Poster session – Abstracts

Plasma-like description for quantum particles	**Andrey Akhmeteli** (LTASolid, Houston)
Space-time resolved quantum field approach to Klein tunneling dynamics of fermions and bosons	**Mohammed Alkhateeb** (CYU Cergy Paris)
From observer-dependent facts to frame-dependent measurement records in Wigner friend Scenarios	**Jawad Allam** (CYU Cergy Paris)
Towards models of wave-particle duality and quantum measurement based on stochastic fields with future-input dependence	**Nathan Argaman** (Ben Gurion Univ., Beer-Sheva)
Obtaining entanglement by particle indistinguishability	**Ewa Borsuk** (Inst. of Nuclear Physics, Krakow)
On a possible Wave-memory interpretation for Quantum Mechanics - An attempt to unify pilot-wave theory with standard QM formalism	**Paulo Castro** (Univ. Lisboa)
Structure de l'onde et paramètres libres.	**Jacques Consiglio** (Fondation Louis de Broglie, Paris)
On Schrodingerist Quantum Thermodynamics	**Leonardo De Carlo** (Libera Univ. Inter. degli Studi Sociali Guido Carli, Roma)
Observation of Fractional Elementary Charges in a Periodic Many-body Quantum System	**Klaus Müller-Dethlefs** and François Michels (Univ. of Manchester)
Une expérience pour mieux comprendre les ondes de phase et de matière de Louis de Broglie	**Alexandre Gondran** (ENAC, Toulouse)

Relaxation to quantum equilibrium and the Born rule in Nelson's stochastic dynamics	**Vincent Hardel** (Univ. Strasbourg)
Fast Atom Diffraction from crystalline surfaces at femtometer wavelengths: where is the quantum limit?	**Hocine Khemliche** (ISMO, CNRS/Univ. Paris-Saclay)
Quantum sensing for gravity cartography	**Samuel Lellouch** (Univ. of Birmingham)
Towards a high data rate atom interferometric gravimeter (HIDRAG) *for gravity map matching navigation*	**Yu-Hung Lien** (Univ. of Birmingham)
Does the 'Complex' wavefunction of Quantum Mechanics represents anything 'Real' at all?	**T. S. Natarajan** (Indian Institute of Technology Madras/Tirupati,)
Modèles de contact pour les résonances à N corps	**Ludovic Pricoupenko** (LPTMC, Sorbonne Univ.)
Multiple Longitudinal Stern Gerlach Effect in Wave Mechanics with Hydrogen Atoms	**Jacques Robert** (Université Paris-Saclay)
Phase and trajectories: face and tail of the same conceptual framework	**Angel Sanz** (Univ. Complutense Madrid)
Corrélation quantiques entre la Terre et la Lune	**Jean Schneider** (Observatoire de Paris-Meudon)
Time, unitarity and normalizability in pilot-wave approach to quantum gravity in Ashtekar formulation	**Indrajit Sen** (Chapman Univ.)
Frequency-comb-driven Atom Interferometry	**Cyrille Solaro** (LKB, ENS,Paris)
Scaling properties of response functions: from quantum fluctuations to quantum potential	**Peter Szabo** (KU Leuven)
De Broglie's Thesis, Constants of Nature and Simplicity	**Alexander Unzicker** (Pestalozzi-Gymnasium München)
Spin evolution in the Stern-Gerlach experiment and the role of the Quantum Potential	**Peter Van Reeth** (University College London)
Matter-wave interferometry: quantum engineering of robust atomic sensors with composite pulses	**Thomas Zanon** (LERMA, Sorbonne Univ.)
Voyage à trois: Mapping between Schrödinger evolution, fluid flow and curved spacetime	**Konstantin Zloshchastiev** (Durban Univ. of Technology)

Plasma-like description for quantum particles

Andrey Akhmeteli
LTASolid Inc., Houston, TX, USA
akhmeteli@ltasolid.com

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."

References

[1] E. Schrödinger. Dirac's New Electrodynamics. *Nature*, 169:538, 1952.

[2] A. Akhmeteli. One real function instead of the Dirac spinor function. *J. Math. Phys*, 52:082303, 2011.

[3] A. Akhmeteli. arxiv:1811.02441.

[4] A. Akhmeteli. Some classical models of particles and quantum gauge theories. *Quantum Reports*, 4(4):486–508, 2022.

[5] A. M. Akhmeteli. arxiv:quant-ph/0509044.

[6] A. Akhmeteli. No drama quantum electrodynamics? *Eur. Phys. J. C*, 73:2371, 2013.

[7] L. de Broglie. RADIATIONS. – Ondes et quanta. *Comptes rendus*, 177:507–510, 1923.

[8] A. Akhmeteli. Plasma-like description for elementary and composite quantum particles. *Entropy*, 24(2):261, 2022.

[9] S. Colin, T. Durt, and R. Willox. L. de Broglie's double solution program: 90 years later. *Annales de la Fondation Louis de Broglie*, 42, numéro spécial:19, 2017.

[10] R. P. Feynman. Simulating physics with computers. *International Journal of Theoretical Physics*, 21:467, 1982.

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

M. Alkhateeb* and A. Matzkin

Laboratoire de Physique Théorique et Modélisation,

CNRS Unité 8089, CY Cergy Paris Université,

95302 Cergy-Pontoise cedex, France

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.

---

[1] . Alkhateeb and A. Matzkin, Phys. Rev. A 106, L060202 (2022)

* mohammed.alkhateeb@cyu.fr

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

J. Allam and A. Matzkin

Laboratoire de Physique Théorique et Modélisation,

CNRS Unité 8089, CY Cergy Paris Université,

95302 Cergy-Pontoise cedex, France

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

Nathan Argaman, BGU and NRCN, Israel

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.

[1] K. B. Wharton and N. Argaman, "Colloquium: Bell's theorem and locally mediated reformulations of quantum mechanics," Rev. Mod. Phys. **92**, 021002 (2020).

[2] I. Neder and N. Argaman, to be published.

[3] N. Argaman, "Quantum Computation and Arrows of Time," Entropy **23**, 49 (2021).

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.

References

[1] B. Yurke and D. Stoler. Bell's-inequality experiments using independent-particle sources. *Phys. Rev. A*, 46:2229–2234, 1992.

[2] Pawel Blasiak, Ewa Borsuk, and Marcin Markiewicz. Arbitrary entanglement of three qubits via linear optics. *Scientific Reports*, 12(1):21596, 2022.

[3] Pawel Blasiak, Ewa Borsuk, Marcin Markiewicz, and Yong-Su Kim. Efficient linear-optical generation of a multipartite w state. *Phys. Rev. A*, 104:023701, Aug 2021.

On a possible Wave-memory interpretation for Quantum Mechanics

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

Paulo Castro

(jpcastro@ciencias.ulisboa.pt)

Centre for the Philosophy of Sciences of the University of Lisbon (CFCUL)

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.

References

[1] Bush, J. W. M., Oza A. U., 2021, Hydrodynamic quantum analogs. Reports on Progress in Physics, IOP Publishing.

[2] Couder, Y., Protière, S., Fort, E. and Boudaoud, A. 2005 Walking and orbiting droplets, *Nature* 437 208

[3] Fort, E., Eddi, A., Boudaoud, A., Moukhtar, J. and Couder, Y. 2010 Path-memory induced quantization of classical orbits *Proc. Natl Acad. Sci. USA* 107 17515–20

[4] Castro, P., Bush, J. W. M., Croca, J. R. (editors) Advances in Pilot Wave Theory - From Experiments to Foundations, Boston Studies in the Philosophy and History of Science, forthcoming, 2023.

[5] Croca, J.R., Towards a Nonlinear Quantum Physics, World Scientific, London, (2003).

Structure de l'Onde et Paramètres Libres.

Jacques Consiglio

Fondation Louis de Broglie

52, Chemin de Labarthe. 31600 Labastidette. France
E-mail : Jacques.Consiglio@gmail.com

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.

References

[1] De Broglie L. Recherches sur la théorie des quanta. *Annales de Physique* - 10e série - Tome III - Janvier-Février 1925.
[2] Consiglio, J. L'Onde et la Constante de Sommerfeld. *Annales de la Fondation Louis de Broglie* - Vol. 47 no 2 (2022) p265-270.
[3] Consiglio J. Structure de l'onde et paramètres libres. Manuscript submitted to *Annales de la Fondation Louis de Broglie*.

On Schrödingerist Quantum Thermodynamics

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

[1] *LUISS Guido Carli di Roma, Viale Romania, 32, 00197 Roma RM*
[2] *retired scientist, Seattle, USA*

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.

References:

[1] L. De Carlo, W. David Wick, arXiv:2208.07688 (2023)

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

Michel Gondran
Académie Européenne Interdisciplinaire des Sciences, Paris, France
michel.gondran@polytechnique.org

Alexandre Gondran
École Nationale de l'Aviation Civile, Toulouse,France
alexandre.gondran@recherche.enac.fr

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.

Références

[1] L. de Broglie, Ondes et quanta, in : C. R. Acad. Sci. t.177, Gauthier-Villard, 1923, pp. 507–510.

[2] L. de Broglie, Quanta de lumière, diffraction et interférences, in : C. R. Acad. Sci. t.177, Gauthier-Villard, 1923, pp. 548–560.

[3] L. de Broglie, Les quanta, la théorie cinétique des gaz et le principe de Fermat, in : C. R. Acad. Sci. t.177, Gauthier-Villard, 1923, pp. 630–632.

[4] M. Gondran, A. Gondran, Double-scale theory, preprint : hal-03960495 (2023).

[5] M. Gondran, A. Gondran, Variation of the double slit experiment to test the wave-particle duality, in progress (2023).

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.

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

H. Khemliche, A. R. Allouche, A. Mukherjee, Ch. Sonny, E. M. Staicu Casagrande, A. Momeni

ISMO, Université Paris-Saclay, CNRS, 91405, Orsay, France

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.

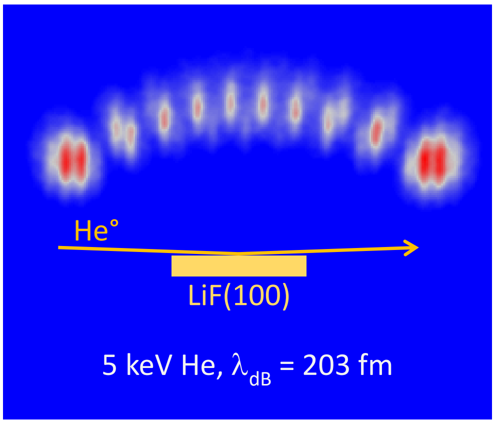


Figure 1. Diffraction pattern form 5 keV He° scattering from a LiF(100) surface at a grazing angle of 0.72°.

[1] Eibenberger S, Gerlich S, Arndt M, Mayor M and Tüxen J., Phys. Chem. Chem. Phys. 15 14696 (2013)
[2] A. Schüller, S. Wethekam, H. Winter; Phys. Rev. Lett. 98, 016103 (2007)
[3] P. Rousseau, H. Khemliche, A.G. Borisov, P. Roncin; Phys. Rev. Lett. 98, 016104 (2007)
[4] H. Winter and A. Schüller; Progress in Surface Science 86, 169 (2011)

Quantum sensing for gravity cartography

Ben Stray[1], Andrew Lamb[1], Aisha Kaushik[1], Jamie Vovrosh[1], Anthony Rodgers[1], Jonathan Winch[1], Farzad Hayati[1], Daniel Boddice[2], Artur Stabrawa[1], Alexander Niggebaum[1], Mehdi Langlois[1], Yu-Hung Lien[1], Samuel Lellouch[1], Sanaz Roshanmanesh[2], Kevin Ridley[1], Geoffrey de Villiers[1], Gareth Brown[3], Trevor Cross[4], George Tuckwell[2,5], Asaad Faramarzi[2], Nicole Metje[2], Kai Bongs[1] & Michael Holynski[1]

[1]School of Physics and Astronomy, University of Birmingham, U.K

[2]School of Engineering, University of Birmingham, Birmingham, UK

[3]Dstl, Porton Down, Salisbury, UK

[4]Teledyne e2v, Chelmsford, UK

[5]RSK, Hemel Hempstead, UK

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.

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

Benjamin Adams[1], Sachin Kinge[2], Kai Bongs[1,3,4], Yu-Hung Lien[1]
[1]School of Physics and Astronomy, University of Birmingham, Birmingham UK
[2]Materials Engineering Division, Toyota Motor Europe, Hoge Wei 33, 1930, Zaventum, Belgium
[3]Ulm University, Ulm, Germany
[4]Institute of Quantum Technologies, German Space Agency (DLR), Ulm, Germany

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.

References

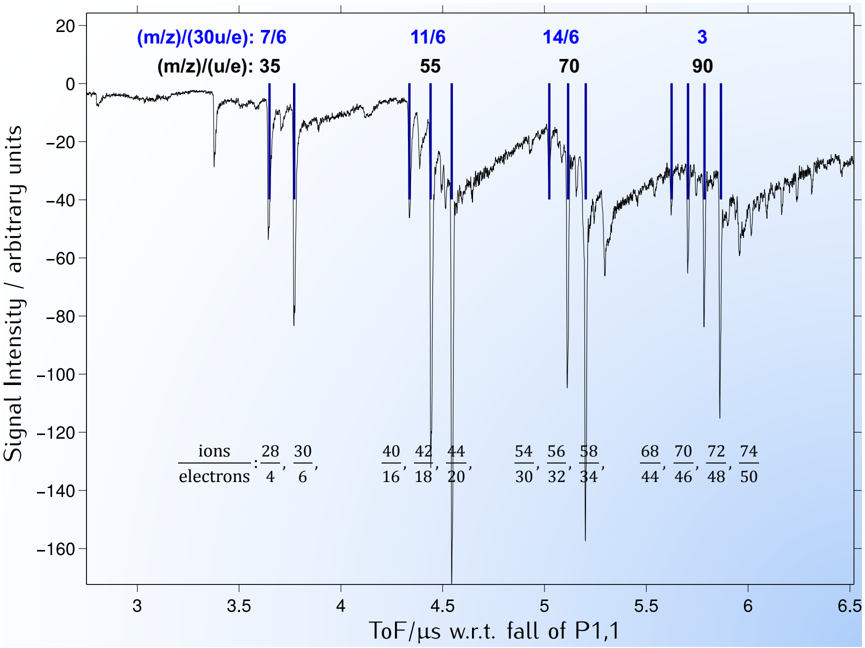
[1] H. Liu, W. T. Pike, C. Charalambous and A. E. Stott, *Phys. Rev. Applied*, 12 (2019) 064057.
[2] H. J. McGuinness, A. V. Rakholia, G. W. Biedermann, *Appl. Phys. Lett. 100(2012)*, 011106.

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

Klaus Müller-Dethlefs* and François Michels
*k.muller-dethlefs@manchester.ac.uk
School of Chemistry and Photon Science Institute, The University of Manchester, Manchester M13 9PL, UK.

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?

Natarajan T S
Indian Institute of Technology Madras/Tirupati, INDIA

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.

Multiple Longitudinal Stern Gerlach Effect in Wave Mechanics with Hydrogen Atoms

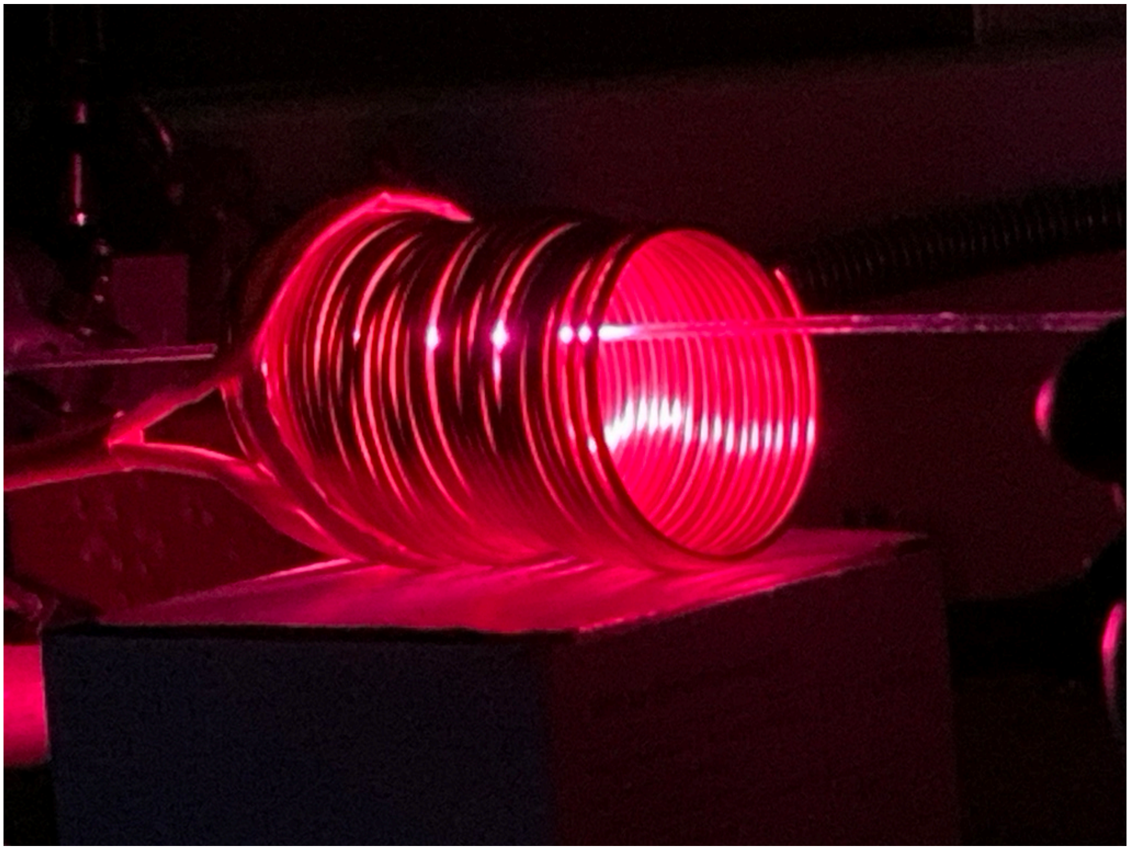
M. Aractingi, Léa Espeyrac, F. Dralet, P. Jeanney, O. Vasilovici, Ch. Ballage, O. Leroy, T. Minea and J. Robert

Université Paris-Saclay, CNRS, Laboratoire de physique des gaz et des plasmas, 91405, Orsay, France

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.



(1) Drabkin and R. Zhitnikov, “Production of supercold polarized neutrons,” J. Exptl. Theoret. Phys. (U.S.S.R.), vol. 38, 01 1960
(2) B. Alefeld, G. Badurek, and H. Rauch, “Observation of the neutron magnetic resonance energy shift,” Zeitschrift fr Physik B Condensed Matter, vol. 41, pp. 231–235, 09 1980

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

ÁNGEL S. SANZ (a.s.sanz@fis.ucm.es)

UNIVERSIDAD COMPLUTENSE DE MADRID

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.

Jean Schneider
Observatoire de Paris
Jean.Schneider@obspm.fr

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.

Références

Schneider J. 2009. Constraining the correlation distance in quantum measurements from the Moon. Présenté au Workshp Gravitation and Fundamental Physics in Space GPhyS "Kick-Off " Colloquium - Les Houches, Oct. 2009 (http://gphys.obspm.fr/LesHouches2009/Home.html) http://luth7.obspm.fr/Les-Houches09-Schneider.pdf

Yin J. et al. 2017. Satellite-based entanglement distribution over 1200 kilometers. *Science*,356, 1140

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

Indrajit Sen
Institute for Quantum Studies, Chapman University,
One University Drive, Orange, CA, 92866, USA

Stephon Alexander
Brown Theoretical Physics Center, Department of Physics,
Brown University, Providence, Rhode Island 02912, USA

Justin Dresell
Institute for Quantum Studies, Chapman University,
One University Drive, Orange, CA, 92866, USA

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:

1. I. Sen (2022). Physical interpretation of non-normalizable harmonic oscillator states and relaxation to pilot-wave equilibrium. *arXiv*:2208.08945
2. S. Alexander, T. Daniel, M. Howard, M. König (2022). Exact fermionic Chern-Simons-Kodama state in quantum gravity. *Physical Review D*, 106(10), 106012.
3. (forthcoming) I. Sen, S. Alexander, J. Dressel (2023). Unitarity and Normalizability in 4D Quantum Gravity through the lens of pilot-wave theory

Frequency-comb-driven Atom Interferometry

Cyrille Solaro, Clément Debavelaere, Pierre Cladé et Saïda Guellati-Khelifa
Laboratoire Kastler Brossel
(ENS-Université PSL, Sorbonne Université, CNRS, Collège de France, CNAM)

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).]

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.

De Broglie's Thesis, Constants of Nature and Simplicity

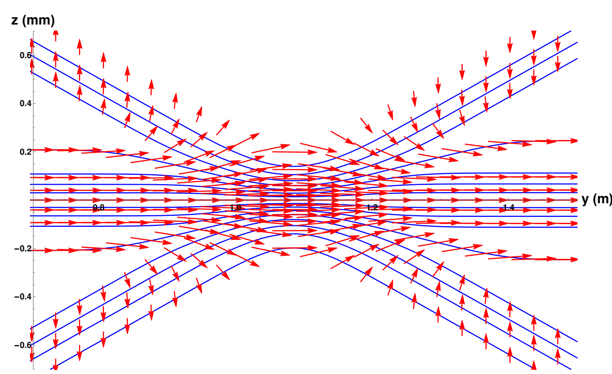
In his 1922 doctoral thesis, de Louis Victor Broglie began his reasoning by merging two of Einstein’s famous formulas, namely $E= hf$ and $E= mc^2$, into the equation $hf = mc^2$. It is argued that this equation could be the seed for a yet to be developed theory of quantum gravity. If one assumes that a proton is a circular light wave, de Broglies equation transforms into $h= \quad \approx \quad c\, m_p\, r_p$, a remarkable coincidence unexplained by current theoretical approaches. It is further shown that this relation closely resembles Dirac's Large Number Hypothesis (LNH). Finally, the general role of such coincidences in the history and epistemology of science is discussed.

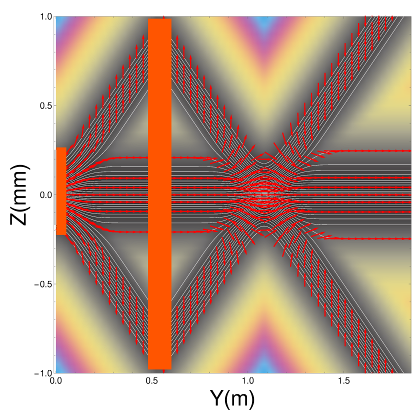
Spin evolution in the Stern-Gerlach experiment and the role of the Quantum Potential

Peter Van Reeth and Basil Hiley
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

T. Zanon-Willette (Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, LERMA, F-75005, Paris, France)**,**

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.

[1] T. Zanon-Willette, D. Wilkowski, R. Lefevre, A. V. Taichenachev, and V. I. Yudin, Phys. Rev. Research **4**, 023222 (2022)

[2] T. Zanon-Willette, D. Wilkowski, R. Lefevre, A. V. Taichenachev, and V. I. Yudin, Phys. Rev. Research **4**, 023117 (2022)

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

Konstantin G. Zloshchastiev
Institute of Systems Science, Durban University of Technology, Durban 4000, South Africa

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.

REFERENCES

[1] de Broglie, L. Sur la Possibilité de Relier les Phénomènes d'Interférence et de Diffraction à la Théorie des Quanta de Lumière. Comptes Rendus 1926, 183, 447-448.
[2] Madelung, E. Quantentheorie in Hydrodynamischer Form. Z. Phys. 1927, 40, 322-326.
[3] Barceló, C.; Liberati, S.; Visser, M. Analogue Gravity. Living Rev. Relativity 2005, 8, 12.
[4] Zloshchastiev, K.G. Spontaneous Symmetry Breaking and Mass Generation as Built-in Phenomena in Logarithmic Nonlinear Quantum Theory. Acta Phys. Polon. 2011, 42, 261.
[5] Zloshchastiev, K.G. An Alternative to Dark Matter and Dark Energy: Scale-dependent Gravity in Superfluid Vacuum Theory. Universe 2020, 6, 180.