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1. Search for hidden sector particles

Elementary particle physics possibly contains a so-called hidden sector with particles not yet accessible for experimental detection. Its existence is evidenced by the presence of dark matter (hidden mass) in the Universe, possibly consisting of a new class of particles. In the CERN experiment NA64, Yu M Andreev and his colleagues undertook a new search for vector bosons of the hidden sector Z' capable of explaining the problem of the muon anomalous magnetic moment and the birth of dark matter particles [1]. A muon beam from the accelerator collided with a nuclear target, and the signal from scattered particles in the calorimeter was measured. The lack of energy in the calorimeter would indicate the birth of hidden sector particles. After processing the data on $\sim 2 \times 10^{10}$ events at the achieved level of accuracy, no lost energy was recorded. This gave new limits on the characteristics of Z'. If Z' is responsible for the muon anomaly, its mass must lie in the range of 6–40 MeV, and the coupling constant will be $g_{Z'} < 6 \times 10^{-4}$. New limits on possible parameters of dark matter particles — products of Z' decay — were obtained.

2. Gallium anomaly

The measured rate of interaction between neutrinos and ^{71}Ga nuclei is much lower than expected. This 'gallium anomaly' was first noticed in the SAGE and GALLEX experiments and has recently been confirmed with extensive statistical material in the Russian experiment BEST, performed at the Baksan neutrino observatory of INR RAS. Oscillations of ordinary neutrinos into sterile neutrinos were proposed as a possible explanation. An alternative is possible errors in the measurement of the half-life $T_{1/2}$ of ^{71}Ge nuclei, which are transformed into ^{71}Ga nuclei in the interaction with neutrinos. To verify this hypothesis, $T_{1/2}$ of ^{71}Ge nuclei was remeasured at the Lawrence Livermore National Laboratory [2]. Three independent samples irradiated in nuclear reactors were used, and X-ray photons emitted during the electron capture in the $^{71}\text{Ge} \to {}^{71}\text{Ga}$ decay were detected. As a result, the obtained value $T_{1/2} = 11.468 \pm 0.008$ years is the most precise today and is consistent with previous measurements. Thus, the gallium anomaly was found not to be due to errors in $T_{1/2}$ measurements.

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3. Superconductivity of $La_3Ni_2O_{7-\delta}$

An indication of unconventional superconductivity not described by the Bardeen–Cooper–Schrieffer theory has recently been obtained for the nikelate $La_3Ni_2O_7$ at a temperature of 80 K, but the key property of superconductivity — zero electric resistance — has not been demonstrated. In their new experiment, Y Zhang (Zhejiang University, China) et al. detected zero resistance of $La_3Ni_2O_7$ for the first time and revealed other interesting properties of this compound [3]. The experiment was performed by two methods — in a cell with a diamond anvil and by compression in a cylinder with a rod. Direct measurement of current through the sample showed that at $P = 20.5$ GPa a sharp jump of resistance begins at $T = 66$ K, and zero resistance is reached at 40 K. Also noticed was the absence of metal–dielectric transition near the region of superconductivity. This property is called strange-metal behavior. Hope remains to finally obtain room-temperature superconductivity at a normal pressure. V L Ginzburg (Lebedev Physical Institute) considered the creation of room-temperature superconductivity as one of the most topical physical problems [4]. At his suggestion, the Center of High-Temperature Superconductivity and Quantum Materials was founded at the Lebedev Physical Institute of RAS in 2004.

4. Superconductivity of $CaKFe_4As_4$

Researchers from the Lebedev Physical Institute of RAS and MSU T E Kuzmicheva, S A Kuzmichev, and A S Medvedev have synthesized a high-quality sample of a nonmagnetic compound $CaKFe_4As_4$ and examined the multi-gap structure of its superconductivity [5]. $CaKFe_4As_4$ belongs to the recently discovered 1144 family of superconductive iron pnictides. It was analyzed using the method of creation of planar contacts on a microcrack (at a temperature of 4.2 K) having the structure S – n – I – n – S of a superconductor S, normal metal n, and insulator I. When the contacts were mechanically adjusted, the cryogenic chips slid with the formation of stacked structures. In the superconducting state in the S – n – I – n – S contact, the effect of multiple Andreev reflections is possible, and, using their spectroscopy, the amplitudes of three bulk superconducting order parameters and a small superconducting gap were determined. As a result, a similarity between the superconducting properties of pnictides of the 1144 family and the related 122 family was shown, which is explained by the same topology of the Fermi surface.

5. Application of Keldysh theory to describe exciton condensation

Interlayer excitons (bound states of electrons and holes) can occur in some layered compounds due to the interaction between electrons from one layer and holes from another layer, even if these layers are separated by a thin dielectric layer. Interlayer excitons have a long lifetime and can be controlled by an electric field. An equilibrium Bose–Einstein condensation of interlayer excitons was experimentally found in quantum Hall bilayers. But, under the action of a potential difference between the layers, a tunnel current must occur, driving excitons out of equilibrium. To investigate such a nonequilibrium regime, a group of researchers from USA and Austria, Y Zeng, V Crepel, and A J Millis, have formulated an exciton condensation theory based on L V Keldysh's nonequilibrium field theory (Lebedev Physical Institute RAS) [6]. In the new theory [7] describing p-wave tunneling between layers, it was found that, for a sufficiently large bias potential, the forbidden band width decreases and the effective exciton temperature increases. The developed theory can be applied both to layered materials based on transition metal dichalcogenides and to composite semiconductors InAs/GaSb used in electronics. For the coherent state of excitons, see also [8].

6. Detector of terahertz radiation

Electromagnetic radiation in the THz range has important practical applications, and active work is being done to create sources and detectors of terahertz radiation. One of the most topical problems is strengthening the interaction between devices and terahertz signals. In the optical range, detectors based on I E Tamm's resonators (Lebedev Physical Institute of RAS, since 1934) have proved themselves to be suited for this purpose. However, extension of their applicability region to the terahertz range is complicated by the fact that, for wavelengths of 10 to 1000 μm, it is difficult to create the necessary coating for resonator surfaces, which is obtained by simple sputtering in the optical case. Nevertheless, X Tu (Nanjing University and Hefei National Laboratory, China) et al. were able to design and assemble an effective terahertz detector in the form of a hybrid Tamm resonator, formed through the introduction of a dielectric layer into a pure Tamm resonator [9]. The detector uses a distributed Bragg reflector with silicon and air layers and a microbolometer detector on a silicon substrate. The resonator modes of the detector can be tuned by regulating the substrate thickness. The experiment has shown that the detector possesses a high-quality factor $Q = 1017$ and a narrow-band sensitivity (bandwidth of 469 MHz). For optical terahertz converters, see [10].

7. Observation of Zel'dovich effect

In 1971, Yu B Zel'dovich predicted theoretically the effect of electromagnetic wave amplification upon its scattering on a rapidly rotating metal cylinder. In a rotating reference frame, the wave frequency shifted by the Doppler effect becomes formally negative, and the absorption of the wave becomes its amplification (the absorption factor reverses sign). This effect was observed earlier for an acoustic analog only when the wave velocity was much lower than the velocity of light. M C Braidotti (University of Glasgow, Great Britain) and her co-authors have become the first to observe the Zel'dovich amplification effect for a real electromagnetic wave [11]. The configuration of the experiment is similar to an induction generator, where, instead of a rotor, there is a solid aluminum cylinder, and the electromagnetic wave in the stator gap is formed by LC contours. This scattering effect is classical, but, as Ya B Zel'dovich himself supposed, this method can be used to amplify quantum electromagnetic fluctuations gaining energy from the energy of cylinder rotation.

8. Investigation of acoustic turbulence

For an ensemble of acoustic waves, strong and weak turbulence regimes are possible, depending on the magnitude of nonlinear interactions. A theoretical description of acoustic turbulence in the case of a low wave dispersion encounters certain difficulties, and two approaches exist, leading to a Zakharov–Sagdeev turbulence spectrum with $E(k) \propto k^{-3/2}$ and a Kadomtsev–Petviashvili spectrum with $E(k) \propto k^{-2}$. E A Kochurin (Institute of Electrophysics of the Ural Branch of RAS and Skoltech) and E A Kuznetsov (Skoltech, Lebedev Physical Institute of RAS and Landau Institute for Theoretical Physics) have performed a numerical simulation of 3D acoustic turbulence and shown for the first time that both spectra are realized, and the transition between them is realized by the level of nonlinearity [12]. The simulation was performed in a Fourier space on the basis of kinetic equations for pair correlators. It was found that, under a weak acoustic turbulence, the Zakharov–Sagdeev spectrum is formed under weak dispersion and in the absence of dispersion, and with increasing pumping power an ensemble of random shock waves appears, described by the Kadomtsev–Petviashvili spectrum. The general theory of turbulence is also developed in papers by K P Zybin, V A Sirota, and A S Il'yn (Lebedev Physical Institute of RAS) [13, 14].

9. Can a black hole be created from light?

The question of whether a region with high energy concentration can collapse into a black hole (BH) upon light beam focusing has been discussed for a long time. The question is now purely theoretical, because the power of existing lasers is 50 orders of magnitude lower than required and astrophysical objects with a necessary electromagnetic field strength are unknown. In a new theoretical study, A Alvarez-Dominguez (Complutense University of Madrid, Spain) and their co-authors have shown the impossibility of BH formation under light focusing [15]. This will be prevented by quantum effects of vacuum polarization associated with the production of particles, for example, electron-positron pairs (Schwinger effect). Long before the necessary energy density is achieved, an intense production of particles carrying away energy will begin, which obstructs BH formation. The results of theoretical studies of the process of particle pair production in a strong field, performed by A I Nikishov and V I Ritus (Lebedev Physical Institute of RAS), were used in the calculations.

10. Mass composition of ultra-high energy cosmic rays (UHECRs)

The origin of UHECRs is not yet quite clear, although processes in active galactic nuclei are considered as a possible mechanism of their production. The Pierre Auger Collaboration used new methods in new investigations of the mass composition of UHECR atomic nuclei up to energies of 10^{20} eV [16]. First, correlations between the data of fluorescence telescopes and surface detectors were established, and then the UHECR mass composition was found from the joint data with the help of machine learning algorithms. The investigation has shown that UHECR nuclei become heavier as the energy increases within the range of $5 \times 10^{19} - 10^{20}$ eV, and their composition becomes more homogeneous (the fluctuation of composition decreases from event to event). A somewhat different result was obtained at the Telescope Array detector, suggesting that, at an energy of $\sim 10^{19}$ eV, the nuclei are rather heavy, then to $\sim 10^{20}$ eV they become on average lighter, and at $> 10^{20}$ eV the mass spectrum becomes heavier again [17].

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