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1. Study of neutrino oscillations in the NOvA experiment

The effect of neutrino oscillations (transformation of some neutrino sorts to others) was reliably confirmed in experiments, but it was necessary to specify the parameters which describe oscillations and are fairly important for understanding some processes in astrophysics and cosmology [1, 2]. The NOvA collaboration presented new results of the study of neutrino oscillations by the data collected during 10 years [3]. In the Fermilab (USA), a neutrino beam is generated in processes of proton collision with a graphite target and a subsequent decay of secondary hadrons. Located at distances of 1 km and 810 km are neutrino detectors displaced from the beam axis. This makes it possible to measure the probability of neutrino oscillations $\nu_\mu \rightarrow \nu_e$ on their way between the detectors. The data level twice as large as before was processed, and improved methods of simulation and analysis were applied. As a result, the most precise value to date was obtained: $\Delta m_{32}^2 = 2.431^{+0.036}_{-0.034} \times 10^{-3} \text{ eV}^2$ (if direct mass ordering takes place) and $\Delta m_{32}^2 = -2.479^{+0.036}_{-0.036} \times 10^{-3} \text{ eV}^2$ (if inverse). Moreover, the direct ordering is 2.4 times more probable than the inverse one. In both cases, the region close to the maximum mixing with an angle of $\sin^2 \theta_{23} = 0.55^{+0.02}_{-0.06}$ is preferable. Together with the data presented by other experiments, the obtained results bring us closer to unraveling the mechanism of neutrino oscillations and clarify the processes involving them.

2. Quantum entanglement of atoms with respect to their state of motion

Quantum entanglement may concern different degrees of freedom of quantum systems, but only the spin entanglement of particles was typically examined experimentally. Only in the case of photons have Bell's inequalities been tested with respect to the states of motion (momenta), and for massive particles such experiments have not been carried out before. Y.S. Athreya (Australian National University) and their co-authors were the first to verify Bell's inequalities for momenta of metastable helium atoms $^4\text{He}^*$ [4]. The use of $^4\text{He}^*$ for this purpose was proposed in the paper by Lewis-Swan R J,

Kheruntsyan K V *Phys. Rev. A* **91** 052114 (2015). The high internal energy of $^4\text{He}^*$ provides an accurate detection of individual atoms with high spatial and temporal resolution. In the experiment of Y.S. Athreya et al., in collision of two Bose–Einstein condensates of $^4\text{He}^*$ atoms, pairs of atoms with opposite momenta were formed and correlations of atoms were measured after they passed through a Rarity–Tapster interferometer. Testing Bell's inequalities yielded a direct evidence of a nonlocal quantum nature of the two-atom system. The study of entanglement of massive particles by the state of motion is important, in particular, for investigation of quantum-gravitational properties of particles moving in the gravitational field.

3. Macroscale structural superlubricity

Superlubricity of solids, i.e., an almost frictionless sliding was only known at micro- and nanoscales. Attempts were made to lower friction of macroscopic objects through creation of multicontact sites on their surface with a large number of microscopic bulges, but the friction coefficient was thus only reduced to $\sim 10^{-3}$, which is three orders of magnitude larger than for superlubricity. Q. Zheng (Tsinghua University, China) and his colleagues were the first to discover a real effect of superlubricity at macroscale within the limits of one submillimeter contact between graphite samples and at the graphite/MoS₂ interface [5]. The authors developed a new method of manufacturing almost effect-free, atomically smooth single-crystal surfaces through epitaxial growth of single-crystal graphite (carbon diffusion through nickel) and photolithography. The measured friction coefficients of 0.02–0.02-mm samples reached values of $\sim 10^{-6}$ in a broad load range from 1 mN to 0.5 N. Negative differential friction factors were also observed, when the friction force decreases with increasing load. Possibly, the suppression of out-of-plane motion of edge atoms or moire protrusions, or edge separation may take place here. The superlubricity effect may appear to be useful in the creation of various micromechanical devices.

4. Pomeranchuk effect for electron subsystems in a polymer

In 1950, I.Ya. Pomeranchuk predicted theoretically that near the solidification point ultracold liquid ^3He can be additionally cooled by compression [6]. Later on, this compression method of cooling was realized in practice [7]. This effect is explained by a higher entropy of solid ^3He at low temperatures compared to the entropy of liquid ^3He . The Pomeranchuk effect in ^3He must be affected by magnetic fields through degrees of freedom associated with nuclear spins. However, in

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experiments with ^3He this influence has not been reliably detected. An analogue of the Pomeranchuk effect was also observed for electron degrees of freedom in some systems. Using hybridization of orbitals of organic molecules with orbitals of inorganic elements in polymers $(\text{DMe-DCNQI})_2\text{-Cu}$, N Matsuyama (University of Tokyo, Japan) and their co-authors [8] discovered the Pomeranchuk effect in the electron subsystem of this polymer and examined the influence of the magnetic field on it. It turns out easier to observe the effect of the magnetic field for such systems than for ^3He because of the high value of Bohr magneton for electrons, the metal–insulator transition being an analogue of the liquid–solid transition. In their experiment, N. Matsuyama et al. observed electron ‘solidification’ (localization) induced by the magnetic field. This suggests suppression of the Pomeranchuk effect in magnetic fields.

5. The detection of dark matter subhalo by pulsar timing

In the hierarchical picture, galaxies are formed in the course of merging of less massive galaxies and capturing a diffuse medium. In particular, the structure of the halo of our Galaxy should still contain captured massive dark matter substructures that did not have time to settle towards the center of the Galaxy and destroy. S. Chakrabarty (University of Alabama, USA) and their co-authors were the first to detect one of these subhalos by the influence of its gravitational field on the orbital velocity in binary systems containing pulsars [9]. Owing to high stability of neutron star rotation, the pulsar timing method, proposed by M.V. Sazhin in 1978 in application to gravitational wave recording, is a sensitive instrument for recording extremely weak effects [10, 11]. Five pairs of binary systems showing an additional change in the orbital period were singled out in [9]. Among them, a pair of systems was found showing the existence of subhalo with the signal-to-noise ratio $S/N \sim 3$ (for others, $S/N \leq 1$). Both systems are pairs of a neutron star and a white dwarf. Observing one system, one cannot distinguish between contributions of mass and distance (M/R^2), but several binary systems already suggest a conclusion about the existence of a subhalo. This was how the presence of an object of mass $2.45_{-0.96}^{+1.07} \times 10^7 M_\odot$ at a distance of ~ 0.9 kpc from the Sun was found. The presence of such a subhalo is consistent with the theoretical calculations of Galaxy formation. The discovered object is of nonbaryonic origin because the mass of gas and stars in it is by two orders of magnitude less than the indicated value. The observations do not yet allow determining the size of the object, and therefore it may be either a dark matter substructure or a supermassive black hole.

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