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1. Test of the equivalence principle

Since it was formulated, the General Relativity Theory (GRT) has undergone several successful tests, including the recent detection of gravitational waves and observation of the black hole shadow. But perhaps GRT is not definitive but the run-up to a more complete theory allowing for quantum effects and additional interactions. It can not be ruled out that these new interactions carried, for example, by dilaton-like particles can at a certain small level violate the weak equivalence principle (independence of the free fall acceleration of bodies of their mass and composition). Paper [1] presents the final results of the MICROSCOPE experiment carried out to test the equivalence principle in Earth's orbit under weak noise. The device contained two concentric cylinders of different compositions (titanium and platinum alloys) soaring in weightlessness, whose mutual accelerations were measured by high-precision electrostatic accelerometers. A reference device also existed with cylinders of the same composition to control systematic uncertainties. Over the entire observation time, the Eötvös parameter was found to be $\eta = [-1.5 \pm 2.3(\text{stat.}) \pm 1.5(\text{sist.})] \times 10^{-15}$, which is 4.6 times better than the previous value. For the currently accessible accuracy, this result confirms the validity of the equivalence principle, which suggests constraints on new interactions.

2. Search for neutrinoless double beta decay

The hypothetic neutrinoless double beta decay, forbidden by the Standard Model of elementary particles, is being searched for in some experiments [2]. Its discovery would mean that the neutrino is a Majorana particle (its own antiparticle). This kind of decay has not yet been revealed, but some lower bounds have been obtained on the lifetime of different nuclei with respect to neutrinoless double beta decay. In its conception, the CUPID-0 experiment, now being performed at the Gran Sasso National Laboratory (Italy), is a development of the CUORE experiment, which has recently obtained the best restrictions on the decay of ^{130}Te nuclei. An additional peak corresponding to a neutrinoless channel is being sought in the spectrum of ^{82}Se nucleus decay. The main novelty of CUPID-0 compared to CUORE is the use of scintillation bolometers. For ^{82}Se decay to the ground state of the ^{82}Kr nucleus, the limit on the half-life was obtained to be $T_{1/2} > 4.6 \times 10^{24}$ years (20 times better than the previous limits) [3]. From this, the limit on the effective mass of Majorana neutrino is $m_{\beta\beta} < (263 - 545)$ MeV. Also obtained were the most stringent limits on ^{82}Se decay to excited ^{82}Kr states, whose signature is the emission of additional gamma-ray photons under deexcitation.

3. Intrinsic c-quark in the proton

The proton consists of two u-quarks, one d-quark, and gluons. A large number of quark-antiquark pairs of all other types (a quark sea) must also appear and disappear inside the proton. Quarks with masses exceeding that of the proton itself are called intrinsic quarks. Of particular interest are intrinsic c-quarks, since their mass (1.25 GeV) is a little larger than the proton mass, and, according to estimates, they can carry over $\sim 0.5 - 2\%$ of proton momentum. However, several previous attempts to detect an intrinsic charm quark gave ambiguous and mutually exclusive results, and this fundamental question has remained open for nearly 40 years. The NNPDF collaboration has undertaken a new analysis of data on pp collisions at the Large Hadron Collider and the data of some other experiments to confirm the existence of the intrinsic c-quark in protons at a 3σ level [4]. The data were processed applying, in particular, 'machine learning' technologies.

4. Electron-photon pairs

A Feist (Max Planck Institute for Multidisciplinary Sciences and Göttingen University, Germany) and their co-authors have developed a new method for obtaining quantum-entangled electron-photon pairs [5] using a circular optical high-quality-photon-chip-based microresonator generating an evanescent electromagnetic field around. While passing near a cavity, the electrons from the electron microscope interacted with the evanescent field, inducing the generation of photons, which left the microresonator through an optical fiber. The electron-photon pairs thus produced were described by a unified wavefunction (were quantum entangled). The obtained pairs possessed a high quantum fidelity. Quantum entangled electron-photon pairs are used in quantum optics for quantum-enhanced visualization and in various fields of quantum communication.

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5. Interference of nonidentical single particles

Quantum interference most often occurs between identical particles. However, it is also possible between different systems [6]. Interference has already been observed between a quasiparticle — a magnon (spin excitation quantum) — and a collective photon state, and also between a photon and a coherent NOON state. K Su (South China Normal University) and their co-authors vere the first to demonstrate quantum interference between nonidentical single particles (a photon and a magnon) in a Hong–Ou–Mandel interferometer and have examined their quantum statistics [7]. In the interferometer, a hybrid splitter was exploited, in which conversion between the indicated particles could take place through the dark polariton state in an ensemble of atoms, and the splitter could be transferred from the Hermitian to the non-Hermitian regime. This allowed a crossover from the bosonic to fermionic quantum statistics, although both the input states were bosonic. Moreover, three fermion states were simulated by three input single photons.

6. Diode effect in superconductivity

In some nonconventional superconductors, an external magnetic field can coexist with superconductivity. This underlay the recently discovered effect of a 'superconducting diode,' when the critical current of a superconductor depends on direction. However, this phenomenon was only observed in the presence of an external magnetic field. J-X Lin (Brown University, USA) and her co-authors have demonstrated for the first time a superconducting diode without an external magnetic field in twisted trilayer graphene [8]. The direction of the diode effect can be changed by an out-of-plane magnetic field (the 'material training' method) and also by changing the carrier density and the layer twist angle. The superconducting diode effect in graphene can evidently be explained by an imbalance in the valley occupation, which perhaps leads to finite-momentum Cooper paring. This study presents direct proof of the coexistence of superconductivity and time-reversal symmetry breaking at the atomic level.

7. "Antilaser"

Coherent radiation absorption (an 'antilaser') has already been realized in experiments through the creation of resonance structures [9], but for only one or several modes with different incidence angles. Y Slobodkin (Hebrew University of Jerusalem, Israel) and his co-authors have proposed theoretically and demonstrated experimentally a method for creating coherent absorption, where the absorber is self-tuned for each possible mode so as to reach its complete absorption [10]. That is, a signal with any wavefront is perfectly absorbed. The method is based on a formal accordance of such coherent absorption with time-reversed degenerate-cavity laser radiation. For the laser effect reversal, it was proposed to place two lenses and a thin layer of absorbing medium in the cavity. Owing to mode degeneracy and interference, the light remains in the cavity and passes many times through the absorbing medium. This provides an ideal coherent absorption of any combination of modes irrespective of their relative phases and directions. The experiment performed by the described method confirmed the conception efficiency — 94% efficiency of absorption of a compound signal consisting of over 1000 modes.

8. Local breakdown of Ohm's law in graphene

Ohm's law ($\mathbf{j} = \sigma\mathbf{E}$) takes place on scales exceeding the average electron free path in a medium, when electricity transport is a diffusive process. It has been predicted, however, that the transport in Fermi liquids can be determined by electron-electron collisions. This leads to viscous transport, where a flow of current resembles a flow of liquid. A Jenkins (University of California, Santa Barbara, USA) and his colleagues have observed a change from one flow pattern to another and a local breakdown of Ohm's law in a graphene monolayer near an etched narrow neck [11]. The magnetic field was registered by a scanning nitrogen-vacancy (NV center)-based magnetometer to find the profile of the field-generating electric current. In the ohmic regime, the current is concentrated near the narrowing boundaries, and at a temperature of < 200 K it is closer to the center. This is consistent with a crossover from diffusive to viscous electron transport. It was also shown that, for a liquid type behavior of the current, the Landauer–Sharvin conductance limit corresponding to the ballistic regime of electrons is overcome.

9. Laboratory modeling of astrophysical discs

In gas disks around black holes, a high accretion rate must be accompanied by angular momentum transport from the central disk region outwards. Exact mechanisms responsible for the angular momentum transport are not yet clear. This may be magnetorotational instability or purely hydrodynamic transport without a magnetic field. Along with analytical and numerical calculations, one of the research methods is astrophysical disc modeling in laboratory experiments. M Vernet, S Fauve (Sorbonne Université, Université de Paris), and C Gissinger (Institut Universitaire de France) have designed a new experimental device [12] to investigate the angular momentum transfer by a turbulent flow of an electrically conducting fluid confined in a thin disk. Two contributions to the local angular momentum transport are identified: one from the poloidal recirculation induced by the presence of boundaries and the other from turbulent fluctuations in the bulk. The latter provides efficient angular momentum transport, irrespective of the molecular viscosity of the fluid, and leads to Kraichnan's prediction for the Nusselt number. In this so-called ultimate regime, the experiment, therefore, provides a configuration analogous to astrophysical accretion disks. This testifies, first, to a correct theoretical description of the transport and, second, allows a prediction of the accretion rates. In 1973, the theory of astrophysical discs was considerably developed in the study by N I Shakura and R A Syunyaev. For disc accretion, see also [13–15].

10. Sources of extragalactic neutrinos

The neutrino telescope IceCube in Antarctica has registered 100-TeV to 10-PeV cosmic neutrinos of yet unknown origin [16]. Several studies showed that the sources of these neutrinos correlate with the positions of some blazers, i.e., active galactic nuclei with jets pointed towards Earth. Important evidence of this kind has recently been obtained by Yu Yu Kovalev and his colleagues [17], who considered correlation with blazar radio emission. S Buson (University of Würzburg, Germany) and her co-authors have carried out a search for blazars and neutrinos in IceCube over 7 years of

observations by new methods — without additional assumptions and with rather uniform samples of events [18]. In such an approach, it has been discovered that 10 of 19 regions with the largest number of neutrino events (hot spots) coincide with blazar positions. This confirmed conclusions suggesting a relation between the neutrino origin and blazars. The probability of a chance association was estimated as 6×10^{-7}.

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