OBSERVATION OF ULTRACOLD NEUTRONS

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Ya. B. Zel'dovich showed in 1959 [1] that neutrons with velocities up to 10 m/sec, which experience total reflection from the walls at all incidence angles, can be stored in a closed cavity. As was noted recently [2], the idea of storing neutrons points to a way of increasing the accuracy of measurement of the neutron dipole moment, an important factor in the problem of CP-violation. We have therefore undertaken to check experimentally the feasibility of extracting and retaining ultracold neutrons.

The experimental setup is shown in Fig. 1. The neutron source was the IBR pulsed reactor [3] operating at an average power of 6 kW at a flash repetition frequency of one every 5 sec. The flux of thermal neutrons in the polyethylene moderator 3 was 1.6×10^{10} neut/cm^2-sec. This moderator was placed in a standard copper tube of 9.4 cm i.d. and 10.5 m length, the inside surface of which was bright-dipped; a vacuum of 5×10^{-3} mm Hg was maintained in the tube. The neutron detectors 11 and 12 were FEU-13 photomultipliers covered with a scin-

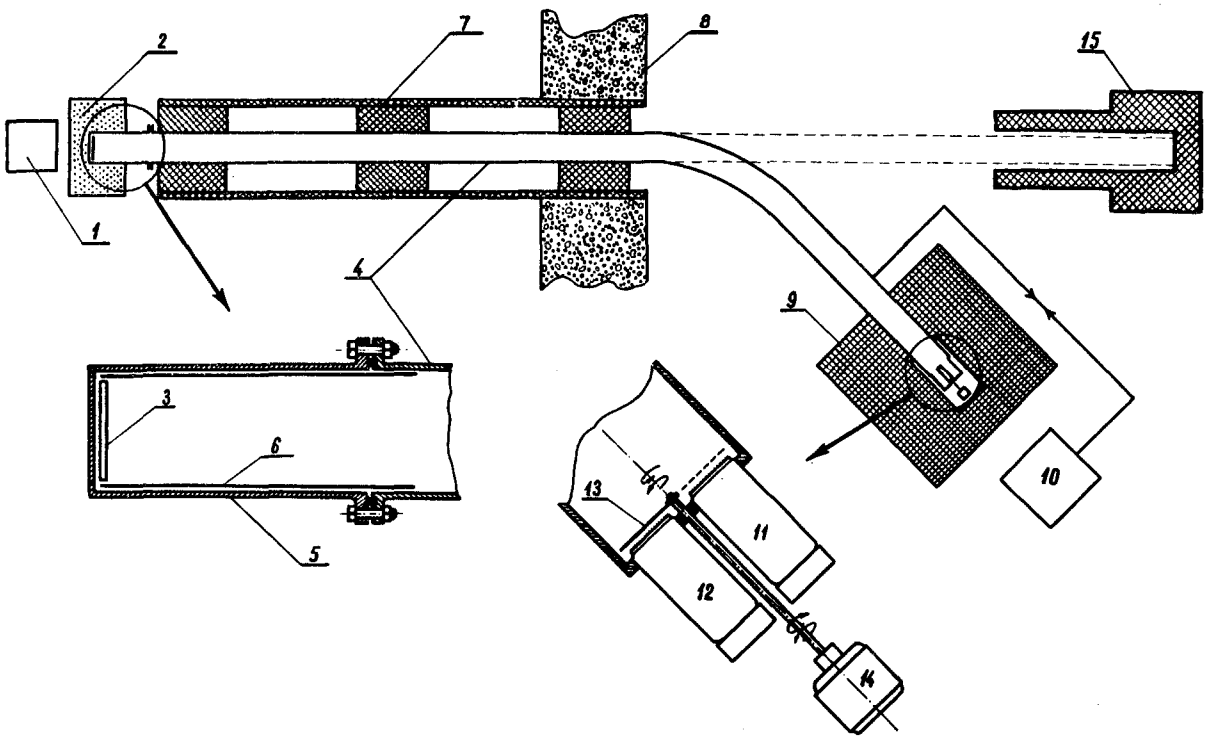

Fig. 1. Diagram of setup. 1- IBR reactor; 2, 3 - moderator (2 - paraffin, 3 - polyethylene layer 1 mm thick); 4 - copper tube, 9.4 cm i.d., total length 10.5 m; 5 - aluminum tube; 6 - copper-foil cylinder; 7 - shield (paraffin with boron carbide); 8 - 2-m concrete wall of reactor chamber; 9 - detector shield (paraffin); 10 - tube filling and evacuating system; 11, 12 - detectors (FEU-13 with layers of ZnS or ZnS + Li compound); 13 - copper shutter (gap between shutter and detector < 1 mm); 14 - shutter mechanism; 15 - trap for direct beam.

tillator layer of ZnS and a thin layer of a lithium compound (0.05 mg/cm^2 Li^6; lithium with 80% Li^6 content was used), and were placed on the bent end of tube 4 out of the line of sight of the moderator. The only neutrons that could reach them in practice were those emitted from moderator 3 with velocities lower than

$$V_{lim} = 2h/m(\pi Nb)^{1/2}. \quad (1)$$

In (1), m is the neutron mass, N the number of nuclei per cm^3, and b the coherent scattering length. For copper, V_{lim} = 5.7 m/sec. Every 200 seconds, the detectors were alternately covered with a thin copper shutter, which was practically transparent to neutrons with a normal velocity component larger than V_{lim}, but should reflect completely neutrons with $V < V_{lim}$. The detector pulses were fed to scaler circuits, which were blocked for 0.3 - 0.7 sec after each reactor flash in order to reduce the background. In some of the measurements, the pulses were fed also to a time analyzer.

Number of counts per 100 sec

Detector[1]	Copper shutter thickness, μ	Background (detector shuttered)	Effect			
			One detector open		Both detectors open	
			Experiment[2]	Theory[3]	Experiment[2]	Theory[3]
ZnS	1.8	0.20 ±0.07	0.08 ±0.10			
ZnS + LiF	1.8	0.41 ±0.05	0.76 ±0.10	0.67	0.72 ±0.21	0.38 (0.22)
ZnS+LiOH·H_2O	1.8	0.45 ±0.05	0.73 ±0.09	0.82 (1.33)	0.70 ±0.20	0.62 (1.16)
ZnS+LiOH·H_2O	15[4]	0.71 ±0.06	1.0 ±0.13			

1) The LiF layer was deposited over the ZnS layer. In the second detector, an aqueous solution of LiOH·H_2O was placed over the ZnS layer and the water was then removed by heating; apparently the LiOH·H_2O was inside the ZnS layer, and not on its surface. Consequently the calculation of the neutron absorption by this detector was made under two assumptions: a) the neutron reflection from the detector surface was determined by the ZnS layer, and b) the reflection was determined by the LiOH·H_2O layer. The results of the calculation under assumption b) are given in parentheses.

2) We give the difference of the counting rates of the detector with the shutter open and closed.

3) The error in the measurement of the thermal neutron flux and the registration efficiency of the products of the $Li^6(n,\alpha)$ reaction leads to an error of ±30% in the calculated values of the effect, disregarding the errors due to the inaccuracy of the assumption made in the isotropy of the angular distribution of the thermal neutrons in moderator 3 (Fig.1)

4) Blocking time after flash 0.3 sec. In all other measurements 0.7 sec.

The measurement results are listed in the table. We see that the detector counting rate is reduced to almost one-third when they are covered by the shutter. Yet in the measurements without the lithium layer the shutter had no effect on the counting rate, thus indicating the absence of a noticeable background due to light quanta are charged particles. Figure 2 shows the time spectrum of the effect; the effect is constant within the limit of errors. This agrees with the assumption that ultracold neutrons, that diffuse along the copper tube during a time much longer than the interval between the reactor flashes, are recorded in the experiment. To estimate the diffusion time, we measured the effect of filling the tube with helium gas. Upon colliding with a helium atom, the neutron acquires a velocity on the order of the mean thermal velocity of thehelium atom ($\overline{V}_{He}$ = 1250 m/sec) and leaves the tube. The average neutron lifetime with respect to collisions with the helium atoms is

$$T = (N_{He} V_{He} \sigma_{He})^{-1} \approx 250/P \text{ sec}, \qquad (2)$$

where N_{He} is the number of helium atoms per cm^3, σ_{He} the total cross section for the scattering of a neutron by an atom at rest(σ_{He} = 0.9 b with allowance for the impurities in the employed gas), and P is the helium pressure in mm Hg. The experimental results are shown in Fig. 3. We see that a pressure of 1 mm Hg decreases the effect to about one-half. According to Eq. (2) it follows therefore that the average neutron diffusion time from the moderator to the detector is about 200 sec.

A quantitative analysis of the described experiments was carried out with the aid of elementary diffusion theory (for details see [4]) under the following assumptions: a) the neutron spectrum inside the moderator corresponds to a Maxwellian distribution; b) the neutrons are scattered by the tube walls diffusely; c) the probability of neutron absorption upon collision with the rough wall of the tube or with the detector is the same as for an ideal plane.

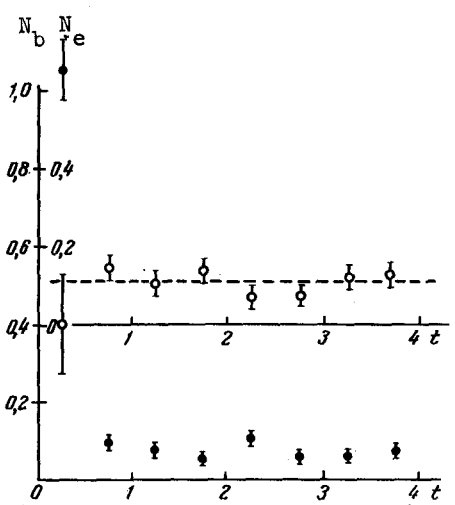

Fig. 2. Background N_b (dark circles) and N_e (light circles) vs. delay time t (sec) relative to the reactor flash. The ordinates represents the number of counts per 100 seconds.

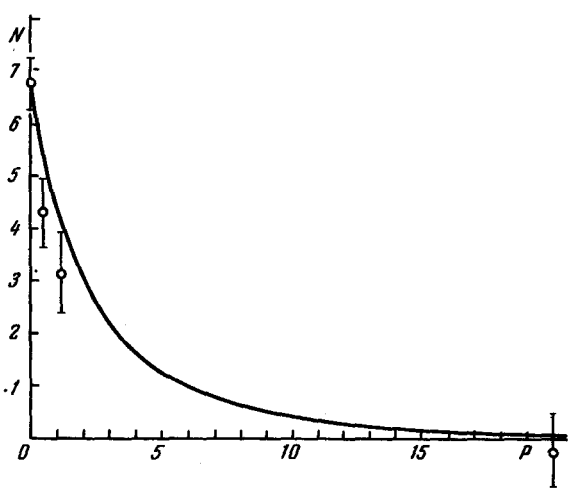

Fig. 3. Counting rate of ultracold neutrons N (counts per 1000 sec) vs. helium pressure P in tube (mm Hg). The theoretical curve is normalized to the experimental N at P = 0.

The experimental data do not differ from the theoretical predictions shown in the table and in Fig. 3 by more than a factor of 2, if at all. Unfortunately, the need to shut down the reactor for reconstruction prevented us from continuing the investigations.

The flux of ultracold neutrons was negligible in the present experiments not only because of the low power of the IBR reactor, but also because of the pressure drop of the neutron gas in the tube as a result of absorption in its walls. The use of a specular neutron duct or one with a larger cross section with a weakly-absorbing coating (say of beryllium) makes it possible to extract an ultracold-neutron flux cloase to the maximum, namely

$$\phi = \frac{1}{8}\phi_0(V_{lim}/V_0)^4,$$

where ϕ_0 - thermal-neutron flux at the start of the neutron duct, V_0 - the most porbable velocity of the thermal neutrons. If the moderator is at room temperature, a beryllium coating is used (V_{lim} = 6.8 m/sec), and $\phi_0 = 10^{14}$ neut/cm^{2}sec, we get $\phi = 1.1 \times 10^3$ neut/cm^{2}sec, which is far from small.

The foregoing results show that ultracold neutrons are produced and propagate in accordance with the theoretical expectations. This allows us to plan experiments aimed at measuring the neutron half-life and its electric dipole moment. We can assume that ultracold neutrons will find also other applications, based on the use of their low energy ($\sim 10^{-7}$ eV), their focusing ability, and other properties.

[1] Ya. B. Zel'dovich, Zh. Eksp. Teor. Fiz. 36, 1952 (1959) [Sov. Phys.-JETP 9, 1389 (1959)]
[2] F. L. Shapiro, Usp. Fiz. Nauk 95, 145 (1968) [Sov. Phys.-Usp. 11 (1969)].
[3] G. E. Blokhin, D. I. Blokhintsev, Yu. A. Blyumkina et al., Atomnaya energiya 10, 437 (1961)].
[4] V. I. Lushchikov, Yu. N. Pokotilovskii, A. V. Strelkov, and F. L. Shapiro, JINR Preprint R3-4127 (1968).

NUCLEAR SPIN-LATTICE RELAXATION IN THULIUM ETHYLSULFATE

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It is known [1] that in solids the direct coupling between the nuclear spin and the lattice vibrations is very weak. The spin-lattice relaxation of nuclei having no qudrupole moment is therefore determined, as a rule, by the dipole-dipole interaction of the nuclear moments with the electronic moments of the rapidly-relaxing paramagnetic ions which are always present in the form of a slight impurity.

The foregoing pertains to the nuclei of diamagnetic atoms; the question of the mechanisms of the relaxation of nuclei belonging to paramagnetic ions in crystals has remained so far unclear, owing to the lack of experimental data. We recall that recently several experiments were performed [2 - 5] on magnetic resonance on rare-earth ions (Pr^{3+}, Tm^{3+}), the ground state of which in the crystal field is an electronic spin singlet. The unusual feature of this version of NMR is essentially that the hyperfine interaction $a\bar{J}\bar{I}$ and the electron Zeeman energy $g\beta\bar{H}\bar{J}$ cause the Hamiltonian describing the behavior of the nuclear sublevels of