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Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation (29 January 2003)

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation was held in the Conference Hall of the P N Lebedev Physics Institute, Russian Academy of Sciences, on 29 January 2003. The following reports were presented at the session:

(1) **Okorokov V V** (Institute of Theoretical and Experimental Physics, Moscow). "Employment of coherent excitation of relativistic nuclei in a crystal in basic research on SRT and GRT";

(2) **Fomin I A** (P L Kapitsa Institute for Physical Problems, Russian Academy of Sciences, Moscow) "Spin currents in pure and 'dirty' superfluid ^{3}He";

(3) **Dmitriev V V, Zav'yalov V V, Zmeev D E, Kosarev I V** (P L Kapitsa Institute for Physical Problems, Russian Academy of Sciences, Moscow), **Mulders N** (University of Delaware, Newark, Del., USA) "Superfluid phases of ^{3}He in an aerogel."

A brief presentation of reports 1 and 3 is given below.

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Employment of coherent excitation of relativistic nuclei in a crystal in basic research on SRT and GRT

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1. Physics of the effect

When a particle (nucleus, atom) which possesses a level $\Delta E = E_{\rm exc} - E_{\rm gr}$ passes through a crystal it is possible to select conditions whereby the frequency of particle 'collisions' with crystal atoms $v_{\rm coll} = v_0/a_0$ (v_0 is the particle velocity and a_0 is the interatomic distance in the crystal) is equal to the transition frequency (or exceeds it by an integer factor):

$$v_{\rm tr} = \frac{E_{\rm exc} - E_{\rm gr}}{h} = v_{\rm coll}\, m\,. \qquad (1)$$

It is clear that the velocity dependence of the probability of Coulomb excitation of the passing particle should be resonant in nature.

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The underlying reason is that the dependence of the energy of interaction $U(t)$ between the passing particle and the crystal atoms is in the form of a periodic sequence of individual bursts (Fig. 1a), each arising from the particle interaction with one of the crystal atoms.

The frequency Fourier spectrum of an individual interaction $S_0(\omega)$ is shown in Fig. 1b for two different velocities of the particle traveling through the crystal.

The Fourier spectrum of the perturbation experienced by this particle in the interaction with n atoms and the spectrum of an individual interaction $S_0(\omega)$ are related by the expression

$$\left|S_0^n(\omega)\right|^2 = \left|S_0(\omega)\right|^2 \frac{\sin^2(\omega T n/2)}{\sin^2(\omega T/2)}\,, \qquad (2)$$

where $T = a_0/v_0$. The resultant spectrum $|S_0^n(\omega)|^2$ for large n is plotted in Fig. 1c for two velocities of the passing particle. One can see from relation (1) and Figs 1b and 1c that increasing the number of interactions n results in a rise, proportional to this quantity, of the spectral density $S_0^n(\omega)$ at frequencies $\omega_m = (2\pi/T)m$ ($m = 0$, 1, 2, etc.) and in a simultaneous narrowing, by the same factor ($\sim 1/n$), of the frequency band occupied near each ω_n ($\Delta\omega_n \sim \pi/nT$).

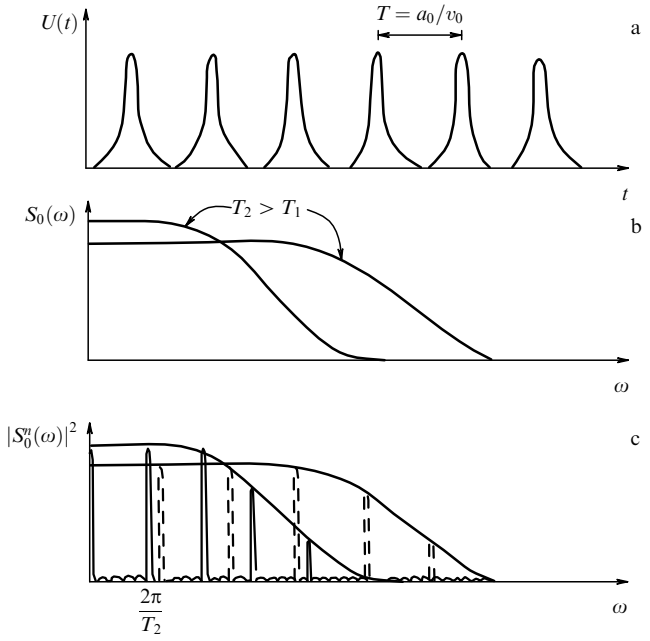

Figure 1. Formation of the Fourier spectrum of multiple interaction between a transit passing and crystal atoms.

Such transformation of the spectrum $S_0^n(\omega)$ into a series of narrow and intense lines at frequencies $\omega_m = (2\pi/T)m$ with an increase in the number of interactions n is due to the coherence [hence the title – coherent excitation (CE)] of the spectral components of individual interactions $S_0(\omega)$ (Fig. 1a), which periodically follow one another (see Refs [1–4]).

Therefore, CE arises from the transformation of a spatially periodic field of a crystal (generally speaking, not necessarily of a crystal!) into a temporally periodic electromagnetic perturbation experienced by a particle passing through the crystal and from the simultaneous use of this periodic perturbation for the excitation in internal degrees of freedom of the passing particle. [1]

When the spectrum of an individual interaction $S_0(\omega)$ extends up to the frequencies $\omega_{\rm exc} = \Delta E/\hbar$, it is always possible to select conditions (by selecting a crystal with a corresponding lattice constant a_0 or by changing the velocity of the particle traveling through the crystal) whereby one of the harmonics $\omega_m = (2\pi/T)\,m$ coincides with $\omega_{\rm exc} = \Delta E/h$. In this case, the probability that the passing particle will go over to the excited state rises sharply:

$$W \sim \left|S_0^n(\omega_{\rm exc})\right|^2 = \left|S_0(\omega_{\rm exc})\right|^2 n^2 . \qquad (3)$$

Thus, the excitation probability rises sharply not only for the 'resonant' velocity $v_0 = a_0/T = a_0 v_{\rm tr}$, but also for velocities $v_0/2$, $v_0/3$, $v_0/4$, etc., when the passing particle is excited at the second, third, etc. harmonics of the Fourier spectrum of the perturbation experienced by the particle in its interaction with the crystal atoms.

This excitation is practically analogous to the excitation of a particle by the periodic field of a monochromatic electromagnetic wave whose frequency coincides with the frequency of the transition between the levels of the particle.

2. On the use of CE in basic research

Coherent excitation research is extensively pursued both experimentally and theoretically [3–51]. Nevertheless, I believe that the direction of these investigations has taken researchers away from the direction corresponding to the full use of the opportunities which CE opens up for basic scientific research. For instance, the acquisition of experimental proofs of the occurrence of CE of relativistic nuclei in crystals would actually signify the discovery of a nuclear reaction of a new type, one proceeding not due to the individual collisions of two particles, but due to the collective interaction of the crystal atoms with the nucleus traveling through the crystal.

This reaction should occur with a significantly higher probability (by a factor of 10^4–10^5) than conventional Coulomb excitation of the nuclei that pass through an isotropic target [2]. Furthermore, it should possess a characteristic resonance dependence on the energy of a nucleus (the resonance half-width $\Delta E/E$ may be brought down to 10^{-5}), which underlies numerous potentialities for employing this effect in basic research in special and general relativity theories (SRT and GRT), as well as in relativistic nuclear physics.

[1] It is pertinent to note that after the publication of Ref. [5] the term 'resonance coherent excitation' gained wide acceptance. At one time denoting the effect as 'coherent excitation', the author had perfectly clear and accurate physical arguments for the employment of this term. 'Resonance coherent excitation' is evidently an excessive term, like 'buttery butter'.

An experiment on the CE of nuclear levels opens up an opportunity to carry out a rather precise verification of relativistic time dilation in the relativistic

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \approx 150 - 200$$

and ultrarelativistic cases. At relativistic energies of the nucleus that passes through the crystal, formula (1) should be written as

$$\frac{\Delta E}{h} = m\,\frac{v_0}{a_0}\,\gamma . \qquad (4)$$

The appearance of a factor γ is due to the relativistic contraction of the dimensions of crystal atoms and the interatomic distances in the frame of reference co-moving with the passing nucleus. In the crystal frame of reference, the appearance of the γ factor stems from the relativistic lengthening of time intervals by a factor of γ in the nuclear frame of reference (i.e., with the lowering, by a factor of γ, of the frequency of the transition between the levels of the passing nucleus).

Thus, an experimental verification of relationship (4) yields information on the variation of the course of time in the frame of reference moving with a relativistic velocity, which is indispensable for the coherent excitation of nuclear levels.

In this experiment, a nucleus that passes through the crystal and possesses a level $h\nu_{\rm exc} = E_{\rm exc} - E_{\rm gr}$ constitutes a moving clock, whose course of time is checked through a series of sequential interactions of the nucleus with the electric field of the atoms located at the sites of the spatially periodic structure that makes up the crystal.

The probability of coherent Coulomb excitation is appreciable in magnitude in very narrow and widely spaced nuclear velocity (energy) intervals [2]. The position of these intervals is defined by the nuclear excitation energy and is easy to calculate.

The qualitative discrepancy between the calculated energy value $E_{\rm kin}$ and the experimental one, which may and should be observable in the nuclear CE, solves the problem of exact experimental verification of the time dilation for a moving clock for values of the Lorentz factor of the nuclear beam employed in the experiment.

The experimental data published in an interesting paper by Y Takabayashi [51] may be treated as such a verification. Ref. [51] is a Doctoral Thesis which collected together, including all the references, the excellent results obtained by the Japanese research teams supervised by K Komaki, Y Yamazaki, and T Azuma. For more details of these papers, see below. The calculated and experimental positions of the resonance peaks corresponding to the CE in relativistic ($\gamma \sim 1.4$–1.6) hydrogen-like Ar^{17+} and Fe^{25+} ions were determined with a relative accuracy on the order of 10^{-4}–10^{-5}.

Therefore, within this accuracy the time dilation in the frame of reference traveling with a Lorentz factor $\gamma \sim 1.4$–1.6 may be thought of as having been experimentally verified.

The conclusions of the GRT as regards the time dilation in a frame of reference moving with acceleration can also be verified in experiments on the CE of nuclear levels. This opportunity arises from the fact that the fast nuclei traveling through a crystal are subject to tremendous accelerations of

$\sim 10^{22}$ cm s^{-2} (due to ionization losses). In accordance with the equivalence principle, such accelerations change the course of time in the frame of reference related to the passing nucleus (the nucleus as if moves in an 'effective' gravitational field which causes these accelerations) and, as a consequence, shift the energy levels in the nucleus which passes through the crystal. These energy-level changes can be detected with the aid of CE, which in this case is a rapid way to accomplish a precise 'in-flight' (inside the crystal) measurement of nuclear level positions.

3. Principal experimental data on CE

The first data testifying to the discovery of the CE effect were obtained in experiments conducted at the Institute for Theoretical and Experimental Physics (ITEP) [3, 4]. In these experiments it was possible to obtain CE of the levels of He^+ ions passing through a single-crystal silver film (Fig. 2). A spike in the intensity of photons (the $n = 4 \rightarrow n = 3$ transition; $\lambda = 4685$ Å) radiated by the hydrogen-like He^+ ions that had passed through a single-crystal silver film with a velocity close to the 'resonance' velocity was recorded, whereby the condition that the frequency of He^+ ion interaction with the atoms of the single-crystal silver film coincides with the ($n = 1 \rightarrow n = 4$) transition frequency is satisfied (Fig. 3). This rise in photon intensity is unambiguous evidence of the existence of the CE effect.

Shortly after the research done at ITEP, additional experimental evidence for the existence of the CE effect was obtained in France (Lyons) [5] (Fig. 4) and the United States (Oak Ridge) [6] (Fig. 5). While the French experiment was a simplified version of the ITEP experiments, in the experiments performed in the United States CE was discovered in

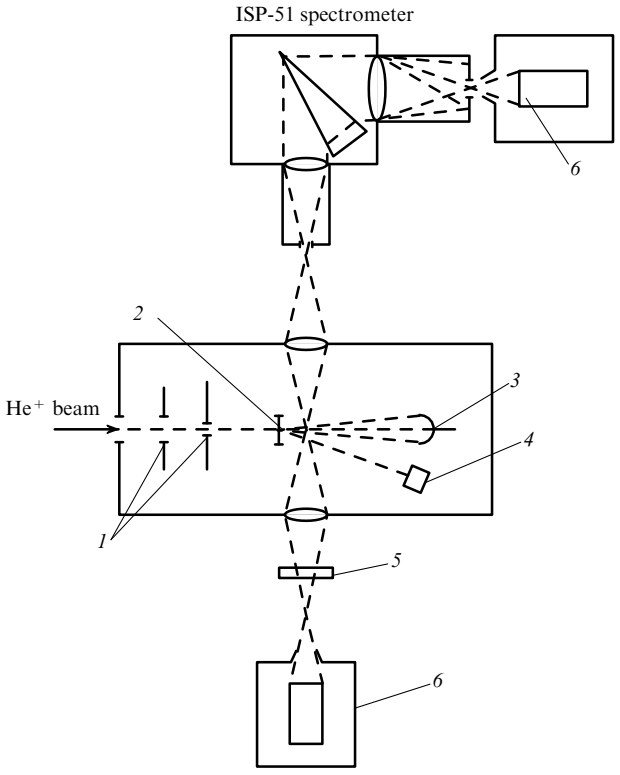

Figure 2. Skeleton diagram of the experiment of Ref. [3]. (*1*) aperture stop; (*2*) single-crystal target; (*3*) current integrator; (*4*) semiconductor counter; (*5*) interference filter; and (*6*) photomultipliers.

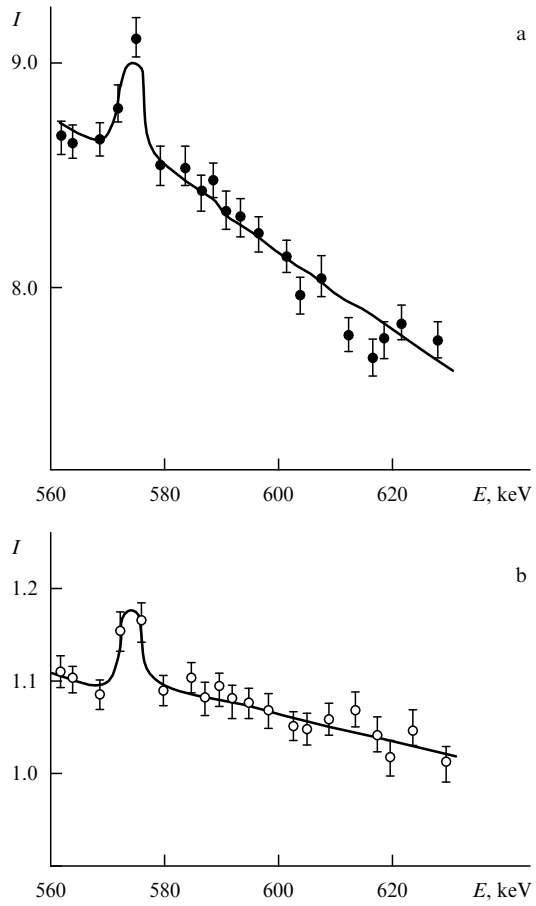

Figure 3. Intensity of the 4685-Å line emitted by the He^+ ion beam passed through a silver target as a function of the beam energy.

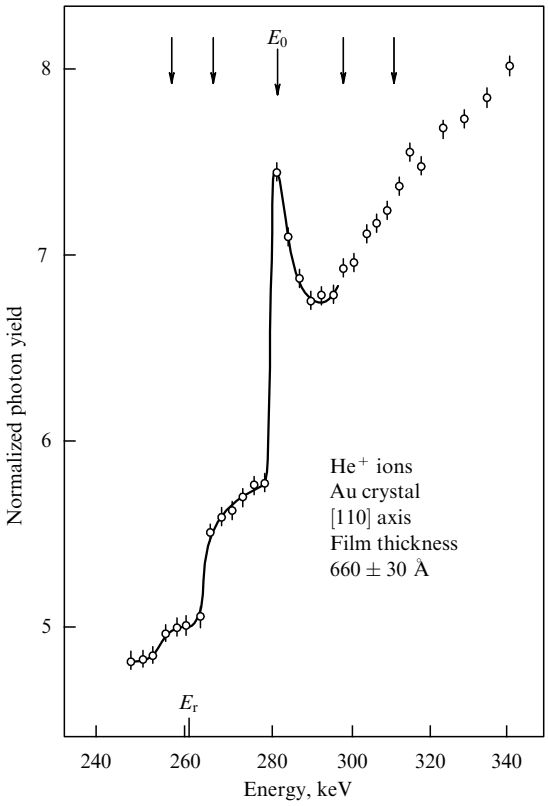

Figure 4. Experimental data of the Lyons group [5].

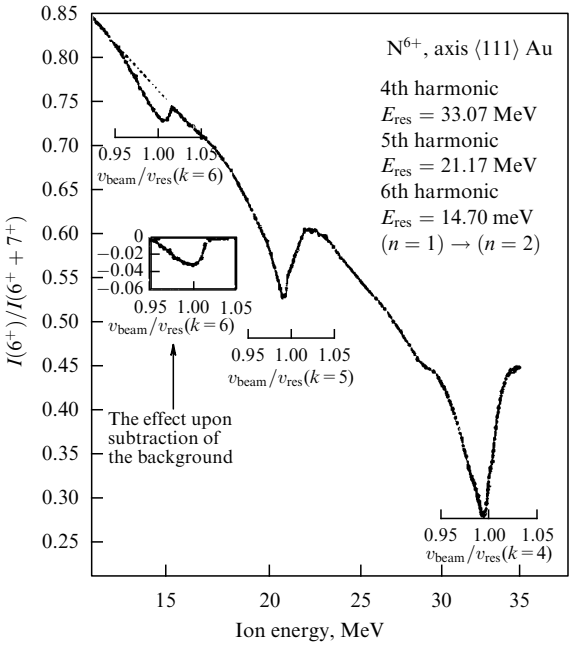

Figure 5. Experimental data of the Oak Ridge group [6].

fast heavy ions of boron, carbon, nitrogen, oxygen, and fluorine from the variation of the hydrogen-like ion charge occurring as a result of a two-stage process inside a single-crystal film: CE from the $n = 1$ state to the $n = 2$ state with subsequent ionization of the excited state due to the larger ion dimension in the excited $n = 2$ state.

An international research group in Canada accomplished the coherent excitation of hydrogen-like Si^{13+} ions at the seventh and eighth harmonics [45] (Fig. 6).

At present, Japan has undoubtedly come to the forefront of experimental CE research. In this country, heavy-ion CE research is pursued in two big acceleration centers located near Tokyo — RIKEN and CHIBA. A problem-oriented laboratory has been set up, whose plans comprise an investigation of the CE of heavy ions.

As a result of such concerted efforts, the most comprehensive experimental data on the CE of heavy ions have been obtained in Japan in recent years. K Komaki, Y Yamazaki, T Azuma, and their co-authors [19, 31, 33, 34, 36] investigated the CE of the hydrogen-like and helium-like ions Ar^{17+},

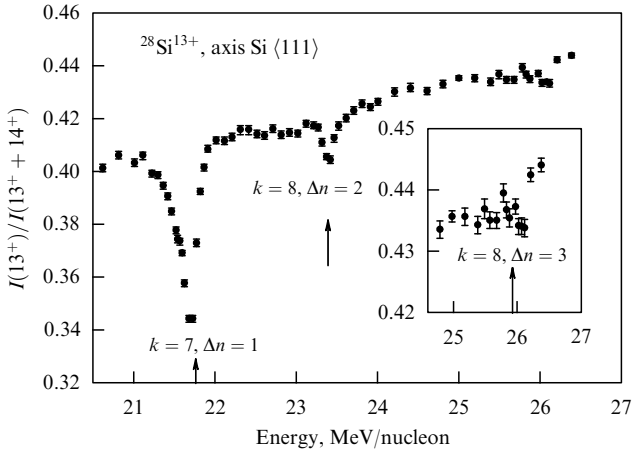

Figure 6. Experimental data of the Canadian group [45].

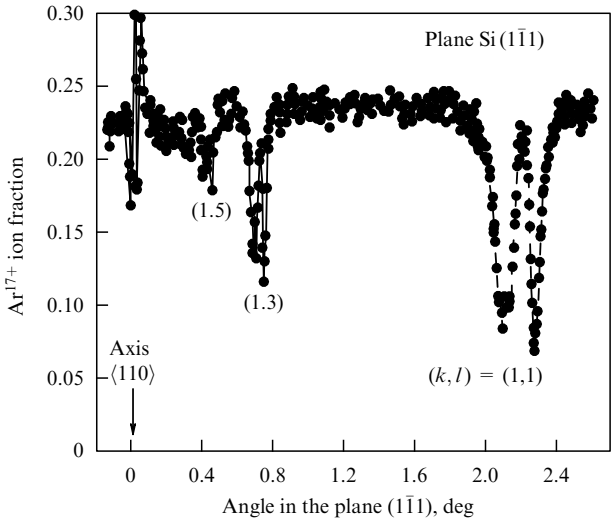

Figure 7. Experimental data on the CE of Ar ions passed through the $(1\bar{1}1)$ Si plane, which were obtained by the Japanese group.

Ar^{16+}, Fe^{25+}, and Fe^{24+}. They measured charge-state distributions of ions passed through a thin silicon crystal and also measured the intensity of X-rays emitted by heavy ions in the radiative decay of excited states produced inside the crystal target.

The position of the resonance CE peak in these experiments can be determined with a high degree of accuracy ($10^{-4} - 10^{-5}$). This signifies that the CE effect has been used validly to implement high-resolution spectroscopy of the excited states of heavy ions, which in turn makes it possible to employ these results, in particular, for a rather precise verification of one of the central inferences of the SRT — the time dilation in the frame of reference moving with a velocity close to that of light, as mentioned in the foregoing.

One of the numerous magnificent experimental data sets obtained in Japan is presented in Fig. 7.

4. Which part of the scientific program of the future γ laser can be realized at present?

There are some crucial problems which can be solved in the future with the aid of a γ laser (yet to be made):

(1) Technological and other applications of a γ laser.

(2) X-ray photographing of individual molecules.

(3) Excited-state spectroscopy of nuclei and other particles.

Generally speaking, a γ laser is hard to apply to spectroscopy, because its frequency is practically untunable, unlike, say, optical and radio frequency oscillators. Nevertheless, the excited-state spectroscopy of nuclei and other particles can be realized at present, for this is precisely the part of the scientific program in which some substitution of a γ laser is possible.

In the frame of reference co-moving with a particle that passes through a crystal, the electrostatic field of the crystal lattice assumes the form of several narrow monochromatic lines of electromagnetic waves at the fundamental frequency $\nu_1 = (v_0/a_0)\,\gamma$ and its harmonics. These 'virtual' photon spectra in the form of narrow lines are practically undistinguishable from the monochromatic line spectra of real plane electromagnetic waves in the relativistic case $\gamma \gg 1$.

The physics of CE of particles traveling through a crystal is totally equivalent to the interaction of a passing particle

with radiation of high spectral density whose frequency can be regulated in a stepless way through variation of the particle velocity. The processes occurring with this particle are therefore equivalent to those taking place when the particle is exposed to coherent monochromatic radiation of high spectral density, i.e., under irradiation by a γ laser beam. The potential of this kind of spectroscopy is due to (i) the possibility of stepless frequency control (tuning to resonance!); (ii) a broad frequency range (from 10 eV to 100 MeV); (iii) the excitation probability $\sim n^2$ (n is the number of layers of the single-crystal target).

From this viewpoint, a 1-mm thick single-crystal target can sometimes be equivalent to a 1-km thick isotropic target.

Therefore, CE can serve as a basis for the development of 'a certain original radiospectroscopy' spanning a dynamic frequency range of seven orders of magnitude, from 10 eV to 100 MeV. In 1981, I made this statement at the plenary session of the International Conference on Atomic Collisions in Solids (Lyons, 1981) [52]. Regrettably, it has never been published. Figure 8 reproduces the original drawing which the author of this paper demonstrated at that conference. And now it can be said with assurance and satisfaction that this high-frequency spectroscopy of excited states of heavy ions has been gathering force and is developing well in Japan. This kind of spectroscopy, which involves the use of the CE effect, has advantages and drawbacks of its own. However, so far there is no other way of investigating the interaction of particles with monochromatic radiation that has a high spectral density and is frequency-tunable over a dynamic range of seven orders of magnitude.

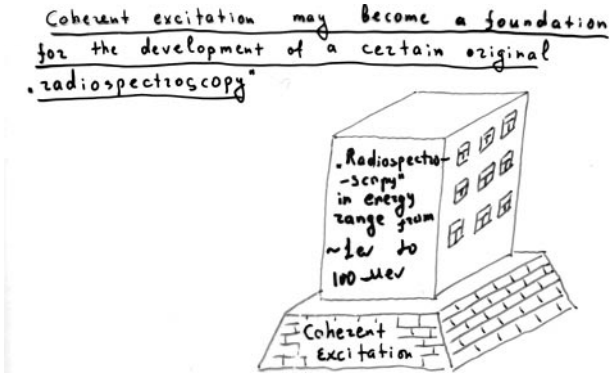

Figure 8. Reproduction of the original drawing from the author's talk given at a conference in Lyons, France, in 1981 [52]. At the top of the drawing one can see a statement that CE provides a possibility for developing 'radio spectroscopy', which was first made by the author.

5. International status of CE effect

Recent decades have seen theoretical and experimental investigations of CE [18–51], which have been pursued in research centers in the United States, Canada, Russia, Germany, and Japan. In the programs of many international conferences on atomic collisions in solids since the late 1970s, investigations of CE of atoms and nuclei that pass through a crystal have been marked out as a new field in the investigation of fast particle–matter interactions, side by side with such well-known phenomena as channeling and channeling radiation.

The majority of domestic and foreign papers concerned with the theoretical and experimental investigation of the CE effect contain references to the ITEP publications as the papers in which this effect was first predicted and first discovered. Further confirmation of the creative contribution of ITEP in the prediction and discovery of this phenomenon is the fact that in the foreign literature it bears the name of the author of the present report [11, 12, 14, 15].

The international status of CE research rose after 2000, when an American scientist S Datz from Oak Ridge was awarded the 2000 E Fermi Gold Medal — one of the most prestigious science and technology awards given by the U.S. government — for his scientific accomplishments, which include extensive experimental investigations of CE. Awarding S Datz an E Fermi Gold Medal ranks him with such outstanding physicists as John von Neumann, Ernest Lawrence, Hans Bethe, and Edward Teller, who were among the first Laureates of this most prestigious U.S. award, which was established in 1956.

As written in the nomination, S Datz was awarded the 2000 E Fermi Gold Medal for his studies 'in atomic physics and ion channeling...' The press-release stated that "His experiments in this field resulted in the first demonstration of coherent excitation of ions by the periodic potential in a crystal lattice..." Despite the fact that this statement is wrong and is a blunder (which was later admitted in written form by the Executive Secretary of the E Fermi Awards Committee on receiving the corresponding information), the very fact that the highest-ranking U.S. Presidential Award was given for investigations including CE experiments signifies that the U.S. scientific community recognizes the significance of the CE effect.

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Superfluid phases of ^{3}He in aerogel

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I V Kosarev, N Mulders

1. Introduction

The superfluidity of pure ^{3}He, in which there is Cooper pairing into a state with total spin 1, has been thoroughly studied, and in many cases it has been found that there is quantitative agreement between theory and experiment [1]. The study of the effect of impurities on superfluid ^{3}He is undoubtedly of great interest for the theory of systems with nontrivial Cooper pairing. The only substance that can be dissolved in liquid ^{3}He at low temperatures is ^{4}He. However, the solubility of ^{4}He in ^{3}He falls off exponentially with temperature, and at $T \sim 1$ mK, i.e., at temperatures at which ^{3}He is a superfluid, is practically zero. Recently there has emerged another possibility for introducing impurities into superfluid ^{3}He connected with the technology of producing low-density aerogel. Aerogel is a 'loose tangle' of SiO_2 strands about 30 Å in diameter, with the characteristic distance between the strands being 500 – 1000 Å (we are speaking about what is known as 98% aerogel with a density of 38 mg cm^{-3}, in which 98% of the volume is free and with which most experiments in this field are conducted). The coherence length of superfluid ^{3}He amounts to several hundred angstroms, i.e., much longer than the strand diameter, in view of which the strands act as impurities.

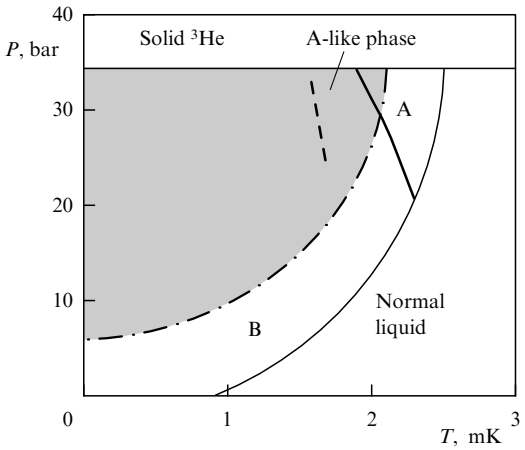

Figure 1. Phase diagram of pure ^{3}He and ^{3}He in 98% aerogel in a weak magnetic field. The hatched section corresponds to the superfluidity region of ^{3}He in aerogel, and the dashed line denotes the line of transitions from the supercooled A-like phase into the B-like phase when the sample is cooled.

Intensive studies of ^{3}He in aerogel began after Porto and Parpia [2] and Sprague et al. [3] discovered that low-density aerogel does not suppress superfluidity completely; rather, it somewhat lowers the superfluid transition temperature (by 20 – 30% at pressures of 20 – 30 bar). As a result, the phase diagram of superfluid ^{3}He in aerogel was established (e.g., see Refs [3 – 7]), which turned out to be similar to the phase diagram of bulk ^{3}He (Fig. 1). It occurred that, depending on the conditions, two superfluid phases were realized, and these were called (by analogy with bulk ^{3}He) the A-like phase and the B-like phase. Note, however, that there is a qualitative difference between the phase diagrams of 'ordinary' bulk ^{3}He and of ^{3}He in aerogel. In a weak magnetic field, the transition into the A-like phase becomes noticeable only on cooling starting from the normal phase, and the A-like phase is metastable (the dashed line in Fig. 1 shows the approximate position of the transition line from the supercooled A-like phase into the B-like phase). It is impossible to observe a clear transition into the A-like phase on warming from the B-like phase, which is, apparently, an indication that such a transition takes place very close to the temperature of the superfluid transition of ^{3}He in aerogel (T_{ca}). In bulk ^{3}He, the A phase can also be in a supercooled metastable phase, but, in contrast to ^{3}He in aerogel, its supercooling region is comparable to its region of existence in an equilibrium state (Fig. 1 shows the A – B equilibrium transition line).

Experiments involving aerogel can be carried out either with pure ^{3}He or in the presence of a small amount of ^{4}He. In the first case, the nuclear magnetic resonance (NMR) signal is strongly influenced by the solid paramagnetic ^{3}He that covers the surface of the strands with two monolayers (because of the van der Waals interaction) and has a high magnetic susceptibility at ultralow temperatures. As a result, near the superfluid transition point the amplitude of the NMR signal from the solid monolayers severalfold exceeds the amplitude of the signal from liquid helium, whose susceptibility is temperature-independent, which complicates the interpretation of the