QUANTON INTERFERENCE

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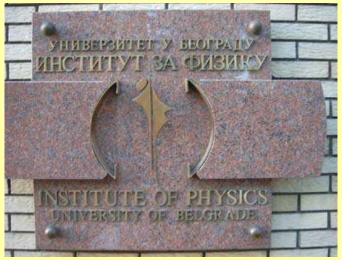
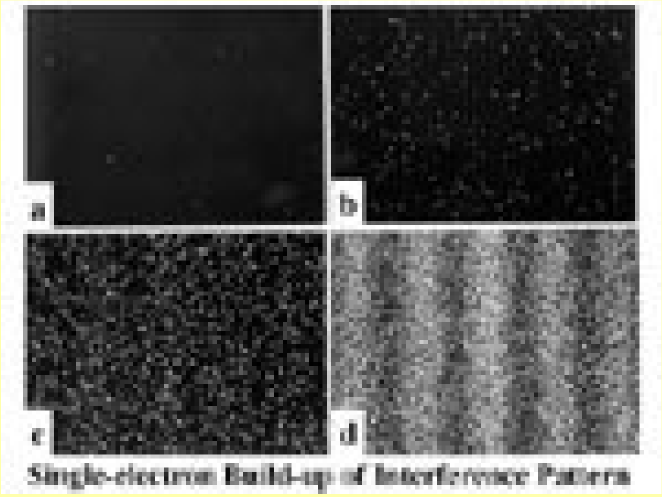


Pure scientific research is ether basic or based.
Mario Bunge

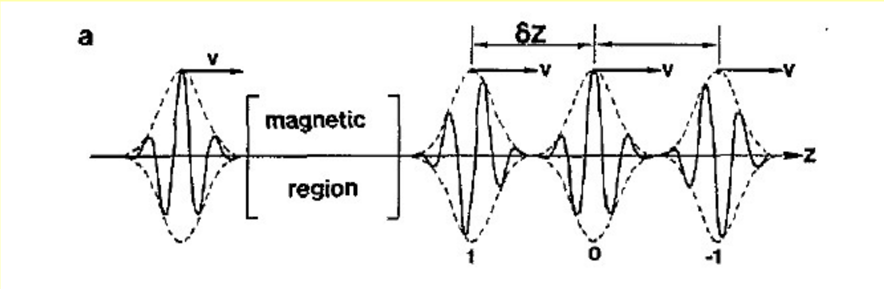
COLLOQUIUM IN HONOR OF VALERIJ BOČVARSKI
Belgrade 13th – 14th October, 2017

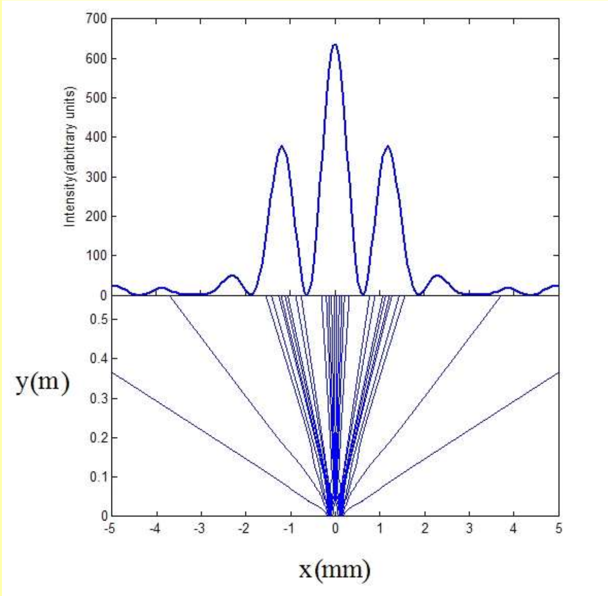
1. In 1973 Bunge coined the term "quanton" to express the fact that objects in the quantum world, like electrons, neutrons, atoms, protons, molecules, photons…, have properties which look strange and escape unanimous theoretical description.



2. Interference, as a process of accumulation of arrivals of individual quantons to the screen/detectors in an interferometer, has been for decades in the center of studies aimed to understand how particle like and wave like properties of quantons are interrelated.

3.





In this talk we shall present how atomic interference experiments, realized by the team of physicists in the Laboratoire de Physique des Lasers in Paris, to which belonged Valerij Bočvarski, contributed to these studies.

4. We shall present also the unified interpretation of interference of quantons which is based on the de Broglie-Bohm trajectories of massive particles and photon trajectories determined by the solutions of Maxwell's equation and the electromagnetic energy flow lines.

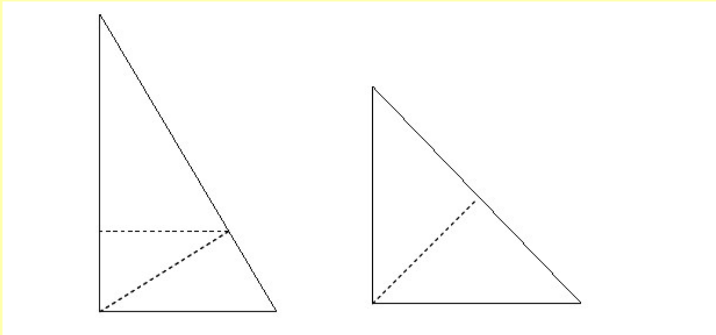
PRECURSORS OF QUANTONS AND QUANTUM PHYSICS

Mario Bunge, Twenty-Five Centuries of Quantum Physics: From Pythagoras to Us, and from Subjectivism to Realism, Science&Education (2003)

The first to discover quanta was not Planck in 1900, but Pythagoras in the 6th century B.C. He did so while studying vibrating strings such as a harp's. Indeed, he found that the frequencies of such a string are integral multiples of a basic frequency or harmonic.

V. Bočvarski, J. Baudon, J. Reingardt, M. Hamamda, F. Perales, M. Ducloy, Morphologie de la physique : Les géométries quantiques, Annales Fondation Louis de Broglie (2012)

Contrairement au monde de l'Europe occidentale moderne dans lequel la catégorie de base est l'action (la force), et où tout se résume à l'énergie, au travail, aux heures de travail, etc. le monde Grec est un monde de formes… Platon introduit pour cela un ensemble de formes élémentaires qui sont, pourrait-on dire, les particules de base. Il est donc parfaitement justifié de nommer, selon une terminologie moderne, « géométrie quantique » une telle description du monde. Les plus simples et les plus fondamentales de ces formes élémentaires sont le triangle rectangle scalène (demi-triangle équilatéral) et le triangle rectangle isocèle (demi-carré). Dans ces triangles, le théorème de Pythagore apparaît de deux façons différentes (c'est un « doublet »), puisque, si a désigne le côté du triangle équilatéral, les côtés du triangle scalène sont *a/2, a, a 3 / 2 alors que, si a est le côté du carré, les côtés du triangle* rectangle isocèle sont *a, a et a / 2.*



Division primaire des deux triangles rectangles de base, (left) scalène, (right) isocèle.

Jean-Marc Levy-Leblond, On the Nature of Quantons , Science & Education · August 2003

The unity of quantics
It may be argued that a part of the misunderstandings which have plagued quantum theory up to now, is due to the older failure to fully assimilate the (classical) notion of field. This is reflected, for instance, in the surviving of the appellation "quantum mechanics", despite the symmetrical status of the classical notions of particle and field with respect to their (unique) successor, the notion of quanton. A simple alternative exists, following the well-established tradition of substantivation for naming the fields of physics; as for acoustics, thermodynamics, electronics (and physics itself!), why do we not simply use the term "quantics" to denote the whole field?

QUANTONS

Mario Bunge, **Quantons are Quaint but Basic and Real, and the Quantum Theory Explains Much but not Everything: Reply to my Commentators, Science&Education (2003)**

We all agree that (a) although the quantum theory is basically correct, its orthodox or Copenhagen interpretation, particularly the claim that quantum events are mind-dependent, is false; and (b) quantons – the referents of the quantum theory – however strange, exist on their own, even if some of their properties depend partially upon their environment. I only differ from some of my commentators on whether the quantum theory has no precursors at all.

Jean-Marc Levy-Leblond, On the Nature of Quantons Science & Education · (2003)

Neither waves, nor particles, but quantons!
For indeed, quantons are novel entities! The best way, perhaps, to stress the originality of the notion is to examine it from the point of view of the discrete/continuous dichotomy. Quantons show discreteness in that they come in units, and can be counted: an atom has an integer number of electrons, and a photographic plate registers the individual impacts of photons. Nevertheless, electrons as well as photons (and all quantons) do show continuous essence as well, since they can be subjected to interferences, superposition, etc.

Feynman: "quantum objects are crazy, but they all have the same craziness".

Marcello Cini (Rome), http://www.intechopen.com/books/theoretical-concepts-of-quantum-mechanics

Waves and particles in quantum mechanics
In spite of the fact that the extraordinary progress of experimental techniques make us able to manipulate at will systems made of any small and well defined number of atoms, electrons and photons - making therefore possible the actual performance of the *gedankenexperimente that Einstein and Bohr had imagined to support their opposite views on* the physical properties of the wavelike/particle like objects (*quantons) of the quantum world* - it does not seem that, after more than eighty years, a unanimous consensus has been reached in the physicist's community on how to understand their "strange" properties. Unfortunately, we cannot know whether Feynman would still insist in maintaining his famous sentence "It is fair to say that nobody understands quantum mechanics". We can only discuss if, almost thirty years after his death, some progress towards this goal has been made. I believe that this is the case.

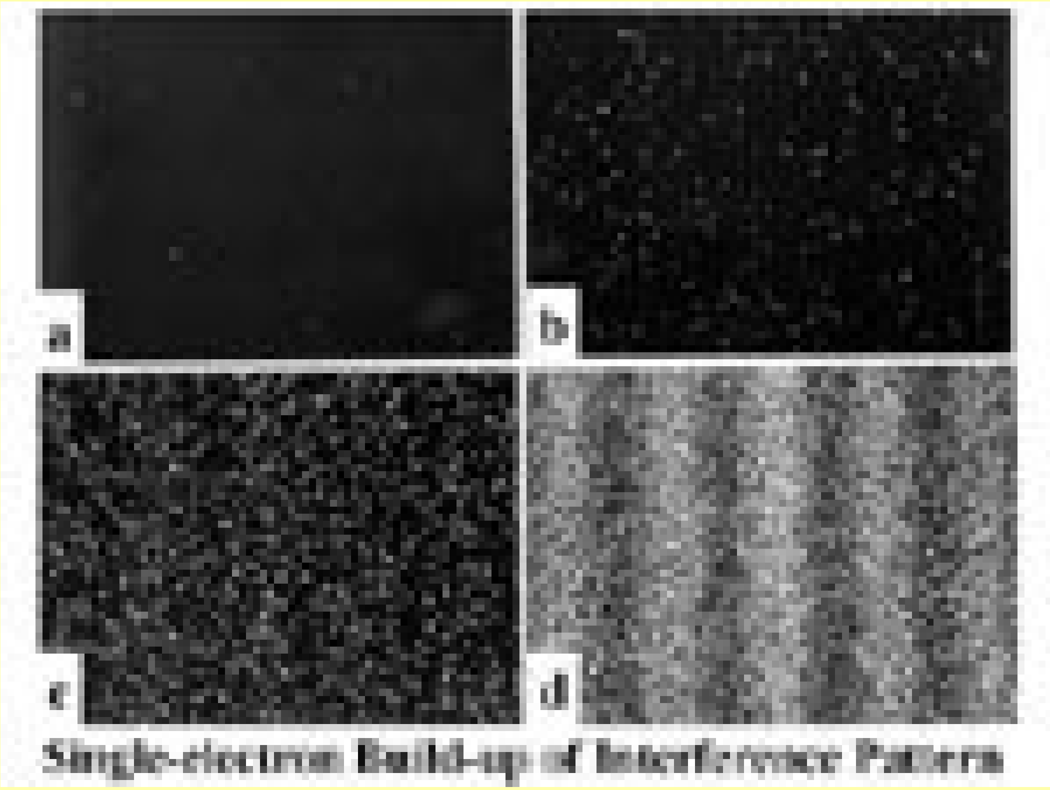
We agree with Cini that since Feynman's statement progress has been made in understanding properties of quantons. Our aim is to present some elements of this progress.

Experimentalists and theoreticians agreed that the notion of quantization and quantum should not be limited to the quantization of quantities like energy, momentum, angular momentum, spin, but should encompass counting of particles, as well. The importance which has been given to the interference experiments with beams of one per one quanton, clearly show this consensus.

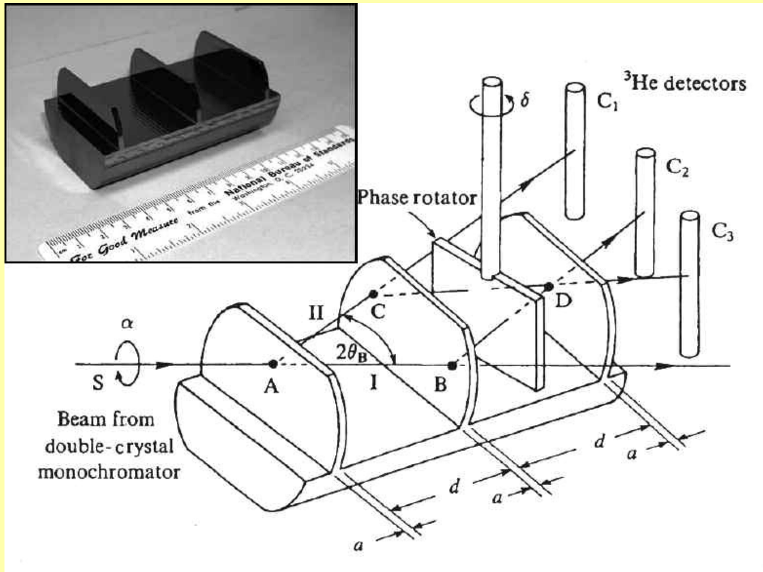
Electron interference,
Johnson, 1961. Zeitschrif fur Physik, AJP 1961.

Bologna experiment, **Pier Giorgio Merli, GianFranco Missiroli and Giulio Pozzi,1974,**

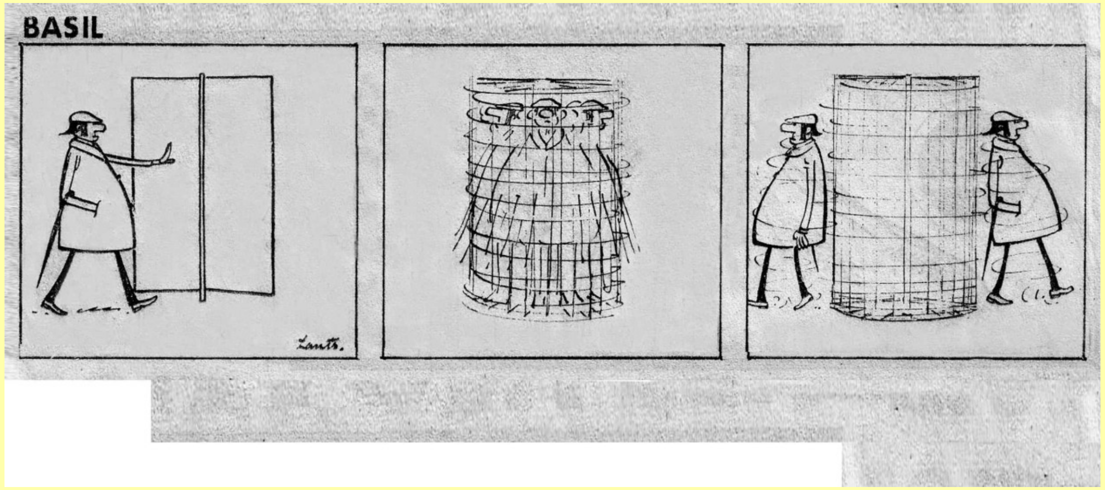
Physics World, September 2002

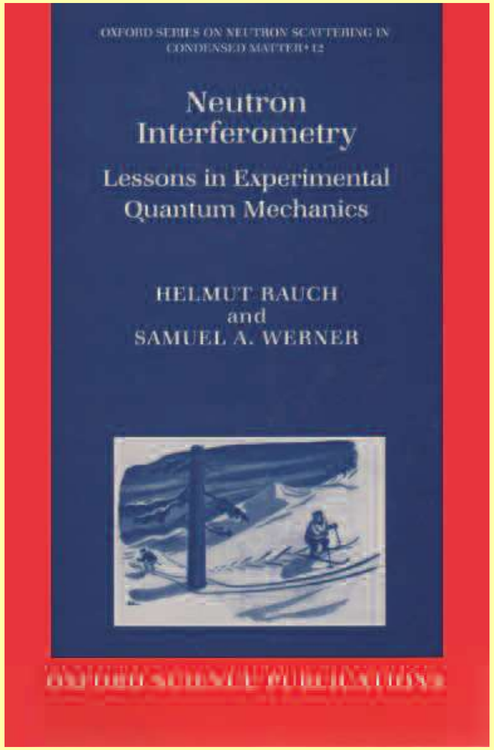


Single electron experiment at Hitachi, A Tonomura, J Endo, T Matsuda, T, Kawasaki and H Ezawa, Am. J. Phys. 57 (1989) 117-120



First demonstration of a working neutron interferometer, Rauch, Treimer, 1974



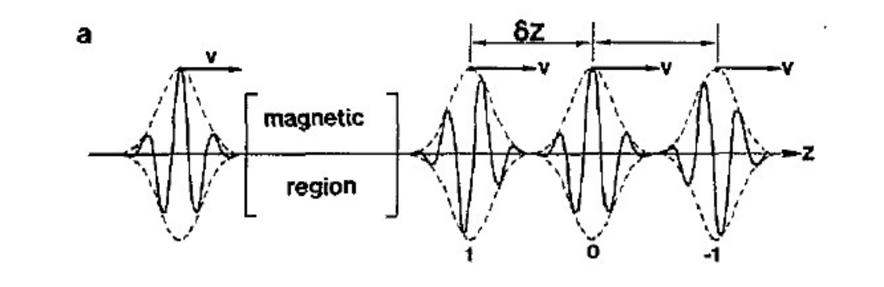


Tony Klein, Neutron interferometry: a tale of three continents
Europhysics News, **Vol. 40, No. 6, 2009**

Atomic interferometry

In 1991, the realization of six different interferometers opened very fascinating perspectives in the field of atomic physics. All these experiments are of the one-particle type in the sense that each particle (atom) interfere with itself.

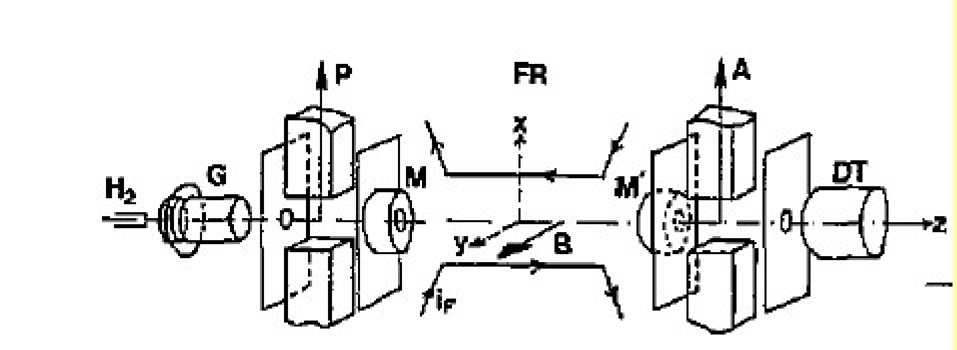
Atomic systems are particularly very well fitted for fine studies of quantum phases since inner and external degrees of freedom can be manipulatet rather easily by means of external field. The occurence of a rich internal structure in atoms is and advantage, compared to photons or neutrons, which can be exploited to act on the external degrees of freedom via the internal ones and vice versa.

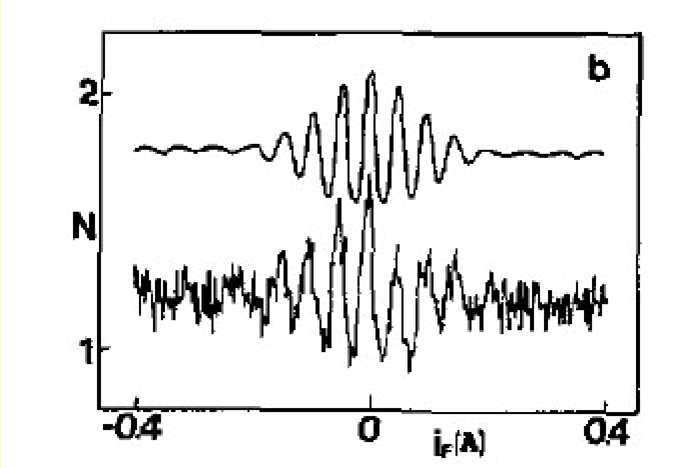


Under the action of the magnetic field on the atomic internal motion (j=1), the incident wave packet with group velocity v is copied into three spatially shifted wave packets with the same group velocity. Each of them corresponds to a definite internal spin state. The atoms coming out of the interferometer in this state are called "beaded" atoms.

Ch. Miniatura *et a*l. A Longitudinal Stern-Gerlah interferometer: the "beaded" atom, Journal de Physique (1991)

One of the atomic interferometers was realized in 1991 in the Laboratoire de Physique des Lasers, Paris.
J. Robert,Ch. Miniatura, S. Le Boiteux, J . Reinhardt, V. Bocvarski and J. Baudon, Atomic Interferometry with Metastable Hydrogen Atoms. *Europhys. Lett., 16 (1)) (1991) 29-34*



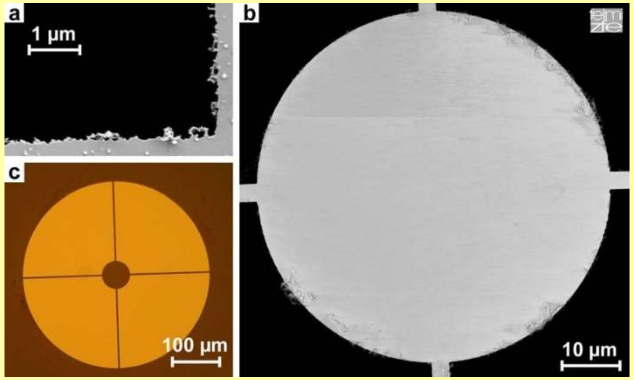


Experimental result and theoretical calculation (upper curve) for the number of H* atoms detected in DT as a function of current i_F and for the velocity selected slice *[4,5 km s-1].* N is in arbitrary units.

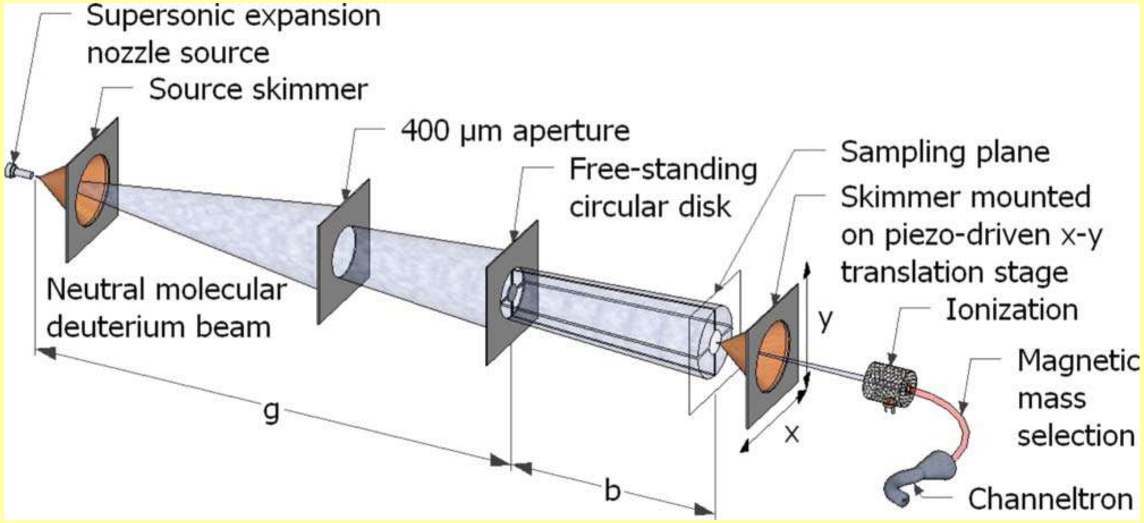
S Nic Chormaic *et al.* , J. Phys. B (1993), Longitudinal Stern-Gerlah atomic interferometry using velocity selected atomic beams

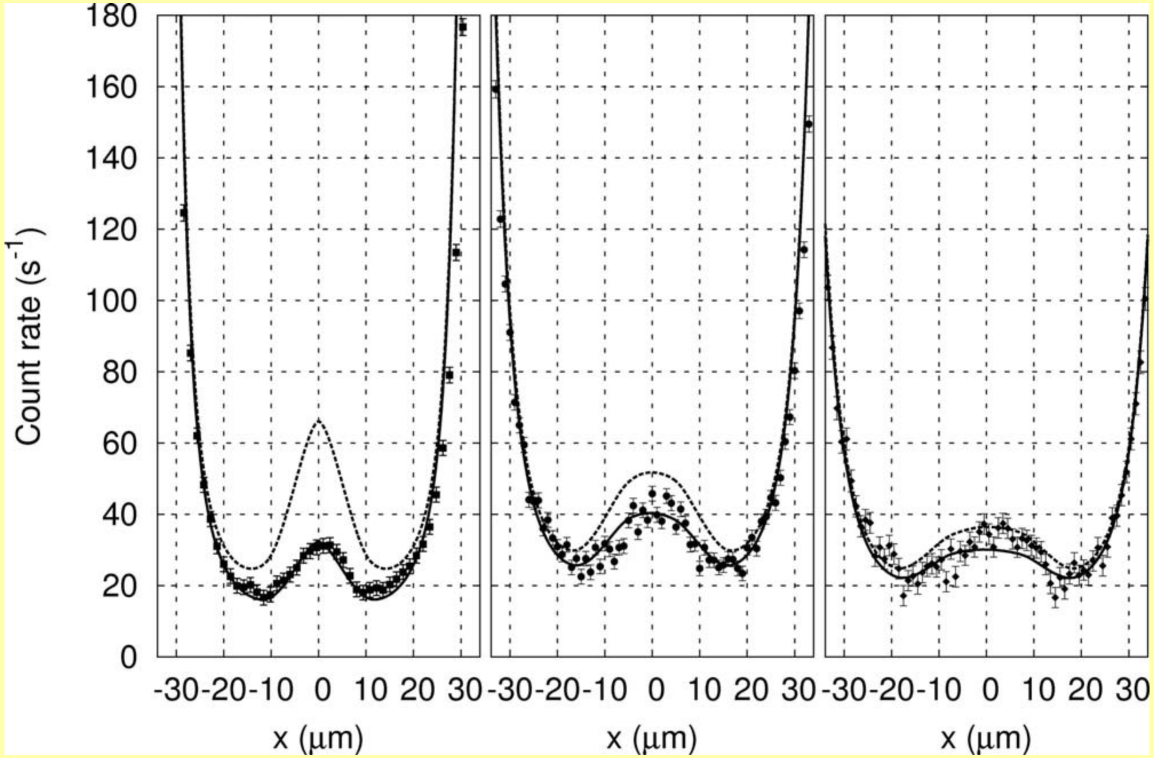
Poisson's spot with molecules

Thomas Reisinger et al. (Norway)
Phys. Rev. A 79, 053823 2009



Electron and optical microscopy images of the circular obstacle. It is a free-standing silicon nitride SiN*x* disk suspended by four narrow support bars.





The interpretation of quanton interference based on trajectories of quantons

Electromagnetic energy flow lines – photon paths

- Light rays
- Newton's rays
- Rays of geometrical optics
- Eikonal rays
- EME flow lines determined by Maxwell's equations and the Poynting vector

Quantum mechanical probability current lines – trajectories of particles

-Schrodinger equation
-Density of probability
-Probability current describes the flow of probability
- Probability current lines - particle trajectories

Schrodinger equation + probability flow lines determined by the current of probability density lead to trajectories of massive particles

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi \quad \frac{d\vec{r}}{dt}$$

$$\vec{J}(\vec{r},t) = \frac{\hbar}{2mi}\left[\Psi^*\nabla\Psi - \Psi\nabla\Psi^*\right] = \frac{\hbar}{m}\operatorname{Im}\Psi^*\nabla\Psi$$

Current of probability density

$$\vec{J} = \vec{v}\rho(\vec{r},t)$$

Classical current density

$$\vec{v} = \frac{\hbar}{m}\frac{\operatorname{Im}\Psi^*\nabla\Psi}{\Psi^*\Psi}$$

$$\left|\Psi\right|^2 = \rho(\vec{r},t)$$

Probability density

$$\frac{d\vec{r}}{dt} = \frac{\vec{J}}{\rho}$$

The equation of a probability flow line-
the equation of a trajectory of a particle with mass

Bohm's quantum mechanics

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi \quad \frac{d\vec{r}}{dt}$$

$$\Psi(\vec{r},t) = \mathrm{R}e^{iS/\hbar}$$

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + V - \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R} = 0 \qquad \frac{\partial R^2}{\partial t} + \nabla\cdot\left(R^2\frac{\nabla S}{m}\right) = 0$$

$$\vec{p} = m\vec{v}(\vec{r},t) = \nabla S(\vec{r},t)$$

$$\nabla S = \hbar\frac{\mathrm{Im}\,\Psi^*\nabla\Psi}{\Psi^*\Psi} \qquad R^2 = \left|\Psi\right|^2 = \rho(\vec{r},t)$$

Probability density

Current of probability density

$$\vec{J}(\vec{r},t) = \frac{\rho(\vec{r},t)}{m}\nabla S(\vec{r},t)$$

The equation of scalar electromagnetic wave

Schrodinger's equation

$$\nabla^2\Phi(x,y,z,t)=\frac{1}{c^2}\frac{\partial^2\Phi(x,y,z,t)}{\partial t^2}$$

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(x,y,z,t)=i\hbar\frac{\partial\Psi(x,y,z,t)}{\partial t}$$

$$\Phi(x,y,z,t)=\varphi(x,y,z)e^{-i\omega t}$$

$$\Psi(x,y,z,t)=\psi(x,y,z)e^{-iEt/\hbar}$$

$$\left(\nabla^2+k^2\right)\varphi(x,y,z)=0$$

$$\left(\nabla^2+\frac{2m}{\hbar^2}E\right)\psi(x,y,z)=0$$

$$k=\omega/c$$

$$\frac{2m}{\hbar^2}E\Leftrightarrow k^2$$

$$E=\frac{mv^2}{2}$$

$$E=\hbar\omega$$

$$\lambda=\frac{h}{mv}$$

$$p=\hbar k$$

$$p=\frac{E}{c}$$

Maxwell's equations, the Poynting vector and the equation of EME flow lines

$$\vec{\tilde{H}}(\vec{r},t) = \vec{H}(\vec{r})e^{-i\omega t} \qquad \vec{\tilde{E}}(\vec{r},t) = \vec{E}(\vec{r})e^{-i\omega t}$$

$$rot\vec{H}(\vec{r}) = -i\omega\varepsilon_0\vec{E}(\vec{r}) \qquad \nabla\vec{H}(\vec{r}) = 0$$

$$rot\vec{E}(\vec{r}) = i\omega\mu_0\vec{H}(\vec{r}) \qquad \nabla\vec{E}(\vec{r}) = 0$$

$$\nabla^2\vec{H}(\vec{r}) + k^2\vec{H}(\vec{r}) = 0$$

$$\nabla^2\vec{E}(\vec{r}) + k^2\vec{E}(\vec{r}) = 0 \qquad c = \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$$

$$\vec{S}(\vec{r}) = \mathrm{Re}[\frac{1}{2}\vec{E}(\vec{r})\times\vec{H}(\vec{r})^*] \qquad U(\vec{r}) = \frac{1}{4}\left(\varepsilon_0\vec{E}(\vec{r})\cdot\vec{E}(\vec{r})^* + \mu_0\vec{H}(\vec{r})\cdot\vec{H}(\vec{r})^*\right)$$

$$\frac{d\vec{r}}{ds} = \frac{\vec{S}(\vec{r})}{U(\vec{r})}$$

The equation that describes electromagnetic energy flow lines has the same form as the Bohmian equation of motion for massive particles.

$$\vec{E} = \left(E_x, E_y, 0\right) \qquad \vec{H} = \left(0, 0, H_z\right)$$

$$\vec{S} = \frac{\lambda}{4\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\,\mathrm{Im}\left(H_z^*\nabla H_z\right) = \frac{\lambda}{8\pi i}\sqrt{\frac{\mu_0}{\varepsilon_0}}\left(H_z^*\nabla H_z - H_z\nabla H_z^*\right)$$

Poynting vector of the electromagnetic field

$$U = \frac{1}{4}\left(\varepsilon_0\vec{E}\vec{E}^* + \mu_0\vec{H}\vec{H}^*\right)$$

$$\vec{J} = \frac{\hbar}{m}\mathrm{Im}\left(\Psi^*\nabla\Psi\right) = \frac{\hbar}{2mi}\left(\Psi^*\nabla\Psi - \Psi\nabla\Psi^*\right)$$

Quantum mechanical current density

$$\frac{d\vec{r}}{d\tau} = \frac{\vec{S}}{U} \qquad \frac{d\vec{r}}{dt} = \frac{\vec{J}}{\rho}$$

Photon path equation

Massive particle equation of motion

Applications to:

- Interference pattern in the far field behind a diffraction grating
- Interference pattern in the near field behind a diffraction grating (Talbot effect)
- Observation of average trajectories of single photons in a two slit interferometer (2011)
- Four Arago-Fresnel laws governing the interference of polarized light
- Poisson-Arago spot phenomenon for photons and molecules

Wave function of a particle and em field behind an *n*-slit grating

$$\Psi(x,y,z,t) = e^{-i\omega t}\psi^i(x,y,z) = Be^{-i\omega t}e^{iky} \qquad y<0$$

$$\Psi(x,y,z,t) = e^{-i\omega t}\varphi(x,y,z) =$$

$$= e^{-i\omega t}\frac{e^{iky}}{2\pi}\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty} dk_x dk_z c(k_x,k_z)e^{ik_x x}e^{ik_z z}e^{-ik_x^2 y/2k}e^{-ik_z^2 y/2k} \qquad y>0,$$

$$c(k_x,k_z) = \frac{1}{2\pi}\int\limits_{-\infty}^{+\infty} dx' \int\limits_{-\infty}^{+\infty} dz'\varphi(x',0,z')e^{-ik_x x'}e^{-ik_z z'}$$

$$= \frac{1}{2\pi}\int\int_A dx'dz'\psi^i(x',0,z')e^{-ik_x x'}e^{-ik_z z'}.$$

$$\Psi(x,y,z,t) =$$

$$= e^{iky} e^{-i\omega t} \frac{1}{2\pi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} dk_x dk_z c(k_x,k_z) e^{ik_x x} e^{ik_z z} e^{\frac{-ik_x^2 \hbar t}{2m}} e^{\frac{-ik_z^2 \hbar t}{2m}} .$$

Time dependent wave function of the transverse motion

$$\psi(x,z,t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} dk_x dk_z c(k_x,k_z) e^{ik_x x} e^{ik_z z} e^{-i\omega_x t} e^{-i\omega_z t}$$

One-dimensional case

$$\omega_x = \frac{k_x^2 \hbar}{2m}$$

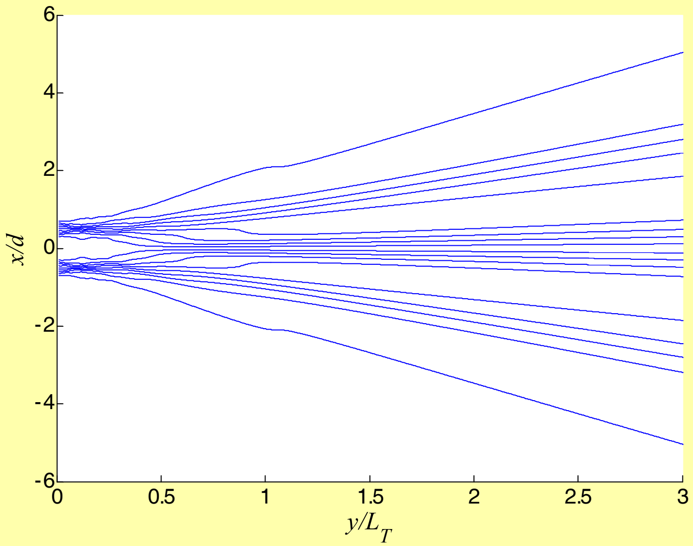
$$\psi(x,t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} dk_x c(k_x) e^{ik_x x} e^{-i\omega_x t}$$

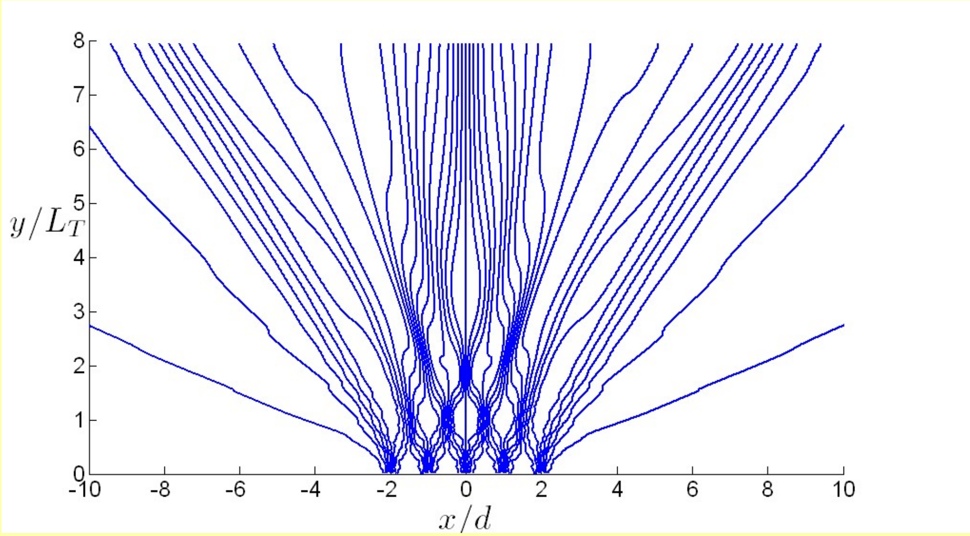
Flow lines behind a specific grating

$$\psi(x,y) = \frac{e^{iky}}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dk_x c(k_x) e^{ik_x x} e^{-ik_x^2 y/2k}$$

$$c(k_x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, \psi(x,0) e^{-ik_x x}$$

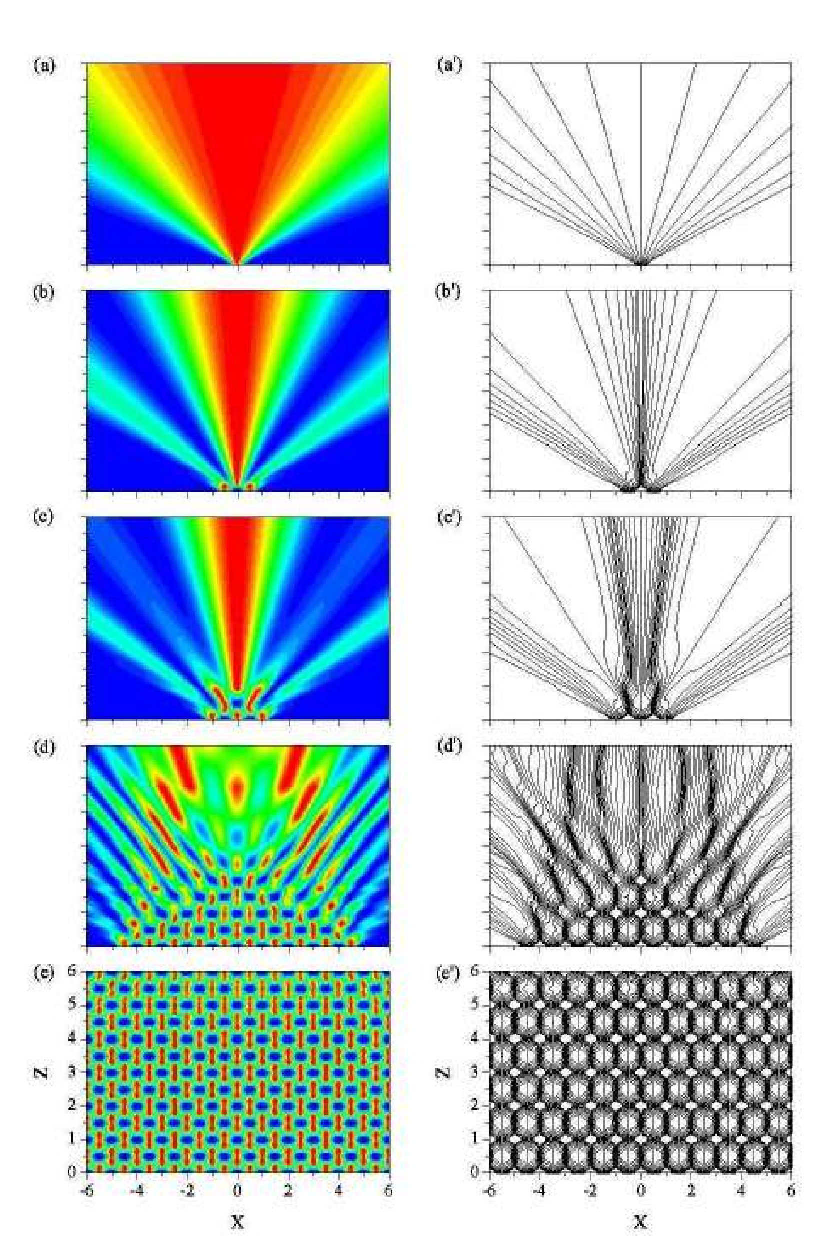
$$c(k_x) = \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{\delta n}} \frac{2\sin k_x \frac{\delta}{2}}{k_x} \qquad \frac{\sin \frac{k_x d}{2} n}{\sin \frac{k_x d}{2}}$$





Energy flow lines behind a grating with two and five slits

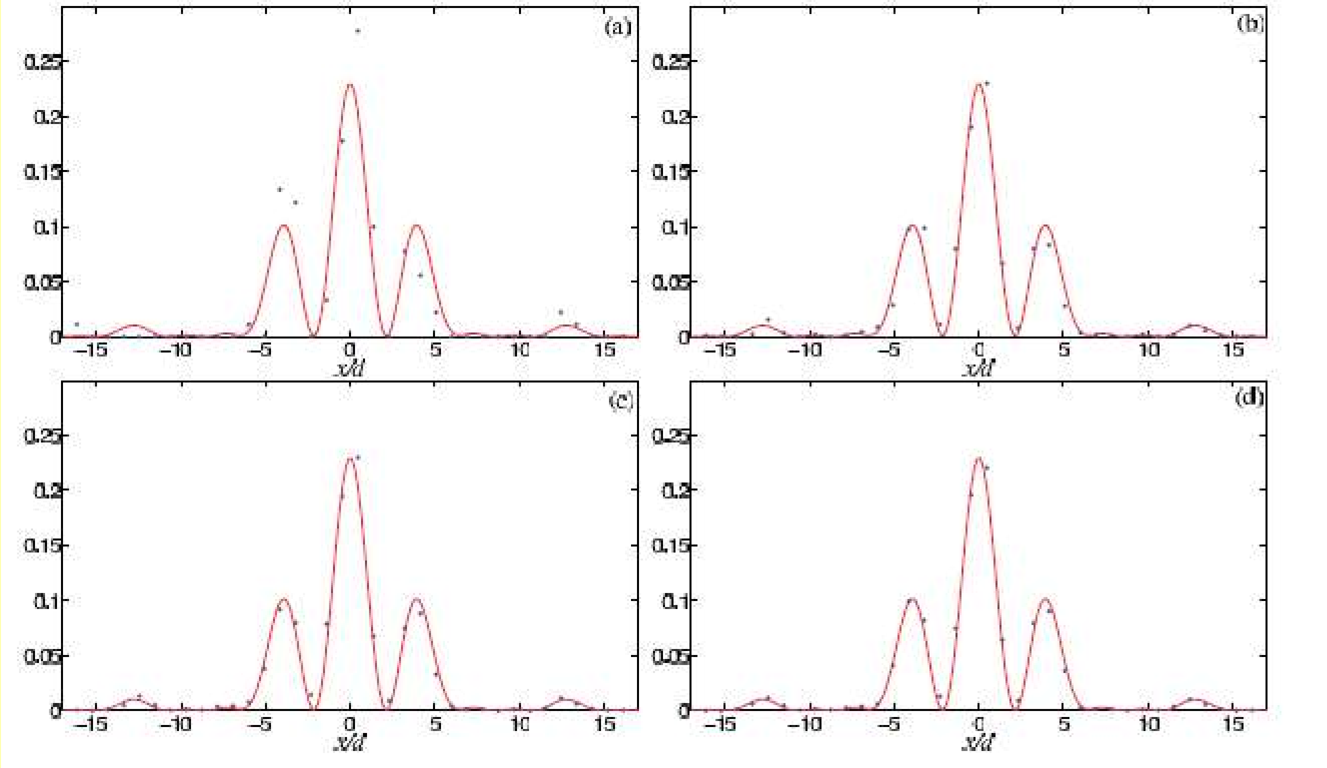
$$L_T = d^2/\lambda = 200\mu m \quad \lambda = 500 \quad nm \qquad d = 20\lambda = 10\mu m$$



Interference pattern in the near and far field for a quanton with mass.

Left: Appearance of the Talbot carpet within a certain space region as the number of slits increases: (a) N = 1, (b) N = 2, (c) N = 3, (d) N = 10, and (e) N = 50. Right: Quantum trajectories corresponding to the cases shown in the left panels. In all panels, the x distance is scaled in units of the grating period d, and z in units of twice the Talbot distance (2zT).

A. S. Sanz and S. Miret-Artes, A causal look into the quantum Talbot effect, The Journal of Chemical Physics 126, 234106 (2007)



Histogram of the number of trajectories ending at various points along the *x-axis at a distance y = 4.3L_T for four different values* of the total number of photons: (a) 100, (b) 1000, (c) 2000 and (d) 5000. Here diffraction is produced by a two-slit grating and the initial conditions (positions along the two slits) for the photon data are chosen at random. The red line is a plot of the function | psi(*x, y)*|2*. It is seen* that at the chosen distance *y = 4.3L_T, the maximum of the distribution at x/d = 8.6, associated with k?xd = 4 pi, is absent. This is* because for *N = 2, d = 2, the second interference maximum, being at k_xd = 4, coincides with the first diffraction minimum.*

M Davidović, A S Sanz, D Arsenović. M. Božić and S Miret-Artés, Phys. Scr. T135 (2009) 014009

Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer

Sacha Kocsis,[1,2]* Boris Braverman,[1]* Sylvain Ravets,[3]* Martin J. Stevens,[4] Richard P. Mirin,[4]
L. Krister Shalm,[1,5] Aephraim M. Steinberg[1]†

***Physics World* reveals its top 10 breakthroughs for 2011, Dec 16, 2011**
1st place: Shifting the morals of quantum measurement

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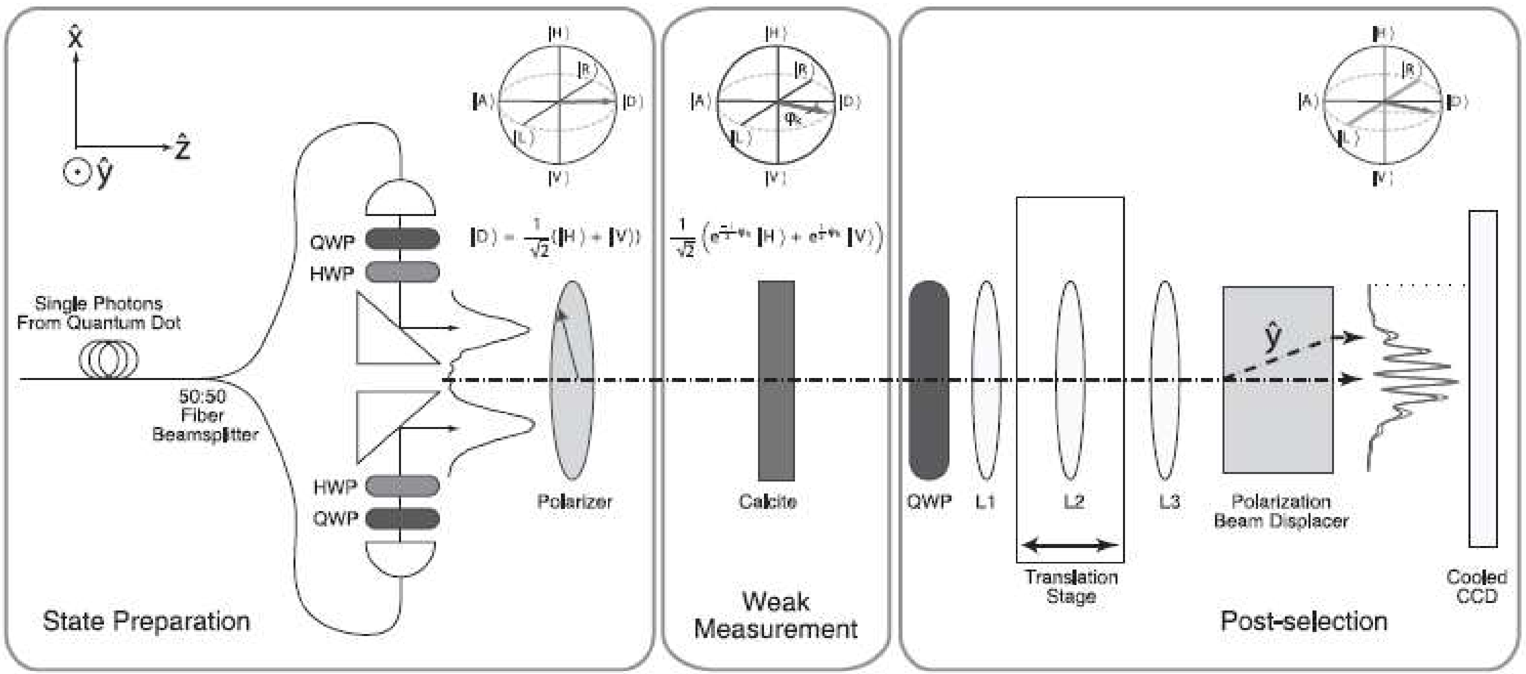
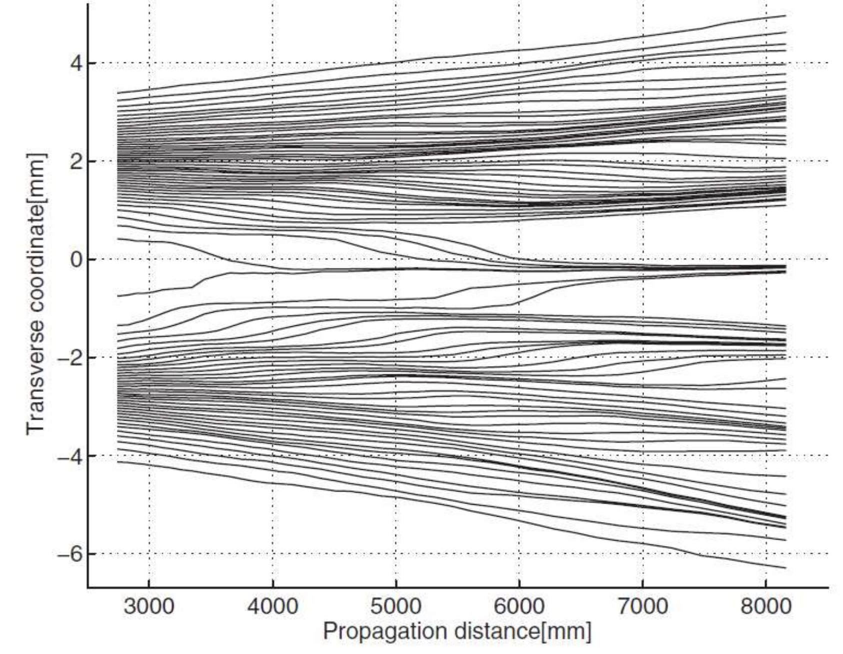
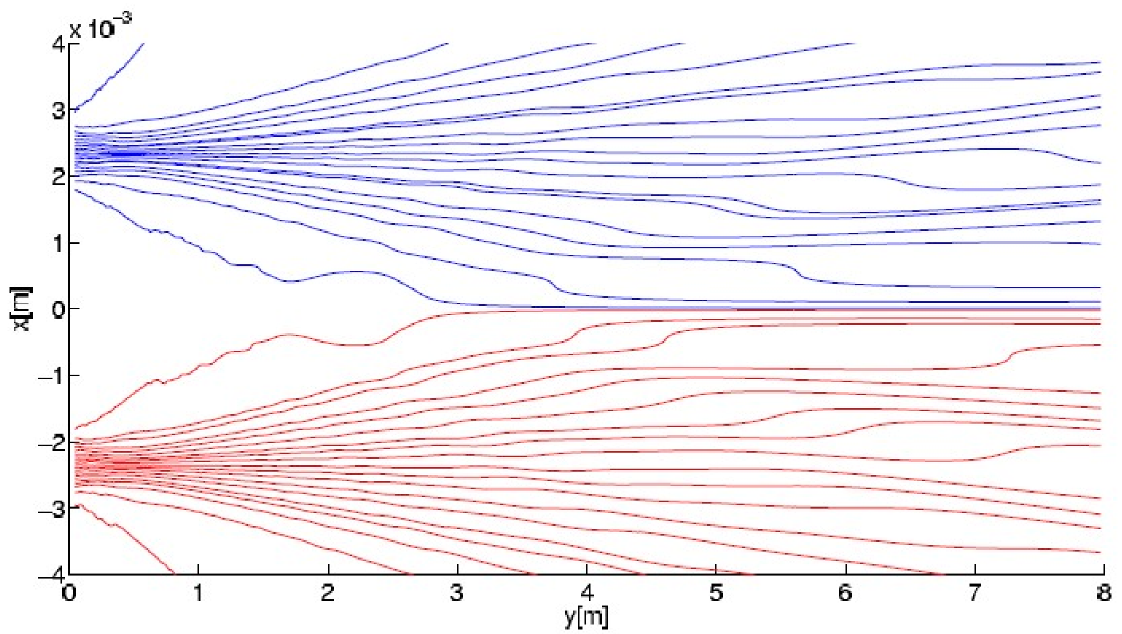


Fig. 1. Experimental setup for measuring the average photon trajectories. Single photons from an InGaAs quantum dot are split on a 50:50 beam splitter and then outcoupled from two collimated fiber couplers that act as double slits. A polarizer prepares the photons with a diagonal polarization $|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$. Quarter waveplates (QWP) and half waveplates (HWP) before the polarizer allow the number of photons passing through each slit to be varied. The weak measurement is performed by using a 0.7-mm-thick piece of calcite with its optic axis at 42° in the x-z plane that rotates the polarization state to $\frac{1}{\sqrt{2}}(e^{-i\varphi_k/2}|H\rangle + e^{i\varphi_k/2}|V\rangle)$. A QWP and a beam displacer are used to measure the polarization of the photons in the circular basis, allowing the weak momentum value k_x to be extracted. A cooled CCD measures the final x position of the photons. Lenses L1, L2, and L3 allow different imaging planes to be measured. The polarization states of the photons are represented on the Poincaré sphere, where the six compass points correspond to the polarization states $|H\rangle, |V\rangle, |D\rangle, |A\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle), |L\rangle = \frac{1}{\sqrt{2}}(|H\rangle + i|V\rangle)$, and $|R\rangle = \frac{1}{\sqrt{2}}(|H\rangle - i|V\rangle)$.

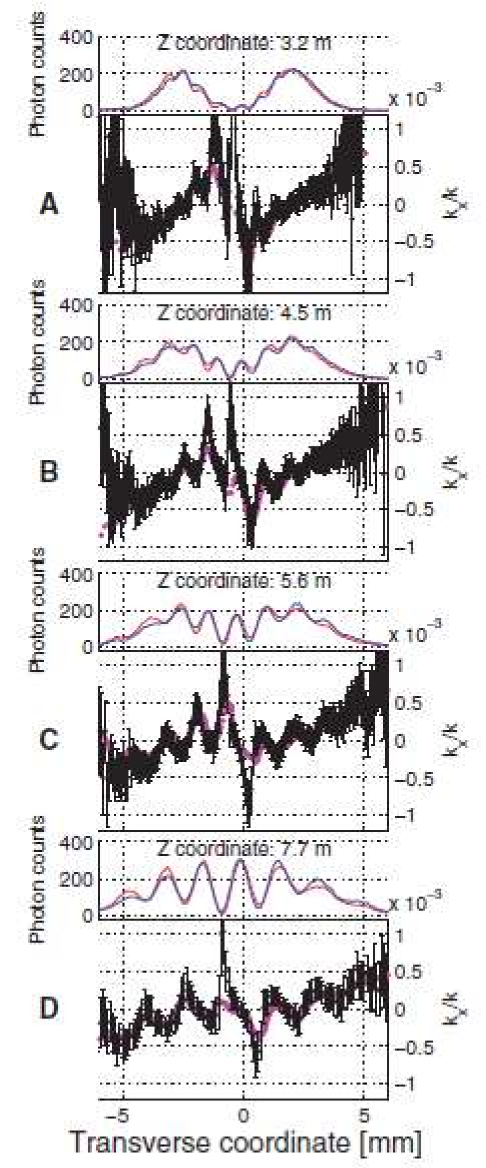


The reconstructed average trajectories of an ensemble of single photons in the double-slit apparatus. The trajectories are reconstructed over the range 2.75 m to 8.2m by using the momentum data from 41 imaging planes.

Photon **trajectories behind a two-slit Gaussian grating. The parameters are chosen as in the experiment carried out by Kocsis *et al:***



M. Davidovic *et. al.*
Phys. Scr. T153 (2013) 014015

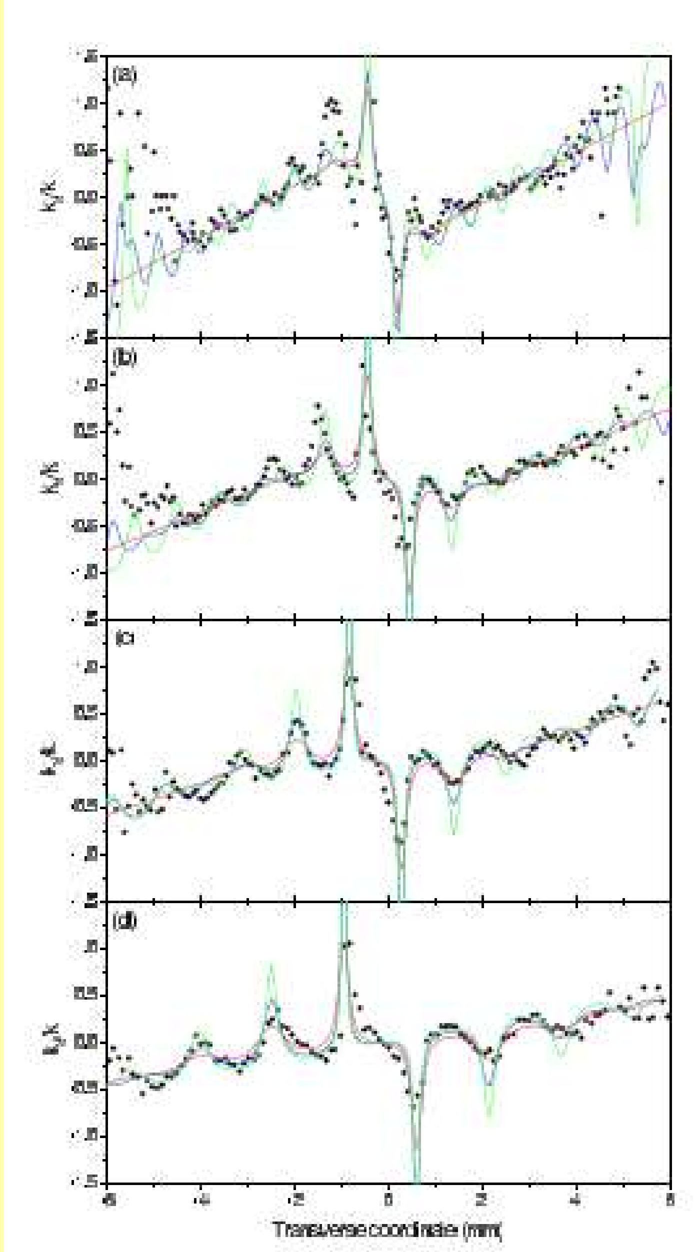


Comparison of our theoretical curves with experimental curves of Kocsis et al. for components of photon momentum.

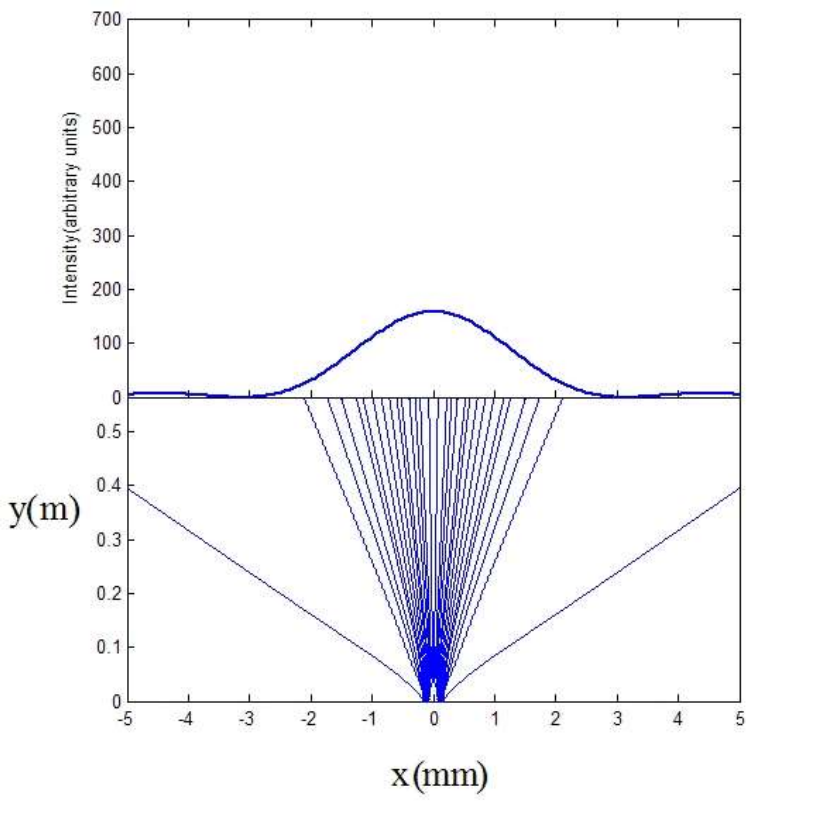
Transverse momentum along the transverse coordinate computed at several distances *y from the two slits: (a) y = 3:2 m, (b) y = 4:5 m, (c) y = 5:6 m, and (d) y = 7:7 m.*

The red line denotes the calculation with full Gaussians, with the blue and green lines refer to calculations where the outgoing beams were Gaussians truncated at *1,9σ and 1,5 σ*, respectively.

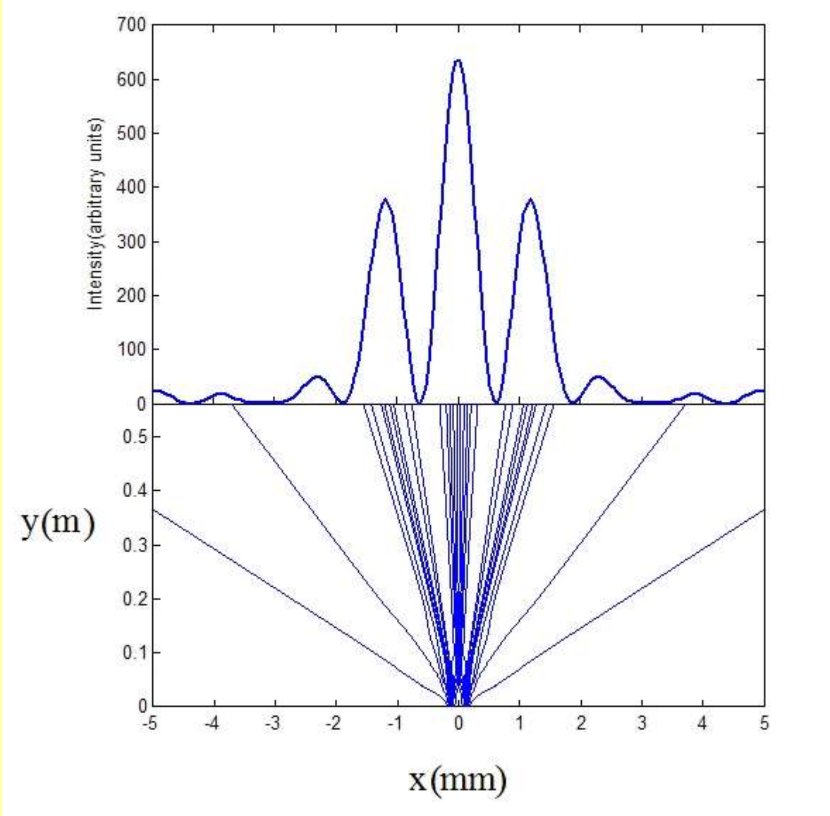
To compare with, the experimental data (black circles) extracted from Kocsis et al are also displayed.



Arago-Fresnel laws
about the interference of polarized light



Top: EME density at *L* = 558 mm from a double-slit grating with orthogonal polarizers upon the slits and illuminated by a circularly polarized laser beam of wavelength 532,5nm.
Bottom : 30 EME flow lines behind a double-slit grating.



Top: EME density at *L* = 558 mm from a double-slit grating illuminated by a circularly polarized laser beam of wavelength 532,5 nm.
Bottom: 30 EME flow lines behind a double-slit grating.

The slits are assumed to be completely transparent, with their support being completely absorbing. The distance between the center of the slits is *d* = 0.25 mm and the slit width is mm.

Poisson-Arago spot

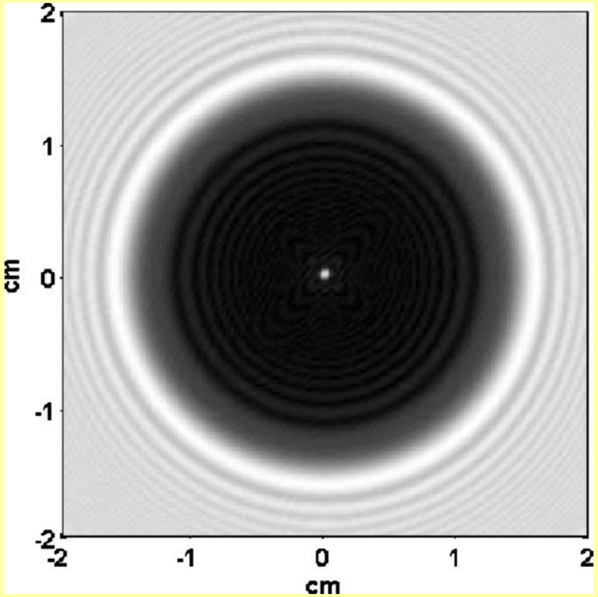


Fig. 4. Spot of Poisson–Arago—the intensity distribution behind a coin ($R=1$ cm) on a detector placed at 5 m. Newton, who carried out this experiment, did not report the presence of fringes within the shadow (Ref. 2). The radius of the spot is 0.1 mm and is just visible to the naked eye.

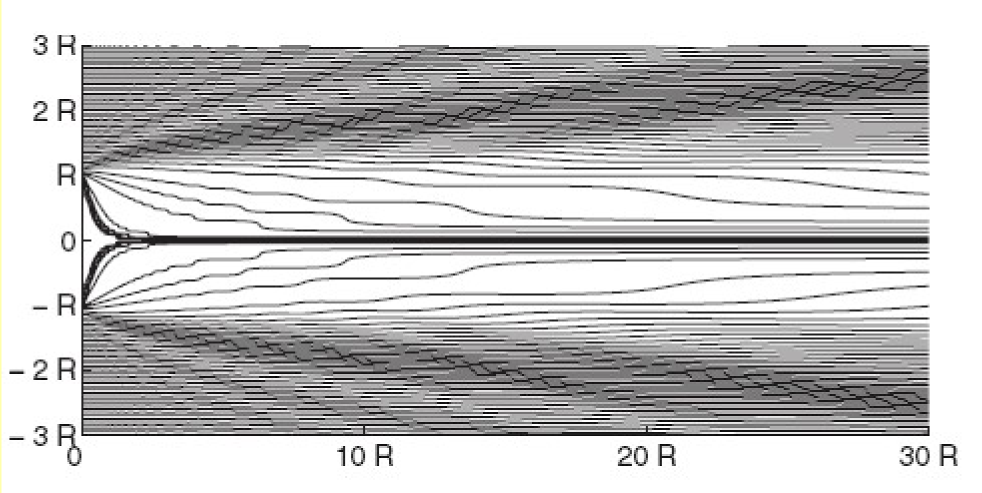
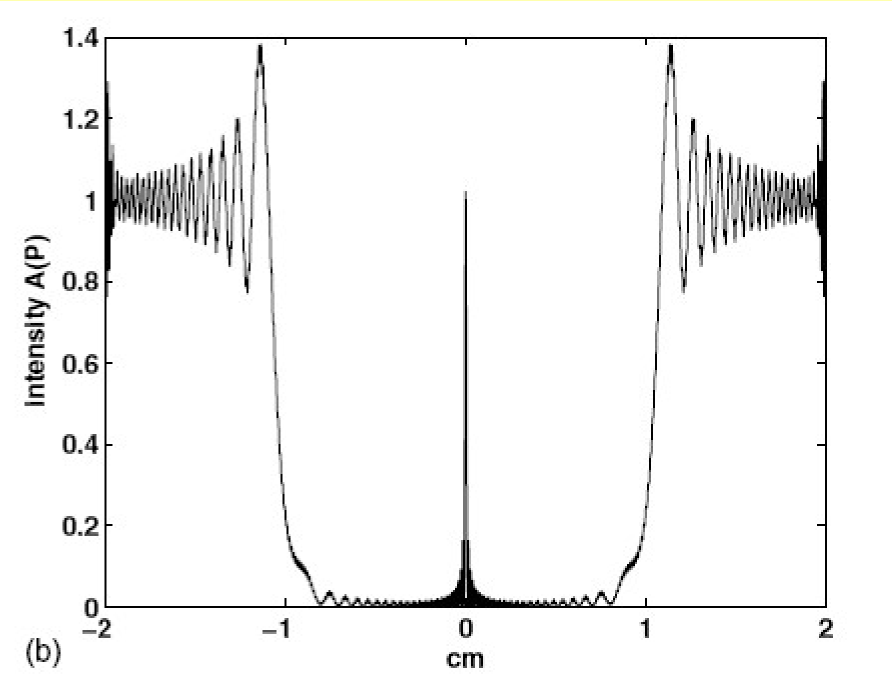


Fig. 6. Energy flow lines behind the circular opaque disk give an explanation of the bright spot of Poisson–Arago.



M. Gondran and A. Gondran, Am. J. Phys. 78 (2010) 598.
M Gondran and A Gondran, hal-00416055, version 1 – 11 Sep 2009

CONCLUSION

In describing, explaining and understanding quantum interference, more and more arguments and evidences have been accumulated supporting the usefulness of the notion of trajectories of quantons in addition to wave functions. The contribution of atomic interferometry is particularly valuable, because it is based on the coupling of the external and internal degrees of atoms' motion.

Thank you for your attention!