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1. Pionic helium

Charged pi-mesons (pions), which are known today to consist of a quark and an antiquark coupled by strong interaction, were discovered in 1947. That same year, Enrico Fermi and Edward Teller proposed that exotic atoms may be formed in which one or more orbital electrons are replaced by mesons [1]. In most cases, the atomic nucleus must quickly absorb the meson and decay. The calculations, however, showed that in pionic helium π^4He^+ a rare situation is realized, where its lifetime is 1000 times longer than that of other pion atoms. The π^4He^+ atom consists of a helium-4 nucleus, an electron, and a π^--meson. Only indirect evidence of π^4He^+ formation in collisions was obtained earlier. M Hori (Max Planck Institute of Quantum Optics, Germany) and co-authors have become the first to obtain experimentally [2] a sufficient number of π^4He^+ atoms and to perform laser spectroscopy on them. A π^- beam obtained on the cyclotron at the Paul Scherrer Institute (Switzerland) was directed to superfluid ^{4}He. Approximately 3.2% of all π^- delayed in helium formed π^4He^+ atoms with a lifetime of several ns. The same target was illuminated by nanosecond laser pulses. They generated cascade processes in π^4He^+ that ultimately led to pion absorption and nucleus decay. The rate of neutron, proton, and deuteron production due to decay had a maximum for a certain laser pulse frequency. This resonance, which had a statistical significance over 7σ, corresponded to the intranuclear transitions $(n, l) = (17.16) \rightarrow (17.15)$. The resonance frequency proved to be somewhat higher than the calculated one. This was possibly due to atomic collisions that perturb the energy levels, as had already been noticed in $\bar{p}^4He^+$ spectroscopy. Thus, the experiment demonstrated the realizability of laser spectroscopy of exotic meson-containing atoms. For exotic atoms, see the review [3].

2. Strong quantum coupling at a distance of 1 m

Coupling between systems realized with quantum accuracy without loss of coherence is of importance for quantum technologies. Such a coupling is readily realized straight between objects in close proximity or through a field in the cavity. However, for distant systems, the creation of quantum coupling presents considerable difficulties, because of the signals weakening and scatterings the quantum information. P Treutlein (University of Basel, Switzerland) and colleagues realized in their experiment [4] long-distance coupling through a laser beam in a loop configuration with several passes in two directions. The coupling loop allows compensating some types of losses at the expense of destructive interference of quantum noise. This method was applied for coupling the collective spin state of 10^7 ^{87}Rb atoms in the magnetic field in an optical dipole trap and a mechanical oscillator, which is a silicon-nitride square membrane in the optical cavity 1 m apart. The spins were perturbed using a small solenoid, and perturbation of the collective spin led to light polarization rotation which was converted to light wave amplitude perturbation, resulting in the end in a force effect on the oscillator, and vice versa, membrane displacements in the reverse order affected the spin. Room-temperature quantum coupling was demonstrated in various regimes with a positive and negative effective mass of an ensemble of spins.

3. Initial stage of molecule photoexcitation

The electron density redistribution in a molecule at the initial stage of its excitation by laser pulses was examined at the SLAC accelerator laboratory. P M Weber (Brown University, USA) and colleagues have investigated relatively small organic molecules of 1,3-cyclohexadiene C_6H_8 in a room-temperature rarefied gas [5]. Immediately after the action of optical laser pulses, the molecules were illuminated by ultrashort X-ray pulses from a free electron LCLS laser. From their scattering, the difference between electron densities before and after the beginning of laser pulse action was found. These direct measurements showed that at a small distance of < 3 Å from the molecule center the electron cloud density decreases, whereas at a large distance of 4 to 9 Å it increases. Such a character of photoexcitation is also reproduced in theoretical calculations as a transition to a diffuse electron 3p-state. Such studies may provide insight into the mechanisms of different photochemical processes.

4. Laser radiation with a large orbital angular momentum

H Sroor (Wits University, South Africa) and co-authors have designed a laser [6] generating radiation with a high value of orbital angular momentum — with quantum numbers up to $l = 100$. In preceding work using liquid crystals, l smaller by at least an order of magnitude were obtained. The new device contained a metasurface integrated in an IR-excited nonlinear-crystal laser-generating medium with a nonlinear

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crystal in an optical resonator. The metasurface consisted of an array of rectangular rods manufactured of amorphous titanium oxide TiO_2 on a quartz substrate. The rods were oriented with their long sides perpendicular to the surface (in the direction of the laser beam). They were of different lengths and were located on the surface in a special manner so that a wave passing through the metasurface gained a certain phase shift in each rod, and in the end acquired a large resulting angular momentum. This method of creating a metasurface allows obtaining structured light with different characteristics in a rather compact device with a small number of optical elements. Light with a large orbital angular momentum may find useful applications in various areas, including quantum communication and metrology.

5. Microwave quantum radar

Probing small objects using low-power electromagnetic pulses has found a number of important practical applications. The most interesting was a case investigating low-reflectivity objects in a medium with high thermal noises. In an optical region, pairs of photons in an entangled quantum state [7] had already been used for this purpose. This method was called quantum illumination. Quantum entanglement allows considerable increasing the signal-to-noise ratio for a reflected signal. The use of this method in the terahertz and microwave regions encounters some difficulties, because here quantum technologies are more poorly developed, and cooling to cryogen temperatures is needed. But, at the same time, this frequency range is very important, for example, for noninvasive biomedical diagnostics [8]. S Barzanjeh (Institute of Science and Technology, Austria) and colleagues have performed an experiment [9] demonstrating quantum probing of a room temperature object by microwave radiation photons. Pairs of microwave photons in a quantum entangled state were generated with the help of a Josephson parametric converter. One of the photons from the pair was reflected from the studied object at a distance of 1 meter and then, in the detector, was compared in phase with the first photon. An important element of these measurements compared to previous experiments was an analog-to-digital signal conversion already at the early stages of measurements, which allowed heightening the output signal quality owing to a more convenient method of information processing. The measurements showed that the use of photons in entangled states improves substantially the results of probing over classical (not quantum) methods, allowing isolation of a signal from the noise level.

6. Intermediate quantum statistics for anyons

In a three-dimensional system, elementary excitations — quasi-particles — can only be bosons or fermions, depending on the change in the phase of the common wave function upon permutation of two particles ($\phi = 0$ or $\phi = \pi$). However, intermediate type statistics with other ϕ were predicted theoretically to be realisable in two-dimensional systems. Quasi-particles satisfying these statistics were called anyons. Until recently, indirect experimental evidence had only been obtained of the fact that quasi-particles can have intermediate statistics. H Bartolomei (Higher Normal School, Paris, France) and co-authors have shown for the first time in a direct collisional experiment [10] that colliding anyons do satisfy intermediate statistics. To this end, in the GaAs/AlGaAs heterostructure retaining a two-dimensional electron gas, two anyon sources — quantum point contacts — were created. A third analogous contact served as a splitter with interacting anyons emitted by the first two contacts. The correlations of electric currents generated by anyons that had passed through the splitter were measured. Using these correlations, the statistical properties of anyons could be determined. Intermediate statistics with $\phi = \pi/3$ were shown to be realized for anyons in this system. For two-dimensional systems, see [11].

7. Searching for solar axions

A new experiment [12] in the search for solar axions has been performed at the Max Planck Institute for Physics (Germany), which continued a series of experiments carried out at the Konstantinov Petersburg Nuclear Physics Institute (PNPI). Hypothetical particles — axions — were proposed theoretically to explain CP symmetry conservation in strong interactions. Axions and axion-like particles were considered to be one of the key candidates for the role of dark matter (hidden mass) in the Universe. Axions were predicted to be produced effectively on the Sun in various processes, and experiments were performed to search for a solar axion flux on Earth. In a new cryogen experiment, resonant absorption of axions by ^{169}Tm nuclei was searched for using a modified low-background bolometer based on an 8-g $Tm_3Al_5O_{12}$ crystal. A distinctive feature of the experiment was the use of a new phonon sensor: a tungsten film evaporated on the crystal between two aluminum films that served as phonon collectors. This construction allowed the energy threshold necessary for axion detection to be overcome. Also, a heater was evaporated on the crystal to maintain the necessary working temperature and calibration. The new detector was much more sensitive than previous detectors that made use of ^{169}Tm nuclei. The measurements lasted several days. Although no resonant absorption of axions has yet been registered, new restrictions on coupling constants of axions with photons and electrons were obtained. Russian scientists from the Kurchatov Institute, PNPI, and the Prokhorov Institute of General Physics of the Russian Academy of Sciences (IOFAN) took part in the experiment.

8. Precession in the star orbit around a supermassive black hole

The GRAVITY collaboration has registered for the first time a Schwarzschild precession in the orbit of the star S2 rotating around the galactic center supermassive black hole (BH) [13]. The explanation for an analogous Mercury orbit precession — an additional displacement of the perihelion — was in the early 20th century one of the most important verifications of the theory of General Relativity. S2 is a star close to a BH with an extended orbit with a period of 15.6 years. This star has been monitored by a number of telescopes for 27 years. To fix the reference system relative to which the positions of the star and BH are measured, flares near the BH, in particular, were used. A relativistic Doppler effect due to the motion of the star S2 and the gravitational red shift due to the BH field has already been recorded. The obtained set of data also testifies with a $(5-6)\sigma$ confidence to the orbits precession exactly as predicted by GR. Thus, the General Relativity Theory has passed another successful test in new conditions. The star motion could in principle be

affected by the gravitational field of continuously distributed invisible matter or of compact objects. The new data impose a restriction on these sources of orbit perturbations. In particular, the mass of an additional compact object (a second BH) inside a region one angular second in size around the galactic center cannot exceed $10^3 M_\odot$. For the experimental verification of General Relativity, see [14, 15].

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