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1. Presence of a particle in the paths of an interferometer

Wave-particle duality in quantum mechanics results in the fact that a particle passes simultaneously through both arms of an interferometer. H Lemmel (Vienna University of Technology, Austria, and Institute Laue–Langevin, France) and his co-authors have performed a new experiment to clarify the physical meaning of this statement concerning individual particles (without statistical averaging) [1]. They used a Mach–Zehnder interferometer through which spin-polarized neutrons passed from a reactor at the Institut Laue–Langevin (Grenoble, France). A solenoid was placed in one of the interferometer paths, inducing a neutron spin rotation (introducing an additional phase to its wave function). Neutron paths interfered in a splitter, and, at the output, a second solenoid capable of compensating the phase shift was placed in front of one of the two detectors. The magnitude of the required compensation is indicative of the neutron path through the solenoid–containing interferometer arm. Thus, the neutron spin played the role of a trial qubit capable of performing weak quantum measurements characterizing the neutron path though a particular arm with retention of the interference pattern. The results of measurements were described in terms of the magnitude of neutron 'presence' in the arm. The concept of presence is based on studies by M Ozawa (2003) and M J W Hall (2004) devoted to quantum measurement accuracy (similar ideas were suggested by V B Braginsky and F Ya Khalili in 1992 [2]; see also [3]), and the above-mentioned phase compensation method was proposed by H F Hofmann (2021). The magnitudes of the neutron presence in the arms, differing because of splitter asymmetry, were measured for different magnitudes of spin rotation and different phase compensation angles. The main conclusion of this experiment, which is fully consistent with the standard interpretation of quantum mechanics, is the presence of a neutron as an individual object in the two interferometer arms at a time, even when the compensation method showed that the neutron was partly affected in one particular arm, namely, the one where a solenoid was placed. In other words, a complete neutron partially passes through each arm, depending on the magnitude of neutron presence in this arm.

2. Quantum calculations on a neutral atom array

Several approaches to creating quantum computers based on different types of quantum logic cells (qubits) are being developed at the present time. In one promising area, qubits are electron states of neutral atoms. M D Lukin (Harvard University, USA) and his colleagues have demonstrated quantum operations on a neutral atom array. In these experiments, the atoms could move in space to set new coherent connections between qubits [4]. ^{87}Rb atoms were trapped in a two-dimensional optical lattice, and quantum information was coded in hyperfine splitting levels. To perform one operation or another, part of the atom array was moved (using 'optical tweezers') to new positions, where the atoms interacted with other atoms. This quantum processor made it possible to realize cluster states and a seven-qubit Steane code state. A surface code state with thirteen data qubits and six ancillary qubits and a toric code state on a torus with sixteen data and eight ancillary qubits were realized. In addition, the quantum entanglement entropy was measured. An experiment with a neutral atom array in an optical grid was also performed by T M Graham (University of Wisconsin–Madison, USA) and his co-authors [5]. They obtained Greenberger–Horne–Zeilinger states with two to six qubits and demonstrated a phase estimation algorithm.

3. Hybrid system of a mechanical resonator and a qubit

Quantum properties of macroscopic mechanical objects have already been demonstrated in experiments. Of great interest is the use of mechanical degrees of freedom together with qubits in quantum calculations. The difficulty in the practical realization of such hybrid systems (a mechanical resonator + a qubit) lies in retaining a rather long coherence time of cubits and mechanical resonators when they are combined in a unit device. Y Chu (Swiss Federal Institute of Technology in Zurich) and her co-authors demonstrated a new hybrid system of a bulk acoustic wave resonator placed above a superconducting transmon qubit on a chip [6]. Acoustic oscillations were excited by a piezoelectric transducer. Vacuum Rabi oscillations between the qubit and phonon modes were observed. The system is characterized by a much longer coherence time than previous devices, which made it possible to reach the strong dispersion regime, when a

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considerable resonator and qubit frequency shift is observed. This allowed transferring the system to required Fock states with a definite number of phonons. One of the main achievements was phonon number parity measurement — only one measurement without the necessity of determining the phonon distribution. This is important, in particular, for error correction in quantum calculations, since a parity hop is a simple error indication. For quantum networks, see [7].

4. Keldysh crossover in a Mott insulator

Mott insulators are substances in which electrons in a partly filled zone are in the state of collective localization owing to strong Coulomb repulsion, which forms an energy gap and makes these substances dielectric. Metal–insulator transitions, nonlinear harmonic generation, and other interesting phenomena have been observed in a variable electric field in Mott insulators. As the Keldysh parameter exceeds unity, a doublon–holon pair production mechanism must change from tunneling to multiphoton absorption. Calculations by the Landau–Dykhne method [8] showed that this transition must be a crossover type, but this has not been observed earlier because of experimental difficulties. The problems were solved and the Keldysh crossover was registered for the first time in an experiment of X Li (California Institute of Technology, USA) and their co-authors [9]. Ultrafast broadband optical spectroscopy was used to examine the multizone Mott insulator Ca_2RuO_4, in which pair production may occur even in a weak 100-W-cm^{-1} field. Under a sub-100-fs laser pulse, the reflectivity fell sharply and then increased exponentially. For a photon pulse energy of 0.3 eV, with increasing field strength above 0.07 W A^{-1} the doublon–holon pair production rate went from a power-law dependence to a threshold type dependence, which is perfectly consistent with the Keldysh crossover theory.

5. Image of the black hole Sgr A*

In 2019, the Event Horizon Telescope, which is a global network of eight radio telescopes, was used to obtain an image of the supermassive black hole (BH) in galaxy M87, also referred to as a BH shadow [10]. On May 12, 2022, the Event Horizon Telescope Collaboration reported a new result, namely, the first image of the BH Sgr A* in the center of our Galaxy [11]. Sgr A* is 2000 times nearer than the BH in M87, but 1500 times less massive and, therefore, the angular dimensions of these BHs are approximately the same. However, observing the image of the BH in our Galaxy is much more difficult because of fast radio emission variations due to a small BH radius. Moreover, on the line of sight in the direction of Sgr A*, a turbulent plasma exists in the Galaxy, smearing the image at long wavelengths. In this connection, more time and computational resources were needed to obtain the Sgr A* image. The BH shadow occurs owing to the gravitational lensing effect, i.e., a light beam declination in the BH gravitational field. The light sources in the two observed cases were bright regions of accretion discs. Because of different disc inclinations, the Sgr A* image looks somewhat different from M87 — along with the bright ring surrounding the shadow, three bright spots are observed. The observation of the Sgr A* shadow made it possible to test and constrain the parameters of some alternative gravitation theories [12]. It was shown that the Sgr A* shadow characteristics are in excellent agreement with the predictions of Einstein's General Relativity.

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