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1. Mass distribution inside the proton

It is mainly quarks that are responsible for the electric charge and spin distribution inside the proton. On the contrary, mass distribution inside the proton is mainly determined by gluons — their color interaction — because the sum of masses of quarks alone is much less than the proton mass. The character of mass distribution inside the proton is also called the gravitational form factor, because the mass determines the gravitational interaction. Gluons do not carry charge and cannot, therefore, be examined directly by electron scattering. However, a method [1] has been recently proposed which allows finding mass distribution through measuring the differential cross section of meson J/ψ photoproduction near the threshold. This method can be figuratively represented as proton probing by a color dipole. With its help, the gravitational proton form factor was determined for the first time at the Jefferson Lab [2]. Liquid hydrogen was illuminated with a bremsstrahlung beam, the photon scattering by protons gave rise to short-lived mesons J/ψ, and the energy spectrum of the e^+e^- pairs produced upon their decay was measured. The determined proton mass radius turned out to be much smaller than its charge radius [3]. Moreover, experimentally determined was the trace anomaly of the proton energy-momentum tensor, which carries valuable information about quark-gluon interactions.

2. Search for coherent scattering of dark matter particles by nuclei

The nature of dark matter (DM) in the Universe has not yet been clarified. It is often assumed to consist of new elementary particles. Since the search for weakly interacting massive DM particles (WIMPs) has not yet yielded results, the search for lighter particles of masses below GeV, which could not be registered by detectors designed to search for WIMPs, is topical. For light particles, their coherent scattering by atomic nuclei becomes possible when a particle interacts with the whole nucleus and not with individual nucleons inside the nucleus. A coherent interaction of neutrinos with nuclei has already been detected in the COHERENT experiment at the Oak Ridge National Laboratory (USA). In the new experiment of the COHERENT collaboration [4], a search was made for the coherent interaction of DM particles with masses of 1 to 220 MeV, presumably produced at an accelerator, with atomic nuclei of the detector. A CsI[Na] scintillator detector weighing 14.6 kg, sensitive to a nucleus recoil energy $\geqslant 9$ keV, was used. The search for coherent interactions of DM particles has not yet yielded results, but new limits on the properties of particles have been obtained. In the mass range of 20–33 MeV, these restrictions are already overlapped by those following from cosmology.

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3. Diffraction by time slits

In Young's famous experiment, light was diffracted as it passed through two slits, and the spatial interference pattern was observed on a screen behind the slits. However, as far back as 1952, M Moshinsky pointed out that interference is also possible in the Fourier space. If a signal occupying a certain frequency band passes through two time-separated 'windows,' oscillations will appear in its frequency spectrum. R Tirole (Imperial College London, Great Britain) and his co-authors have demonstrated this effect for the first time for electromagnetic radiation in the optical range [5]. To create time slits, a thin layer of indium tin oxide (ITO) on a glass substrate was used. It was exposed to two pumping light pulses with a frequency close to a zero dielectric constant (227 THz) at an interval of 225 fs. Under their influence, the layer reflection coefficient changed from the usual value of 0.08 to 0.6. The reflection of light with a frequency of 230.2 THz, bandwidth of 1 THz, and duration of 794 fs overlapping two time slits was examined. In the frequency spectrum of reflected light, which played the role of a screen, up to six oscillations appeared, corresponding to interference. The optical properties of the ITO layer were found to vary much faster than was believed earlier, within 1 to 10 fs. This provides new perspectives for ultrafast optical signal processing.

4. Nonlocal quantum interference without quantum entanglement

Nonlocal quantum interference between spatially separated systems is usually assumed to require quantum entanglement of these systems. K Qian and colleagues (Nanjing University, China) have demonstrated for the first time that this condition is not necessary [6]. Their experiment is based on the use of photons undetected in the experiment but, in principle, detectable. Used in the experiment were a source of photons, nonlinear crystals, a photo-splitter, detectors, and several auxiliary elements. The nonlocal interference of three photons was obtained by adjusting the phase of the fourth undetectable photon, which is a part of the complete quantum system. This phenomenon can find application in photonic quantum computers [7].

5. Ferroelectricity in a simple substance

The phenomenon of ferroelectricity (spontaneous polarization in the absence of an external electric field) exists in substances consisting of two or more different elements. It is due to a relative displacement of charges in different atoms. J Gou (National University of Singapore) and his co-authors have discovered ferroelectricity in a simple substance consisting of atoms of only one element [8]. A thin bismuth layer on a graphite substrate resembles in its properties black phosphor in an anisotropic α phase. Bismuth atoms in a lattice could be in one of two states with a different configuration of chemical bonds. When atoms in one state were displaced relative to atoms in the other state, charge redistribution occurred, and polarization appeared in the sample plane. Thus, two states of identical atoms imitated the presence of two elements. The tip of a scanning tunnel microscope was used to generate an electric field in the sample plane, which induced switching of ferroelectric properties. Given this, the motion of domain walls between regions with different polarizations was observed.

6. Vortices in the superconducting diode effect

Some substances have recently demonstrated a superconducting diode effect, when the critical current depends on the direction determined by the external magnetic field, but a reliable theoretical explanation of this effect has not been given. The asymmetric dynamics of superconducting vortices, obviously responsible for the diode asymmetry, was observed by A Gutfreund (Hebrew University in Jerusalem) and his co-authors in their new experiment on an Nb/EuS bilayer (superconductor/ferromagnetic) in a magnetic field [9]. The measurements were carried out using a superconducting contact (SQUID) fixed at the microscope tip, and the Nb/EuS bilayer was a bar in the configuration commonly employed to observe the Hall effect. The flow of vortices in the bar was observed both by direct local measurements and by the macroscopic characteristics of the sample. On the basis of these measurements, a model of the superconducting diode effect was constructed, which explains it in terms of vortex dynamics and does not require the occurrence of Fulde-Ferrell–Larkin–Ovchinnikov states, as was assumed in some models.

7. Generalization of the Monin–Obukhov theory

The self-similar theory of atmospheric turbulence, proposed by Monin and Obukhov in 1954 in [10], is widely employed in calculations of various atmospheric phenomena. The applicability of the theory, especially in mountainous areas, is limited to the assumption of a horizontally homogeneous atmosphere. On the basis of a large amount of empirical data, I Stiperski (Innsbruck University, Austria) and M Calaf (University of Utah, USA) have proposed a generalization of the Monin–Obukhov theory [11] with the addition of anisotropic terms allowing for terrain nonuniformities. The fitting of the data from 13 arrays of atmospheric turbulence observations carried out in regions with different reliefs made it possible to determine the model parameters and present the resultant relations convenient for calculations. Using them, one can calculate the transfer of momentum, heat, and impurities in the atmosphere for different terrains. For the impact of atmospheric turbulence on optical observations, see [12].

8. Turbulence in a Bose–Einstein condensate

Turbulence that emerges in many processes can also appear in a Bose-Einstein condensate driven out of equilibrium. As distinct from hydrodynamic turbulence, in this case we are dealing with wave turbulence due to the interaction of a chaotic set of waves on different scales. Y Zhu (Université Côte d'Azur, France) and their co-authors from France and Russia have studied turbulence in a Bose–Einstein condensate theoretically and with numerical experiments [13]. Their model is based on the kinetic wave equation derived in [14] and applied to describe Bose stars and axion miniclusters. An unusual property of turbulence in Bose–Einstein condensate is not only the presence of a direct energy flow from large to small scales but also an inverse flow. For a high-resolution numerical simulation, the Gross–Pitaevskii model was applied and good agreement with the theory was obtained. The constructed turbulence model successfully describes the available experimental data, including an explanation of the observed spectrum exponent $k^{-3.5}$ by means of logarithmic corrections.

9. Dark matter density peaks around black holes?

According to theoretical calculations, dark matter (DM) condensation and density peaks can occur around black holes (BHs). The peak structure depends on the history of BH formation and the surrounding conditions. Having analyzed data on the motion of two X-ray binary systems A0620-00 and XTE J1118 + 480, researchers from the Education University of Hong Kong (China), M H Chan and C M Lee, have obtained indirect evidence of the presence of DM peaks [15]. Each system is a bound pair of a BH of stellar mass and a low-mass star. The orbital period of these systems slows down anomalously fast ($\dot{P} \sim -1$ ms yr^{-1}) — two orders of magnitude more than due to gravitational radiation losses. The interaction of the stellar wind with the magnetic field and the tidal interaction with an extensive gas disk were discussed, but the high deceleration rate cannot be explained in the framework of these mechanisms. As a new explanation, M H Chan and C M Lee considered the hypothesis of interaction between a star and the DM density peak around a BH by way of dynamic friction and showed that this mechanism can explain observational data. Agreement between the theory and observations is best when the power-law profile of DM density has an exponent of 1.7–1.85, which could have appeared under the effect of a process analogous to stellar heating [16]. Thus, the orbital motion deceleration in binary systems can be a new indirect method for observing DM.

10. Dark matter cusp in the Small Magellanic Cloud

One of the unsolved cosmological problems is the 'cusp–core.' An extensive region with a constant DM density (a core) is observed in the center of many dwarf galaxies, whereas the numerical simulation of galaxy formation predicts a power-law growth towards the center (cusp). A possible solution to this contradiction is cusp destruction by supernova explosions or other baryon processes. M de Leo (Catholic University of Chile, Millenium Institute of Astrophysics, Chile, and University of Surrey, Great Britain) and his co-authors assumed that a DM cusp could be preserved in the center of the Small Magellanic Cloud (SMC) — a dwarf satellite of our Galaxy [17]. To search for it, researchers developed an algorithm to clean the image from the substance thrown out by tidal forces and not related gravitationally to the SMC. Spectroscopic data for ~ 6000 stars were used that made it possible to find radial velocities together with data on their proper motions, obtained by the Gaia telescope. As was shown by dynamic modelling based on Jeans equations, the density distribution in the SMC center does agree with the presence of a cusp down to 400 pc from the center, the DM density within 150 pc being $3 \times 10^8 M_\odot$ kpc^{-3}. Such a high DM density indicates that, in this case, the cusp did not have enough time to transform into a core. This makes the SMC a promising object for DM annihilation searches.

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