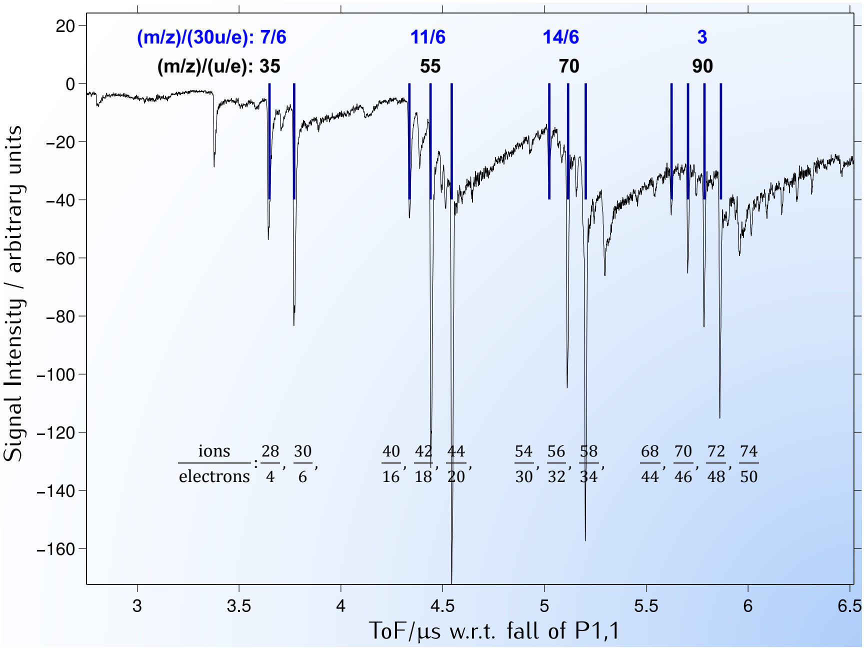
We report the experimental observation of a very striking periodicity in a many-body system--an ultra-cold plasma. A long lifetime (>0.3 ms) *quantum degenerate* molecular Rydberg plasma is generated in the high-density region of a pulsed supersonic jet expansion by two-colour resonant excitation of nitric oxide (10%) in neon (5bar) into the high-*n* Rydberg threshold region close to the ionization limit. Experimentally, two synchronous UV laser pulses produce the plasma a few mm away from the jet nozzle. For plasma densities of > 10^{16} cm^{-3} reached in our experiments the electrons should become quantum degenerate, *i.e.* the **electron *de Broglie wavelength*** becomes larger than the Wigner-Seitz radius ***a*** relevant to describe the mean distance between the particles.

A time-of-flight (ToF) mass spectrometer is used to analyse the plasma by applying two successive high-voltage pulses of 3.6 kV with a 0.2μs gap. The observed positively charged objects of mass to charge ratio *m/z* in the ToF spectrum follow a strictly reproducible progression of (*m/z*) from 35 to 92.5 (blue: *w.r.t.* $m(NO^+)$ = 30u). From the *m/z* numbers one obtains the corresponding ***ion to electron ratios*** of the 12 peaks (bottom of figure), from 7/1 to 37/25 (ratios are given in even ion/electron numbers).



In conclusion, we observe a many-body system consisting of a series of objects that contain magic numbers of ions and electrons for which the ion/electron ratio follows a periodicity. These objects are manipulated by fields in a ToF spectrometer without being destroyed, which shows that they behave as objects with a center of mass. The observed 12 many-body states have periodic ion/electron ratios of 28/4, 30/6; 40/16, 42/18, 44/20; 54/30, 56/32, 58/34; 68/44, 70/46, 72/48; 74/50 equivalent to *Fractional Elementary Charges*, *FEC*'s (*i.e.* electron/ion ratios) of **1/7, 1/5; 2/5, 3/7, 5/11; 5/9, 4/7, 17/29; 11/17, 23/35, 2/3; 25/37**. This progression looks very much like one observed for the *Fractional Quantum Hall Effect*. Following de Broglie's matter-wave reasoning one could also represent the FEC's as waves that are strongly coupled by their phase correlation, similar to quantum entanglement of electrons in many-electron atoms (a deeper reason for the periodic system of the elements as described in common textbooks).

Does the “Complex” Wave Function in Quantum Mechanics Represents Anything “Real” at all?

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Recent attempts at “Quantum Reconstruction” is to rebuild the highly successful Quantum Mechanics (QM) from a few simple principles to understand the “real” meaning of its highly successful mathematical structure. In addition, perhaps, we must recognize the “real” role the constant ‘c’ plays in physics! It would be shown here that this constant has a more crucial role at the foundations than what Relativity envisaged. Einstein postulated in his Special Theory of Relativity (SR), that the velocity of light is invariant for all inertial observers! This is counter-intuitive: if the magnitude of ‘c’ cannot be affected by the motion of the inertial frame from which it is measured, then the converse that, this ‘c’ also cannot affect anything happening in these frames must be equally true! However, the entire relativity is to show how ‘c‘ affects the measurements of length, mass, and time in these frames! Another mystery from QM is Schrodinger’s “zitterbewegung” (ZB) phenomenon which is a mathematical extension of Dirac’s electron theory. By integrating these two concepts into physics at the foundational level we can rebuild a fairly consistent model which seems to unify SR and QM by giving a geometrical interpretation to the “complex wave function” as representing a helical trajectory of particles like electrons. Helix being a geodesic on a cylinder accommodates “quantization of energy” and is a three-dimensional wave having all the properties that we are familiar with the 2D wave. Thus by postulating an internal motion to these fundamental particles consistent with ZB, many of the results of QM and SR which are at present purely based on intuitive mathematics, can be understood in a simple and “realistic’ way.

Levitated nanoparticles: the road ahead to macroscopic superpositions

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Abstract

In the century since Louis de Broglie's proposal of the matter-wave hypothesis, matter-wave interference has been observed for a range of particles, ranging from sub-atomic particles to atoms to highly complex molecules. Is there an upper limit to the particle mass for which interference can be observed? We do not know. If there is a limit, we also do not know if it is simply due to technical complexity or if it reveals a fundamental gap in our understanding of quantum mechanics.

Levitated nanoparticles are a promising experimental system with which to investigate these questions. Recently, nanoparticles levitated in optical traps have been cooled to the motional ground state. This achievement can be seen as a starting point for preparing quantum-mechanical states of a nanoparticle's motion, including macroscopic superposition states. A major hurdle, however, is the decoherence introduced in optical traps via both direct light scattering and particle heating. Here, I will present an alternate approach based on ion traps.

We have recently demonstrated a new method for precise position measurement and cooling of (charged) nanoparticles in an ion trap [1]. Furthermore, we will examine how techniques originally developed for trapped atomic ions, such as sympathetic cooling, can be transferred to the domain of nanoparticles [2]. Finally, we will see that a nanoparticle oscillator in ultra-high vacuum can obtain quality factors above 10^10 [3], evidence of its extreme isolation from its environment.

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De “ La Nouvelle Théorie de la Lumière ” aux équations quantiques relativistes à deux particules

Pierre Pelcé

RESUMÉ : Après ses grands succès des années 1920 sur la mécanique ondulatoire des particules matérielles, L.De Broglie propose au début des années 1940, d' établir dans des lignes analogues, une mécanique ondulatoire du photon. Il propose alors, dans “la Nouvelle théorie” de la lumière, puis dans “la théorie de la fusion”, de considérer le photon comme une particule composée de deux particules de spin $\frac{1}{2}$ et de mêmes masses, la fonction d' onde de chaque particule satisfaisant l' équation de Dirac. Par une condition de liaison appropriée, il obtient une fonction d' onde du photon à 16 composantes satisfaisant deux groupes de 16 équations, desquelles on peut déduire les équations de Maxwell de l' électromagnétisme lorsque la masse d' un des corpuscules tend vers 0.

Cette approche peut être revue et complétée par l' étude des équations quantiques relativistes à deux particules comme l' équation de Bohm et Hiley. Il apparaît cependant que cette équation n' est pas invariante par transformations de Lorentz. Une autre équation, celle de Durt et Pelcé peut être élaborée dans son voisinage, en introduisant de façon appropriée dans le Lagrangien de Bohm et Hiley, la matrice α_0 de Dirac. Cette équation devient invariante par transformations de Lorentz et peut donc être utilisée pour étudier des solutions simples comme les ondes planes d' un corpuscule composé et du mouvement relatif de deux particules de spin $\frac{1}{2}$ issus d' une même source, se déplaçant en sens opposés le long d' une même direction Ox, comme dans la version de Bohm de l' expérience EPR. L' étude du corpuscule composé montre que les dynamiques déterminées par la méthode de fusion et l' équation de Durt et Pelcé sont les mêmes. L' étude du mouvement relatif permet d' obtenir la correction relativiste à la corrélation de spins mesurée. avec les appareils A et B, à différents angles avec l' axe Oz, le long des vecteurs $\vec{a}$ et $\vec{b}$.

Exposé 30 min. à la conférence L.De Broglie, 3-5 Juillet 2023, La Sorbonne.

From " La Nouvelle Théorie de la Lumière " to the quantum relativistic equations for two particles

Pierre Pelcé

ABSTRACT : After his great success in the years 1920 in wave mechanics of mater particles, L. De Broglie suggests at the beginning of the years 1940, to establish along similar lines, a wave mechanics of the photon. He proposes in "la Nouvelle théorie" de la lumière, then in "la théorie de la fusion", to consider the photon as a particle composed of two particles photon of spin $\frac{1}{2}$ and same masses, the wave function of each particle satisfying the Dirac equation. With an appropriate binding condition, he obtains a wave fonction of the photon of 16 components, satisfying two groups of 16 equations, from which he can deduce the Maxwell equations for electromagnetism when the mass of one particle tends to 0.

This approach can be reviewed and completed with the study of quantum relativistic equations for two particles as the Bohm and Hiley equation. However, this equation is not invariant under Lorentz transformations. Another equation, from Durt and Pelcé, can be established closely, in introducing in the Bohm and Hiley equation the Dirac matrix α_0. This equation become invariant under Lorentz transformations and so can be used to study simple solutions, as plane waves of a compound particle and of the relative motion of two particles of spin $\frac{1}{2}$ emitted from a same source, moving in opposite directions along a same axis Ox, as in the Bohm version of the EPR experiment. The study of the motion of the compound particle shows that the dynamics determined from the L.De Broglie fusion method and the Durt and Pelcé equation are the same. The study of the relative motion allows to obtain the relativistic correction to the spin correlation measured with apparatus A and B, at different angles with the Oz axis, along the vectors $\vec{a}$ and $\vec{b}$.

Lecture 30 min. at the conference L.De Broglie, 3-5 July 2023, La Sorbonne.

Trajectories in quantum cosmology

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Abstract

The simplest possibility to quantise gravitation consists in writing a Hamiltonian formulation of general relativity, define a Hilbert superspace of states and use the correspondance principle for the canonical variables. Restricting attention to the highly symmetric case of the Friedmann-Lemaître-Robertson-Walker cosmological solution and its perturbations permits to solve the Wheeler De Witt equation, which then takes the form of a timeless Schrödinger equation. Although the use of trajectories is considered irrelevant in many cases, when it comes to the evolution of the entire universe, it becomes an essential tool that permits not only to provide a solution to the time problem (at least in the minisuperspace approximation) but also to perform actual calculations and make cosmological predictions.

Multiple Longitudinal Stern Gerlach Effect in Wave Mechanics with Hydrogen Atoms

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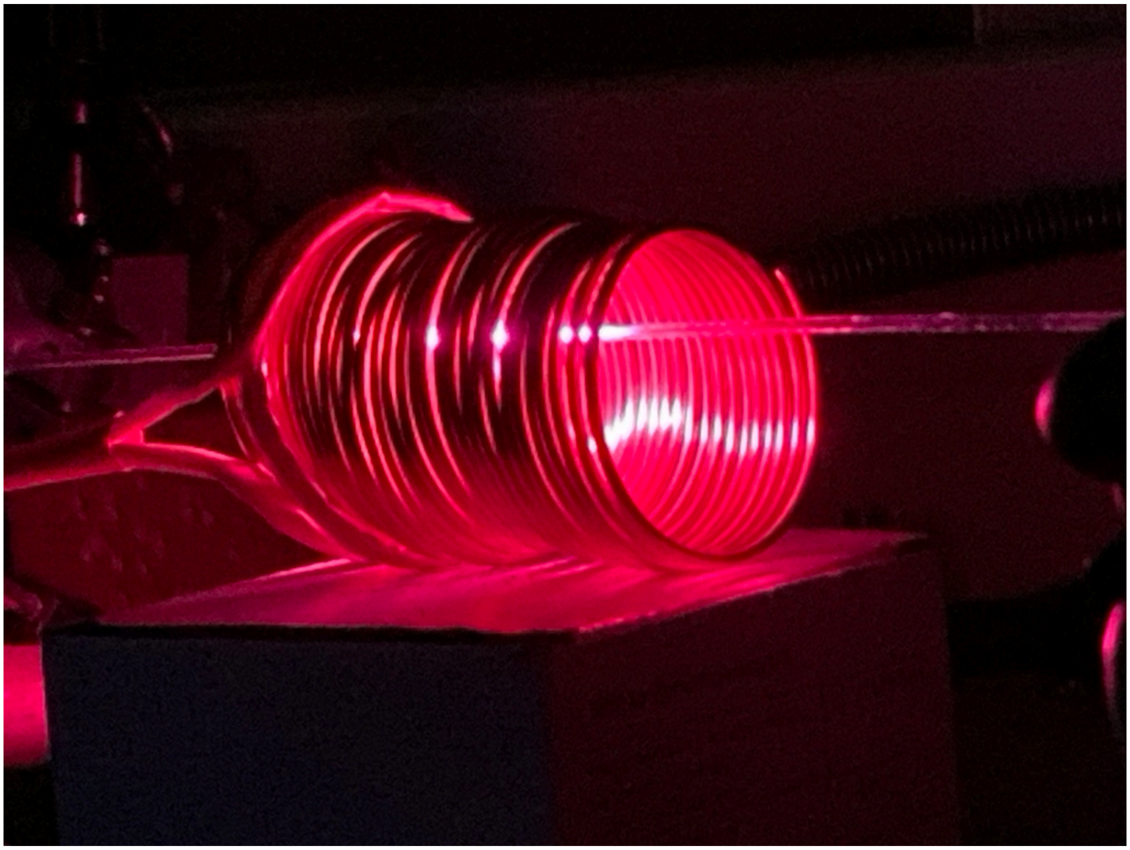
Abstract

In 1960, G.M. Drabkin and R.A. Zhitnikov (1), working on spin polarisation and neutron spectroscopy, proposed a very clever experimental scheme that uses Stern's longitudinal Gerlach effect to modify the speed of a beam of slow neutrons. The idea is crystal clear and was tested and proven to work with neutrons in 1980 by B. Alefeld, G. Badurek and H. Rauch (2). However, to be effective, due to the minute value of the neutron magnetic moment, it requires the use of multiple interaction zones to be experimentally relevant for velocity manipulation purposes and has been studied to improve the polarisation of the neutron beam. The original method used a classical description of motion and did not extend to the dynamics of the particles within or between the deceleration zones.

Here we present the first results of the first stage of a wave mechanical description of the motion of paramagnetic particles in a series of Drabkin zones i.e., an one-dimensional configuration. This theoretical work is applied to a hydrogen atom in the electronic ground state. This is to take advantage of the fact that the electron magnetic moment of the hydrogen atom is 1000 times higher than that of a neutron, making it possible to envisage more visible effects with reasonable constraints such as the use of permanent magnetic fields. We present the device for producing an atomic jet of hydrogen atoms in a small-diameter capillary (see figure) that can be inserted into the Drabkin zones.



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PHASE AND TRAJECTORIES: FACE AND TAIL OF THE SAME CONCEPTUAL FRAMEWORK

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ABSTRACT.- In 1952 David Bohm proposed an alternative conceptual framework to understand quantum phenomena in terms of so-called hidden variables that did not violate von Neumann's theorem on the impossibility of such variables. In essence, and leaving aside "second order" subtleties, the model gets back to de Broglie's pilot wave conceptual framework and Madelung's hydrodynamical rewriting of Schrödinger's equation. In brief, because Schrödinger's equation can be recast as a Hamilton-Jacobi equation, where Newtonian trajectories arise as the time-evolving normals to surfaces of constant action (the optical wavefronts), also in quantum mechanics (Bohmian) trajectories are associated with the (also time-) evolving normals to surfaces of constant phase. These trajectories specify the instantaneous position of the particles described, which are interpreted as and acquire the role of "hidden" variables determining the state of the quantum system described beyond a vague probabilistic description.

The above "message" has been taken for granted by part of the community, both defenders and detractors of Bohm's model. However, a thorough reflection on this model leads us to two considerations:

(1) There is no empirical evidence for such instantaneous positions to be uniquely identified with actual particle positions, which takes us back to Bohr's and Born's former view of quantum phenomena.

(2) Not only the mathematical structure of the model (including the trajectories) is not new at a formal level (theory of characteristics), but it is actually at the heart of optics.

From those two considerations one can conclude that the model is actually a valid one, on the same footing as any other picture or model of quantum mechanics., where the main difference and, hence, also the main advantage is that quantum phenomena are described at a local level, in terms of the local phase variations undergone by the associated quantum states (de Broglie's matter waves) and the dynamics that they generate. Indeed, the local phase variations determine a local velocity field, which, in standard quantum theory, corresponds to the field that transports the probability density throughout the configuration space in the manner of a quantum flux. Trajectories (Bohmian ones) simply arise when a given position is acted by this field, which provides us with valuable information, at a local level (instantaneous positions), about the diffusion of the quantum state in the above-mentioned configuration space. This simple and intuitive idea, though, can be extrapolated to other fields, e.g., optics, where the concept of ray as carrier of energy loses its physical meaning in wave models.

In this Communication, the above view will be considered to discuss a series of phase-related aspects in different quantum scenarios, such as high focusing or nonlinear (BEC) dynamics, as well as to investigate the peculiar behavior displayed by certain types of structured light. The later will serve as a convenient example to show the suitability and generality of the model beyond the quantum realm and, therefore, also beyond its routinary consideration of a hidden-variable model.

Corrélations quantiques sur la distance Terre-Lune.

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La Physique Quantique orthodoxe admet que le résultat des mesures pour des grandeurs complémentaires (non commutatives) deux sous-systèmes intriqués sont statistiquement corrélés de manière instantanée quelle que soit la distance entre eux. Cette corrélation se présente comme s'il y avait une corrélation avec une vitesse infinie, exprimée par le Théorème de Bell. Elle a jusqu'à présent été vérifiée expérimentalement jus/qu'à une distance de 1200 km (Yin et al. 2017), impliquant une vitesse apparente de 10^7 c.

Je propose de discuter l'intérêt et la faisabilité d'étendre cette distance à 300.000 km, gagnant ainsi un facteur 300 (Schneider 2009). L'idée est d'installer un des polarimètres sur la Lune, l'autre étant sur Terre.

Une telle expérience apporterait un nouveau test de la Physique Quantique et permettrait peut-être de discriminer la théorie orthodoxe de l'approche bohmienne par exemple.

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Time, unitarity and normalizability in pilot-wave approach to quantum gravity in Ashtekar formulation

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The Kodama state is an exact solution to the quantum Wheeler-deWitt equation in Ashtekar formulation of quantum gravity. Recently, a modified Kodama state was found with the inclusion of fermions. However, the solution remains fraught with conceptual and technical difficulties – it is timeless, non-normalizable and the notion of unitarity is murky. In this talk, I will show how a pilot-wave theory of quantum gravity in Ashtekar variables addresses these issues. First, I will show how the assumption of a definite configuration in the theory leads to a natural time parameterisation for all the relevant constraints. Second, I will show how to obtain a formal continuity equation and thus define the guidance equations. Third, I will show how to extract normalized probabilities in the theory. Lastly, I will discuss how to recover the de Sitter solution with quantum corrections in the theory.

Based on:

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What is the de Broglie Wave? Revisiting the famous thesis of 1923

De Broglie's insight that a massive particle has associated wave characteristics was crucial to the formulation of quantum mechanics. But under the current orthodoxy, the de Broglie wave makes no physical sense: it is of unknown origin and ontology and has a superluminal velocity that becomes infinite as the particle comes to rest.

Yet while such a velocity is not that of any physically reasonable wave, it is characteristic of the modulation of an underlying carrier wave. There is a significant literature that began with the writings of the late Milo Wolff that asserts that this is indeed the true nature of the de Broglie wave. According to this view, the Broglie wave is not a true wave, but the relativistically-induced modulation of an underlying wave structure that is itself evolving through space at the classical velocity of the particle. In the rest frame of the particle, this underlying structure has the form of a standing wave, and it is easily demonstrated that when considered from any other frame, a standing wave does indeed acquire a modulation having the superluminal velocity and characteristics of the de Broglie wave. Considered in this way, this modulated waveform *is* the particle, thereby resolving the mystery of wave-particle duality in favour of a waveform that simulates the behaviour of a particle.

Less well-known is the support for this interpretation to be found in de Broglie's own thesis of 1923. The de Broglie wave is clearly identifiable as a modulation in de Broglie's depiction of the wave in Minkowski spacetime, as also in his modelling of the wave by an array of oscillating springs. Although de Broglie did ultimately conclude that the wave is a wave in its own right, there is, as I will show, a discontinuity in the "harmonizing of phases" by which he reached that conclusion. He began by proposing that a particle is surrounded in its rest frame by a spatially extended "periodic phenomenon". But when he went on to consider how this extended waveform would change under a Lorentz transformation, he confined his attention to a single point in the waveform. In effect, what he derived was not a spatially extended wave, but a record through space and time of the varying phase of a moving and oscillating point.

Considered as a modulation, the de Broglie wave acquires an origin consistent with special relativity and well understood in classical wave theory. And unlike the de Broglie wave considered alone, the full modulated wave is a covariant relativistic object capable of taking its place in the tensor equations of relativistic physics.

Once the existence of the underlying wave structure is recognized, it becomes apparent why the wave functions of quantum mechanics have seemed so mysterious. The Schrödinger and other wave equations from which those wave functions emerge have known only the de Broglie modulation. But while it is the modulation that identifies the energy and momentum of the particle, it is the full modulated wave structure that shows why that is so and defines the position and trajectory of the particle.

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Frequency-comb-driven Atom Interferometry

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Abstract

Light-pulse atom interferometry, where light pulses are used as atom beam splitters, has led to extremely sensitive and accurate quantum sensors that offer many applications in fundamental physics, geosciences and inertial navigation. Until recently, light-pulse atom interferometry had only exploited continuous-wave (cw) laser sources. I will present atom interferometers where the beam splitters are realized with pulsed lasers, or more specifically frequency-comb lasers [1]. This technique, which we demonstrated in the visible spectrum on rubidium (Rb) atoms, paves the way for extending light-pulse interferometry to other wavelengths (e.g. deep-UV to X-UV) and therefore to new species, since one can benefit from the high peak intensity of the ultrashort pulses which makes frequency conversion in nonlinear media efficient.

[C. Solaro et al., “Atom interferometer driven by a picosecond frequency comb”, Physical Review Letters **129**, 173204 (2022).]

Fluctuat nec Mergitur – atom waves tunneling, spinning, colliding, and resonating in structures made of light

Aephraim Steinberg
(Toronto)

Abstract

I will present the latest work from our ultracold Rubidium laboratory, in which starting from a Bose-Einstein condensate we use atomic lensing effects ("delta-kick cooling") to prepare an atom cloud with a temperature on the order of 1 nK, corresponding to a coherence length over 5 microns. This enabled us to study tunneling of the atoms through a one-micron-thick barrier created by a focused laser beam, and carry out the first conclusive measurement of the time transmitted atoms spend in the classically forbidden region. More recently, we observed surprising spin-waves in the reflected cloud, which we now understand as an indistinguishability-driven interaction term between incident and reflected atoms. I will describe future plans for these tunneling studies, along with ongoing work to compensate aberrations in our "atom lenses" and to build Fabry-Perot cavities for atoms. I will also show some pictures of atomic interference we observed on the way to testing a prediction of quantum-enhanced sensitivity to magnetic field gradients.

Scope of the action principle

Ward STRUYVE
(KU Leuven)

Abstract

Laws of motion given in terms of differential equations can not always be derived from an action principle, at least not without introducing auxiliary variables. This is the case for the Bohmian dynamics which can not be derived from an action that depends only the particle positions and the wave function. By allowing auxiliary variables, e.g. in the form of Lagrange multipliers, an action is immediately obtained. We consider some ways how this can be done. A particularly interesting approach brings the theory in the form of a gauge theory, with the auxiliary variables as gauge degrees of freedom. So any theory with a dynamics given by differential equations, in particular Bohmian mechanics, can be derived from an action principle by turning it into a gauge theory.

Scaling properties of response functions: from quantum fluctuations to quantum potential

Peter Szabo
(KU Leuven)

Linear response functions in physics and chemistry provide a quantitative framework for understanding and predicting the behavior of systems subjected to small perturbations. Polarizability, a key response property of physical and chemical systems, plays a crucial role in describing intermolecular interactions and determining spectroscopic observables.

In our recent study, we explored the system-size dependence of polarizability, denoted as α, within a quantum-mechanical framework. Interestingly, we found that the general quantum-mechanical system-size dependence of polarizability follows a four-dimensional scaling law, which deviates from the commonly accepted classical result (classical 3D scaling: $\alpha \sim \text{Volume} \sim R^3$, where R represents the system's radius). This four-dimensional scaling law is a pure quantum effect arising from quantum fluctuations and remains valid for quantum-mechanical systems with varying spatial dimensions, symmetry, and excitation states. Our unified formula can be extended to arbitrary response functions by renormalizing the quantum fluctuations caused by external perturbations. This departure from classical scaling also enables us to establish connections between polarizability and the quantum potential of Bohmian mechanics.

Beyond the Born rule in quantum gravity

Antony Valentini
(Clemson Univ.)

Abstract

We have recently developed a new understanding of probability in quantum gravity. In this talk we provide an overview of this new approach and its implications. Adopting the pilot-wave formulation of quantum physics, we argue that there is no Born rule at the fundamental level of quantum gravity with a non-normalisable Wheeler-DeWitt wave function. Instead the universe is in a perpetual state of 'quantum nonequilibrium'. Dynamical relaxation to the Born rule can occur only after the early universe has emerged into a semiclassical or Schrödinger approximation, with a time-dependent and normalisable wave function. We also show that quantum-gravitational corrections to the Schrödinger approximation can generate tiny deviations from the Born rule. The possibility of observing these effects is discussed.

Reference

A. Valentini, Beyond the Born rule in quantum gravity, Found. Phys. 53, 6 (2023).

Spin evolution in the Stern-Gerlach experiment and the role of the Quantum Potential

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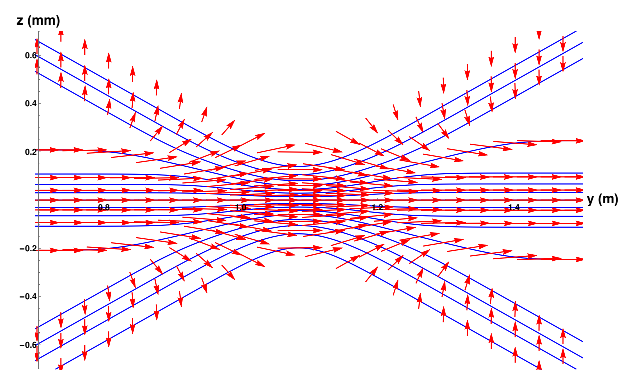
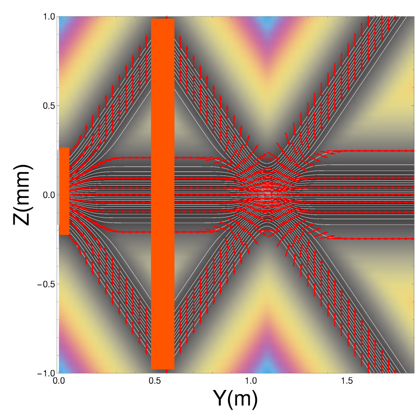
University College London

The importance of the Stern-Gerlach (S-G) experiment in revealing the role of spin quantisation and the development of both experimental and theoretical quantum physics over the last 100 years is well established. In a standard S-G experiment an atomic beam, which is taken to be originally in a mixture of m_s eigenstates, emerges from the magnetic field gradient into a set of sub-beams corresponding to the number of m_s eigenstates. In the standard interpretation, the splitting into these sub-beams is considered to be instantaneous as no evolution of the spin orientation is allowed.

We present a theoretical modelling of the S-G process using the Bohm approach, as presented in [1] for spin 1/2 atoms, extended to spin 1 atoms which will allow us to describe in detail how the spin states of the atoms evolve after leaving the magnet, i.e. while they are in an interaction free region. In order to present this evolution of the spin vectors more explicitly we consider a set-up of two S-G magnets with their field gradients aligned along the same axis but with opposite polarity. As can be seen in the figures below the spin vector evolves over a macroscopic distance when it leaves the first magnet and when the two beam converge to the z-axis.





The Bohm approach, by separating the real and imaginary parts of the Schrdinger equation, allows us to consider the particle flow-lines which reveal that their behaviour outside of the magnet is very different from that predicted by the standard interpretation of quantum mechanics. For instance, as shown in the figures above, the flow lines will not cross and therefore there is a significant deviation from the expected 'straight' lines. This behaviour of the atoms is directly related to the quantum potential which we show to act outside of the magnet at macroscopic distances and is responsible for the evolutionary behaviour of the spin vectors and for the change in the transverse momentum of the particles.

The main outcome of our investigation is that we show how the evolution of the spin vectors and changes in transverse momentum are amenable to experimental investigations which would reveal clear differences with the standard interpretation of quantum mechanics.

[1] Quantum Trajectories: Real or Surreal? B. Hiley and P. Van Reeth *Entropy* 2018, **20** 353

Matter-wave interferometry: quantum engineering of robust atomic sensors with composite pulses

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A new class of atomic interferences using ultra narrow optical transitions are pushing quantum engineering control to a very high level of precision for the next generation of sensors and quantum gate operations. In such context, we propose a new quantum engineering approach to Ramsey-Bordé interferometry introducing multiple composite laser pulses with tailored pulse duration, Rabi field amplitude, frequency detuning and laser phase step [1]. We explore quantum metrology with hyper-Ramsey and hyper-Hahn-Ramsey clocks below the 10^{-18} level of fractional accuracy by fine-tuning control of light excitation parameters leading to spinor interferences protected against light-shift coupled to laser-probe field variation [2]. We review cooperative composite pulse protocols to generate robust Ramsey-Bordé, Mach-Zehnder, and double-loop atomic sensors shielded against measurement distortion related to Doppler and light shifts coupled to pulse area errors. Fault-tolerant auto-balanced hyper-interferometers are introduced eliminating several technical laser pulse defects that can occur during the entire probing interrogation protocol. Quantum sensors with composite pulses and ultracold atomic sources should offer a new level of high accuracy in the detection of acceleration and rotation inducing phase shifts, a strong improvement in tests of fundamental physics with hyperclocks while paving the way to a new conception of atomic interferometers tracking space-time gravitational waves with very high sensitivity.

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Voyage à trois: Mapping between Schrödinger evolution, fluid flow and curved spacetime

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ABSTRACT

We use the Madelung ansatz [1-2] to demonstrate a mapping between Schrodinger-type equations and equations describing inviscid flow of irrotational barotropic fluid in three-dimensional Euclidean space. Then we study small perturbations of the fluid, to demonstrate the emergence of four-dimensional curved spacetime [3-5]. We derive the metric tensor of this spacetime and study its special cases and limits, such as the linear-phase flow and linearized gravity limit. We thus show that the gravitational potential can be defined in terms of the quantum information entropy of the background superfluid.

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