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1. New constraints on parameters of sterile neutrinos

It is still unknown what the hidden mass of the Universe consists of, but one of the well theoretically motivated versions is sterile neutrinos ν_s with masses of the order of keV [1, 2]. Researchers from IKI RAS, INR RAS, and MIPT undertook a new search for the decay path of ν_s in data from the X-ray NuSTAR space telescope from 11 years of observations [3]. Photons were selected that had come from angles of several degrees from the telescope optical axis (such illumination is called 'stray light') in the energy range of 3 to 20 keV and directions $> 3^\circ$ from the galactic plane, where the contribution of astrophysical disc objects is small. The radiation spectrum turned out to be approximately exponential, and an additional maximum corresponding to ν_s decays was not revealed. This made it possible to obtain new rigid constrains on the mixing angle of ν_s and the width of their decay. Although there still remains a small region of admissible parameters, constraints have already approached closely to closing the simplest models of ν_s as the main component of dark matter.

2. Joint analysis of neutrino oscillation data

While some neutrino oscillation parameters have already been measured rather precisely, others still remain uncertain. The T2K and Super-Kamiokande collaborations have jointly analyzed their data in the common range of measured neutrino energies [4]. In the T2K (Tokai-to-Kamioka) experiment, neutrinos from the accelerator are recorded in the near detector and in the far one (at a distance of 295 km), which is the Super-Kamiokande detector. The squared mass differences measured by T2K (depending on ordering) and the mixing angle δ_{CP}, responsible for CP violation, make a similar contribution to the asymmetry of neutrino and antineutrino oscillations, which is responsible for the degeneracy. But this degeneracy can be broken with allowance for the Super-Kamiokande data for atmospheric neutrinos that passed through Earth and experienced resonant amplification of oscillations. A similar complementary analysis of T2K and Super-Kamiokande showed that the CP invariance conservation in neutrino oscillations is excluded at a level of 1.9σ and the inverse order of masses is excluded at 1.2σ. The main error in the result is due to the uncertainty in the hadron production models.

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3. Landau–Zener tunneling in an open system

The tunneling theory formulated independently by L.D. Landau and S. Zener in 1932 describes transitions between quantum energy levels, which, under external parameter (e.g., magnetic field) variation, first converge to a minimal gap distance Δ and then diverge. This type of energy spectrum is realized in many physical systems. The tunneling regime is called weak or strong, depending on the ratio of the characteristic noise energy, generated by the surroundings, to Δ. X. Dai (University of Waterloo, Canada) and his coauthors have performed an experiment with a superconducting tunable qubit, where a transition from weak to strong Landau–Zener tunneling was demonstrated and a nonmonotonic behavior of the tunneling rate predicted theoretically was revealed for the first time [5]. The authors worked out a theoretical model of 'spin bath' qualitatively reproducing their experimental results.

4. Nonstandard quantum statistics

As a rule, particles obey Fermi–Dirac or Bose–Einstein quantum statistics and, accordingly, are called fermions or bosons. An exception is enion statistics of quasiparticles in some two-dimensional systems. In their theoretical work [6], Z. Wang and K.R.A. Hazzard (Rice University, USA and Max Planck Institute of Quantum Optics, Germany) have shown that, for identical quasiparticles, the fourth version of quantum statistics (parastatistics) is possible for any number of measurements, which is in a sense intermediate between fermion and boson statistics, but not, however, reducible to either of them. In this case, an interchange of two particles makes the wavefunction undergo a more complex transformation than merely a change of sign. The hypothesized possibility of parastatistics was considered as far back as 1953, but then parastatistics was thought of as equivalent to the fermion or boson statistics. In paper [6], the rules of secondary quantization of paraparticles were formulated, a generalized exclusion principle was derived, and nontrivial thermodynamic properties of paraparticle systems were pointed out. Possibly, the quasiparticles that obey the rules of parastatistics can be identified in solid state physics, but such properties can also be inherent in now unknown elementary particles.

5. Fractional quantum Hall effect

In the case of the fractional quantum Hall effect observed in two-dimensional electron systems, quasiparticles only carry a part of a unit electric charge. It was predicted that, in layered systems, interlayer excitons (bound states of electrons and holes) can be fermions or enions due to pairing between the components carrying fractional charges, but this effect has never been demonstrated experimentally. N.J. Zhang (Brown University, USA) et al. have become the first to perform a corresponding experiment to discover new interesting properties of excitons [7]. Two graphene layers in Corbino geometry, separated by hexagonal boron nitride, were included in independent electric circuits, and a condensate of interlayer excitons appeared in a strong magnetic field. Two classes of states of the fractional quantum Hall effect with nonintegral occupation numbers were revealed, namely, a fractional analog of exciton condensates and a two-layer generalization of fermion Jane states. Their properties are explained by the presence of exciton quasiparticles with fractional statistics, called 'fractional excitons.'

6. Long-lived quantum Schrödinger cat state (SCS)

Coherent states such as the quantum entanglement state or SCS are of great interest for quantum information devices, quantum metrology, and fundamental research, including the search for effects beyond the Standard Model [8, 9]. However, the common problem of nonclassical states is decoherence leading to their short lifetime. In their experiment with the ^{173}Yb atom in an optical lattice, Y.A. Yang (University of Science and Technology of China) et al. have managed to reach a record large SCS coherence time of $\simeq 1.4 \times 10^3$ s [10]. The SCS was realized on two oppositely directed nucleus spins with projections $m = +5/2$ and $m = -5/2$. The necessary nonlinearity was due to the effect of Stark shift. With the help of a special sequence of laser pulses, the system was brought to the region of Hilbert state space, where the influence of noise is very weak. Ramsay interferometry showed that in this region the indicated SCS with $m = \pm 5/2$ is long-lived.

7. Spectroscopy of nuclear quadrupole resonance of individual nuclei

Spectroscopy of nuclear quadrupole resonance based on recording the interaction between the electric quadrupole moment of nuclei and electric field gradients is being widely used in practice to reveal and identify various substances. But earlier this method helped to detect only resonance from large macroscopic ensembles of nuclei. S.A. Breitweiser (University of Pennsylvania, USA) and his co-authors have become the first to demonstrate the method of nuclear quadrupole resonance for singe nitrogen nuclei in nitrogen-substituted vacancies in diamond (in NV centers) [11]. The experiment was performed at room temperature by the method of dynamic-decoupling spectroscopy. The NV centers served there as quantum sensors and studied systems. The measurements revealed significant differences in quadrupole and hyperfine parameters between different NV centers, as well as a yet unknown term in the Hamiltonian of NV centers, which arose as a result of symmetry breaking. The developed method can be applied to create hypersensitive nuclear sensors.

8. Icelike shells around nanoparticles in water

In 2010, A.F. Bunkin and S.M. Pershin (IGP RAS) revealed the existence of an icelike structure of water molecules around large protein molecules in a water solution. In the new experiment [12], the measurement of the shift of the 'gravitational center' of the Raman OH band as well as Mandelstam–Brillouin resonances has shown the formation of an icelike structure around quartz nanoparticles in a water suspension at room temperature. A laser beam was directed to the suspension located in a quartz cuvette. The scattered radiation was recorded by a Raman spectrometer and Fabry–Perot interferometer. An OH-band shift towards the ice component was revealed and the known water line with a shift of 7.5 GHz and a new line of 14.3 GHz were observed in the spectrum. The latter shift of the line of the Stokes component gives a velocity of sound of ~ 2900 m s^{-1} in the medium around nanoparticles. This value is much larger than the velocity of sound in water and is close to the velocity of sound in ice, which confirms the formation of icelike hydrate shells around quartz nanoparticles. This study, as a continuation of a series of studies by the winners of a competition of scientific papers of RAS, performed jointly with NAS of Belarus, is of importance, in particular, for cryogen biotechnologies.

9. Localization of fast radio burst (FRB) source

The mechanism of generation of millisecond cosmic radio pulses coming from intergalactic distances is not yet clear. According to one of the theories, such FRBs occur near magnetars — neutron stars with strong magnetic fields [13]. But it remained unclear how far the region of radio emission generation is from the compact stellar remnant. K. Nimmo (Massachusetts Institute of Technology, USA) and her coauthors have managed to localize this region by observing scintillations of FRB 20221022A10 [14]. Scintillations occur upon radiation scattering by stochastic inhomogeneities of space on the line of sight. In the 20221022A10 spectrum, obtained with the CHIME telescope, two scintillation regions were revealed: one in the FRB galaxy and the other in our Galaxy. The position of these regions and the constraints on the electron number density indicate that the size of the generation region is $\leqslant 3 \times 10^4$ km, and it is located within the magnetosphere or near its boundary. This excludes nonmagnetospheric models of FRB generation at a large distance from the compact object, for example, in a propagating shock wave. In 2024, R. Mckinven et al. arrived at a similar conclusion for FRB 20221022A10 from the observation of changes in the radiation polarization angle.

10. Evolution of dark energy (DE)

Inhomogeneities in the distribution of galaxies (large-scale structure of the Universe) contain valuable information on the spectrum of initial perturbations and the Universe's composition determining the dynamics of its expansion [15]. Furthermore, data on the inhomogeneities can be used to verify the gravitation theory for seeking differences from Einstein's General Theory of Relativity (GTR) [16–18]. The DESI (Dark Energy Spectroscopic Instrument) project is aimed at investigating clusterization of galaxies and quasars, as well as lines Ly_α in the quasar spectra using specially configurated surveillance telescopes. The DESI collaboration has presented new results from five years of observations [19]. They contain the spectra and correlation functions of 40 mln galaxies and quasars at $0 < z < 4$ and the measured position of the peak corresponding to baryon acoustic oscillations. The obtained value of the Hubble constant is close to the results of Planck satellite measurements, and the restriction on the sum of neutrino masses has the form $\sum m_\nu < 0.071$ eV. With the existing precision, all the data agree with GTR predictions. An interesting new result is that the parameter of the equation of the DE state probably differs from -1 (at the present time $w = -0.761 \pm 0.065$) and increases with the expansion of the Universe. Then, the DE density can evolve with time and is not a cosmological constant (for DE, see [20, 21]).

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