MEASUREMENTS WITH A SLOWING-DOWN-TIME NEUTRON SPECTROMETER EMPLOYING LEAD. EXCITED LEVEL OF THE He⁴ NUCLEUS

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Results of measurement of the energy dependence of the cross sections are presented for the following reactions: (n, γ) in Fe, Pb and Cl; (n, p) in He^3, N^{14} and Cl; (n, α) in Li^6 and B^{10}. Neutron energies up to 30 kev were employed. It is shown that the cross section for the B^{10} (n, α) reaction lies below the 1/v law, the deviation being smaller than 5 — 10%. The deviation of the Li^6 (n, α) cross section from the 1/v law is even less. It is concluded that the B^{11} nucleus has an excited level with an angular momentum $J = 5/2^+$ or $7/2^+$, a neutron resonance energy $E_r \sim 250$ kev, and widths $\Gamma_\alpha \sim 400$ and $\Gamma_n \sim 200$ kev. An appreciable deviation of the He^3 (n, p) cross section from the 1/v law has been detected which may indicate the existence in the He^4 nucleus of an excited level with one of the two sets of parameters: 1) $J = 1^+$, $-E_r \sim 200$ kev, proton width for an excitation energy equal to the neutron binding energy $\Gamma_{p0} \sim 200$ kev and 2) $J = 0^+$, $-E_r \sim 500$ kev, $\Gamma_{p0} \sim 1200$ kev.

I. Measurements with the slowing-down-time-in-lead neutron spectrometer[1,2] were extended in the neutron energy region up to ~ 30 kev. To determine the resolving power and the dependence of the average neutron energy E on the slowing down time t, of the energy dependence of the capture cross section was measured for a number of elements with widely spaced levels. A scintillation counter with a stilbene crystal of small size was used to register γ-rays from neutron capture in the samples. The duration of the neutron burst and the width of the channel of the time-of-flight analyzer were 0.5 μ sec each. The results of the measurements are presented in Figs. 1 and 2. For E < 1000 ev the effective flight path[2] of the spectrometer is constant to within ± 1.5% and is

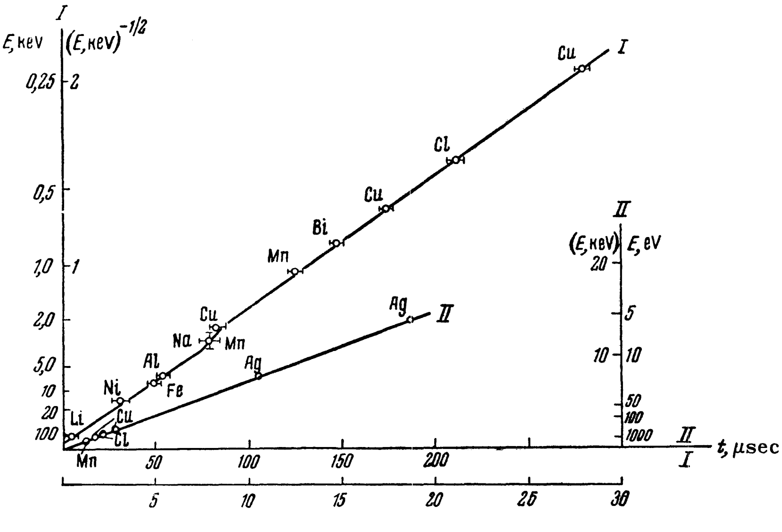

FIG. 1. Curve of $E^{-1/2} = f(t)$, where t is the slowing-down time corresponding to the maximum of the resonance peak and E is the energy corresponding to the resonant state. I — energy region E > 0.2 kev. II — E > 5 ev. Data on the energies of the levels are taken from Ref. 4 for Cl, Ref. 5 for Al, and Ref. 3 for the other elements. Note added in proof: The points for Al and Fe must be raised somewhat in accordance with the latest published data.[18] As a result the change in slope of curve I disappears and all points lie on one straight line given by $E^{-1/2} = 0.074\ (t + 0.3)$.

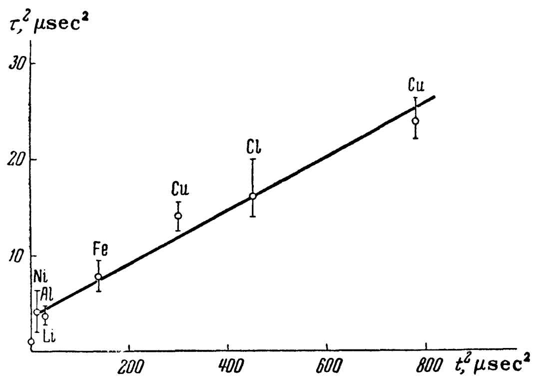

FIG. 2

L = 600 cm. For E > 1 kev, L keeps the same value within 3 — 5%, which shows that the average scattering cross section of neutrons in lead is constant within these limits.

The half-widths of the resonance peaks satisfy the relation $\tau^2 = at^2 + b$, where the coefficient a is 40 — 50% larger than the theoretical value for pure Pb: $a = (16 \ln 2)(3M)^{-1}$, where M = 207, the atomic weight of lead.[2] The constant term b is a characteristic of the experimental spread and of the spread connected with the width of the original neutron spectrum. From the measurements of the half-widths of the resonance peaks it follows that the spread of the neutron energies around the average value for the assigned analyzer channel is $(\overline{\Delta E^2})^{1/2}/\overline{E} \cong 15\%$ for E < 1 kev and $(\overline{\Delta E^2})^{1/2}/\overline{E} \cong 35\%$ for E = 10 kev. Such a spectrum width, while not favorable for the resolution of resonance peaks, permits nevertheless a sufficiently precise measurement of cross sections that vary smoothly on energy. In this work we investigated principally light nuclei, where the smooth variation of the cross section in the interval E < 30 kev is connected with the large distances between levels. The second possible field of application of the slowing-down-time spectrometer is the measurement of the cross sections of (n, γ) reactions in heavy nuclei in the energy region greater than several hundred electron volts, where because of the large number of levels the averaging of the cross sections over the resonances is of interest.

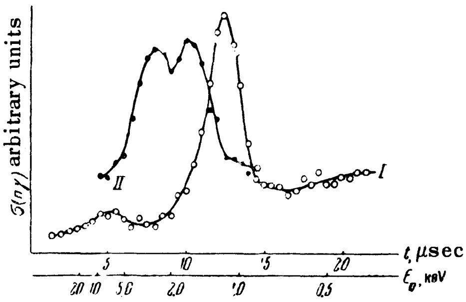

FIG. 3. Energy dependence of the cross sections of the (n, γ) reactions in iron and lead. I — specimen of A iron (99.7% Fe) 4 mm thick; II — background in the absence of a specimen. The curves are represented in different scales; in the Fe peak at 1.2 kev, the ratio of the effect to the background is ~ 3 : 1.

Together with the known levels, used for calibration, three new levels were found in the course of the measurements (Fig. 3). In measurements with iron a level appeared at an energy $E_r = 1200 \pm 100$ ev. The absence in this region of any peak in the total cross section curves for iron[3] indicates that this level is either narrow or belongs to one of the rare isotopes of iron. In measurements on lead (γ-background of the spectrometer*) levels with energies $E_r = 1700 \pm 150$ and $E_r = 2800 \pm 200$ ev appeared.

2. With the help of proportional counters, filled with N_2 and CCl_4 vapors, measurements were carried out on the energy dependence of the ratios of the cross sections of the N^{14}(n, p) and Cl^{35}(n, p) reactions to the Li^6(n, α) reaction cross section. For nitrogen the ratio of the cross sections is constant to within 3% up to an energy of ~ 5 kev, beyond which it increases. The rise reaches a magnitude of the order of 10% for E = 25 kev. In the measurements with chlorine, which will be continued, the level at 405 ev[4] appeared both in the (n, p) and in the (n, γ) reactions (the latter was detected by the yield of γ-rays measured with a scintillation counter). In the region below this resonance and down to E = 40 ev the σ(n, p)/σ(n, γ) cross-section ratio decreases with decreasing neutron energy. This indicates that the odd-parity chlorine level,[4] principally responsible for the (n, γ) cross section at low energies, has a substantially smaller proton width than the 405-ev level.

3. Measurements of the ratios of the cross sections of the reactions Li^6(n, α) and B^{10}(n, α) were continued (Fig. 4). For E > 25 kev the known resonance maximum of Li^6 at $E_r = 250$ kev appeared in the measurements. The area of the peak in Fig. 3 corresponds to the known parameters of the 250-kev level[3] if one assumes that in the spectrum, formed as the results of multiple inelastic scattering of the primary neutrons (E = 14 Mev) with lead nuclei, ~ 30% of the neutrons have an energy less than 250 kev.

In the region E < 25 kev the ratio σ_{Li}/σ_B changes very little, varying by not more than 3% from its value for thermal neutrons. The constancy of the cross section ratio indicates the small magnitude of the deviation from the 1/v law in the course of the cross sections of both reactions. Indeed, if one were to assume appreciably larger deviations from the 1/v law, these must be almost precisely the same for the Li^6(n, α) and B^{10}(n, α) reactions [and also for N^{14}(n, p) — see above]. But the Li^7, B^{11} and N^{15} nuclei differ sharply in the location and character of their excited states. Because of this any constancy in the deviations from the 1/v law for the above reactions is unlikely.

4. Since the reactions B^{10}(n, α) and Li^6(n, α) are often used in measurements of the flux of neutrons of low and intermediate energies, it is essential to obtain a quantitative estimate of the deviation of the

*Control experiments have shown that in the 1 — 5 kev region the background is connected with the ground state neutron capture in lead (grade SO, 99.99% Pb), and the contribution from capture in the materials of the amplifier and assembly is negligible.

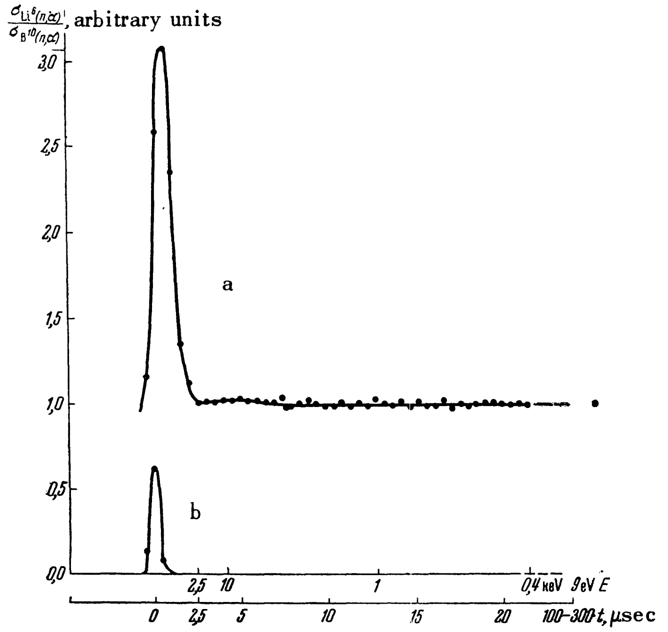

FIG. 4. a — ratio of the cross sections of the reactions $Li^6(n, \alpha)$ and $B^{10}(n, \alpha)$ vs. the slowing-down-time t or of the neutron energy E ; b — the shape of the primary neutron burst (in arbitrary units).

cross sections of these reactions from the 1/v law. With this goal we shall analyze the course of the cross sections of these reactions using the known facts[6] on the excited states of Li^7 and B^{11}. In these nuclei, at excitation energies on the order of the neutron binding energy, the distances between neighboring levels of the same momentum and parity is large compared with the widths of the levels. Since for $E \to 0$ the cross section of a reaction is inversely proportional to the square of the energy of the level, one can assume that for low energies the cross section is determined to a large extent by a single level (or by two levels with different momenta). In that case the course of the cross section will be described by the Breit-Wigner formula for a single level. From this formula it is not difficult to obtain the following expression for the course of the cross section of the (n, x) reaction with s-neutrons for $E \ll E_r$, where E_r is the energy of the resonance state, and E is the neutron energy (in the laboratory system of coordinates):

$$(\sigma E^{1/2})_0/\sigma E^{1/2} = 1 + \alpha\sqrt{E} + \beta E, \tag{1}$$

where

$$\alpha = \frac{m}{\pi\hbar^2}\left(\frac{A}{A+1}\right)^2\frac{(\sigma E^{1/2})_0}{g}, \tag{2}$$

$$\beta = -\frac{2-\alpha E_1^{1/2}}{E_r} - (1-\alpha E_1^{1/2})\left(\frac{d\ln\Gamma_x}{dE}\right)_0 + \frac{\alpha}{2E_1^{1/2}}, \tag{3}$$

m is the neutron mass, A is the mass number of the target nucleus, $g = (2J+1)/2(2i+1)$, i and J are respectively the momenta of the target nucleus and of the compound nucleus, Γ_x and Γ_n are respectively the widths for emission of particles x and of a neutron by the compound nucleus, and E_1 is the neutron energy at which the neutron width Γ_n, proportional to $E^{1/2}$, becomes equal to the width Γ_{x0}. The index 0 always indicates the value of the term at zero neutron energy.

The term $\alpha\sqrt{E}$ in (1) is connected with the energy dependence of the neutron width which appears in the denominator of the Breit-Wigner formula. The values of the coefficients α, presented in Table I for several nuclei, are computed from formula (2) using the values of $(\sigma E^{1/2})_0$ from Ref. 3. In several non-interfering levels introduce a contribution in the cross section of the reactions for low neutron energies, then the values of α will be less than those shown in Table I. For levels excited by p-neutrons for $E \ll E_r$ we get $\sigma E^{1/2} \sim E$, i.e., such levels influence the value of the coefficient β in (1).

The energy dependence of the ratio of the cross sections of the two reactions is also described by expression (1), but with coefficients α and β equal to the difference between the corresponding coefficients for the two reactions.

5. Combining by the method of least squares the ratio σ_{Li}/σ_B obtained in our measurements with the relation (1) gives the following values for the coefficients:

TABLE I.

Target Nucleus	$\alpha\cdot 10^2$, $keV^{-1/2}$ — Momentum of the compound nucleus: $J=i+1/2$	$J=i-1/2$
He^3	1.55	4.65
Li^6	0.40	0.80
B^{10}	2.22	2.96

$$\alpha_B - \alpha_{Li} = (1.5 \pm 0.7)\cdot 10^{-2}\ \text{kev}^{-1/2},$$

$$\beta_B - \beta_{Li} = (-2 \pm 1)\cdot 10^{-3}\ \text{kev}^{-1}.$$

Since $\alpha_{Li} \leq 0.8\times 10^{-2}\text{kev}^{-1/2}$, it follows from the results of the measurements it follows that $\alpha_B \leq (2.3 \pm 0.7)\times 10^{-2}\ \text{kev}^{-1/2}$ which is in agreement with the theoretical estimate (Table I).

In estimating the constant β it is necessary to use information on the location and character of the levels of Li^7 and B^{11} closest to the binding energies.[6] The large cross section of lithium for thermal neutrons may be due to the wide level at $E_r = -750$ kev. In that case, taking also into account the level with $E_r = 250$ kev, excited by p-neutrons, the calculated value becomes $\beta_{Li} \approx 0.6\times10^{-3}$ kev^{-1}. If distant levels contribute appreciably to the thermal cross section of lithium, then $\beta_{Li} \approx -1.7\times10^{-3}$ kev^{-1}. With the help of these estimates we find, from the experimental value of $\beta_B - \beta_{Li}$ that $(-1.4 \pm 1)\times10^{-3} \geq \beta_B > (-3.7 \pm 1)\times10^{-3}$ kev^{-1}. The $B^{10}(n, \alpha)$ cross section for $E > 400$ kev is appreciably below the values extrapolated from the 1/v law.[7] This indicates that the main contribution to the cross section at low energies is due to levels with $E_r < 400$ kev. On the other hand, the levels of B^{11} located below the binding energy cannot lead to a negative value for β_B. The course of the $B^{10}(n, \alpha)$ cross section for $E < 1$ Mev (in particular the non-linear decrease of the cross section for $E > 400$ kev) and the course of the total cross section of B^{10} in the same energy interval[8] can be satisfactorily explained by the existence in B^{11} of a wide level with momentum $5/2^+$ or $7/2^+$, with $E_r \sim 250$ kev, with alpha width $\Gamma_\alpha \sim 400$ kev, and with neutron width $\Gamma_n \sim 200$ kev. Such a level leads to a value $\beta_B \sim -5\times10^{-3}$ kev^{-1}. This value can be brought into agreement with the estimate, which follows from our measurements, if some contribution (of the order of 30%) to the thermal cross section of B^{10} is introduced by odd-parity levels of B^{11}.

The wide level of B^{11} which we discussed above may coincide with the level at $E_r \sim 370$ kev noticed in the study of the $N^{14}(n, \alpha)$ reaction[9] and with the possible level at $E_r \sim 200$ kev being discussed in the literature.[5] The downward deviation of the $B^{10}(n, \alpha)$ cross section from the 1/v law, connected with the $\alpha\sqrt{E}$ term, is compensated to an appreciable extent by the βE term to the extent that for boron $\beta < 0$. As follows from the estimates of α_B and β_B introduced earlier, the $B^{10}(n, \alpha)$ cross section in the interval $E < 25$ kev goes below the 1/v law with a deviation not exceeding 5 — 10%. For the $Li^6(n, \alpha)$ reaction the deviation from the 1/v law in the same energy interval is even less.

6. The slowing-down-time-in-lead neutron spectrometer was also used to measure the energy dependence of the ratio of the effective cross sections of the $He^3(n, p)$ reaction and the $Li^6(n, \alpha)$ and $B^{10}(n, \alpha)$ reactions. Proportional counters filled with a mixture of He^3 + Ar + methylal or Co_2, and proportional counters or ionization chambers with a thin layer of boron of Li^6F were used to detect the corresponding reactions.

It turned out that the ratios $\sigma_{He^3}/\sigma_{Li}$ or σ_{He^3}/σ_B decrease with increasing energy, with the decrease exceeding 15% for E = 27 kev (Fig. 5). It was shown above that the cross sections of boron and lithium in this energy region are somewhat lower than given by 1/v. Therefore, the cross section of the $He^3(n, p)$ reaction decreases with energy appreciably faster than by the 1/v law. This result is confirmed by the measurements carried out at Harwell[3] at $E \geq 120$ kev (Fig. 5).

One can attempt to attribute the large cross section of the $He^3(n, p)$ reaction ($\sigma = 5400 \pm 300$ bn for thermal neutrons[3]) and the energy dependence of the cross section to the existence in the He^4 nucleus of an excited state with momentum 0^+ or 1^+ located not far from the binding energy of a neutron in He^4. The values of the coefficient α in formula (1) expected in this case are indicated in Table I. Combining by the method of least squares the results of the measurements with expression (1) gives the following value of the coefficient of the term $\sqrt{E}$:

$$\alpha_{He} - \alpha_{Li} = (1.9 \pm 0.6)\cdot 10^{-2}\ \text{kev}^{-1/2};$$
$$\alpha_{He} - \alpha_{B} = (0.4 \pm 0.6)\cdot 10^{-2}\ \text{kev}^{-1/2}.$$

The errors shown are root-mean-square statistical errors; the true uncertainty in the result is greater because of the possible systematic errors. To the extent that $\alpha_{Li} \leq 0.8\times10^{-2}$ kev$^{-1/2}$ and $\alpha_B \leq 2.3\times10^{-2}$ kev$^{-1/2}$, the experimental results are not in disagreement (taking into account the experimental error) with the value $\alpha_{He} = 1.55\times10^{-2}$ kev$^{-1/2}$ and agree less well with the value $\alpha_{He} = 4.65\times10^{-2}$ kev$^{-1/2}$.

The β_{He} coefficient related to the level energy was determined from measurements of σ_{Li}/σ_{He}; β_{Li} was taken equal to 0.6×10^{-3} kev^{-1}, $\alpha_{He} - \alpha_{Li} = 0.95\times10^{-2}$ kev$^{-1/2}$ for J = 1 and $\alpha_{He} - \alpha_{Li} = 4.05\times10^{-2}$ kev$^{-1/2}$ for J = 0. β_{He} was found equal to 7.6×10^{-3} kev^{-1} if J = 1 and equal to 1×10^{-3}kev^{-1} if J = 0. Assuming that the introduced proton and neutron widths of the He^4 level are equal to each other, we obtain the estimate $E_1 = 630$ kev. With the help of (3), introducing a small correction for the contribution of p-neutrons in the $He^3(n, p)$ cross section (see below), we obtain for the level energy the value presented in Table II. Values of Γ_{p0}, the proton width at an excitation energy equal to the binding energy of a neutron in He^4, are also given in Table II. Γ_{p0} is determined from relation (4) which is derived from the Breit-Wigner formula:

$$\Gamma_{p0}/\,|\,E_r\,| = [2\alpha E_1^{1/2}/(2 - \alpha E_1^{1/2})]^{1/2}. \quad (4)$$

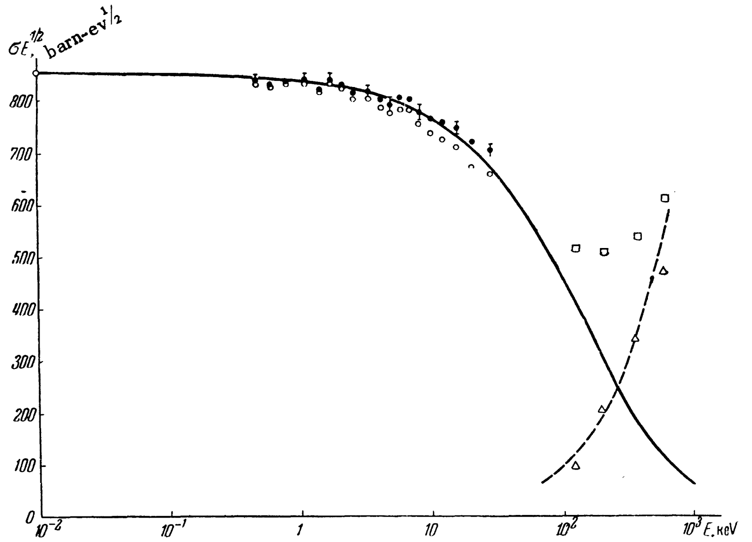

FIG. 5. Energy dependence of the cross-section of the He^3(n, p) reaction. ● — values of σ_{He}/σ_{Li} obtained with the slowing-down-time spectrometer (normalized to $(\sigma_{He}E^{1/2})_0$). ○ — values of $\sigma_{He}E^{1/2}$ calculated from ●, assuming that the variation of the cross section of the $Li^6(n, \alpha)$ reaction in this region is due only to the level with E_r = — 750 kev. □ — values of $\sigma_{He}E^{1/2}$ from the Harwell[3] measurements. Δ — differences between points □ and the solid curve. The solid curve represents the values of $\sigma_{He}E^{1/2}$ calculated for levels with parameters J = 1, E = — 250 kev, Γ_{p0} = 250 kev (contribution of s-neutrons). The dashed curve represents the dependence of const × E (which can be interpreted as the contribution of p-neutrons).

The negative sign of E_r shows that the level is located below the binding energy of a neutron in He^4.

The solid curve of Fig. 5 represents $\sigma E^{1/2}$ = f(E) calculated for a level with parameters J = 1^+, E_r = — 250 kev, Γ_{p0} = 250 kev. For E ≥ 120 kev the experimental points lie above this curve while the difference $(\sigma_{exp.} - \sigma_{calc.}) E^{1/2}$ is approximately equal to E which would be expected if the reaction were cause by p-neutrons.

7. The investigated level of He^4 must manifest itself in the scattering of protons by tritium, at a proton resonance energy of E_r ~ 800 kev if J = 1 and E_r ~ 500 kev if J = 0. In the only work in this energy region,[10] measurements carried out at E = 700, 990, 1100 kev (etc) showed a sharp rise in the scattering cross section from the point at 990 kev to that at 700 kev. In light of the arguments presented above, we consider this result as the manifestation of resonance scattering although the authors of Ref. 10 adhere to another explanation. Frank and Gammel[11] have carried out a phase analysis of the data on the p — H^3 scattering in the energy region of 1 to 3.5 Mev and obtained an indication of the existence of a 0^+ level with a proton resonance energy E_r ~ 800 kev and a width of a few Mev. To explain the magnitude of the He^3(np) cross section for slow neutrons, the reduced neutron width of such a level must be several times less than the reduced proton width, which is difficult to reconcile with the charge independence of nuclear forces.

A 1^+ level, unlike a 0^+ level, could appear in principle in the $H^3(p, \gamma)$ reaction. The experiment discussed in Ref. 12 gives no indications of a resonance in the yield of γ-rays. However, this fact cannot be used as evidence for J = 0^+ since, as follows from the angular distribution of the γ-rays, s-protons generally do not make any appreciably noticeable contribution to the $H^3(p, \gamma)$ reaction.[12] References 13 and 14 report on a study of the energy spectrum of protons scattered from He^4 and Ref. 15 reports on the spectrum of the products of the $He^3(d, p)He^4$ reaction. No excited state of He^4 with excitation energy less than 28 Mev was observed and an upper limit of 0.1 — 1 mb/sterad was established for the cross sections for scattering or for the excitation to such an excited state. This result indicates that the 1^+ (0^+) level of He^4 considered in that work either does not exist or for some reason the transition probability to it is extremely small (the same situation is also true of the 2^- state of He^4, evidence for which is contained in the work of Refs. 16 and 17).

TABLE II. Parameters of the He^4 level derived from the course of the cross section of the He^3(n, p) reaction.

Momentum and parity	Resonance energy E_r, in kev	Excitation energy of the He^4 nucleus in Mev	Proton width Γ_{p0} in kev
1^+	—200	20.3	200
0^+	—500	20	1200

To clarify this question, and to get more accurate data on the behavior of the He^3(n, p) cross section, it is proposed to carry out in the first place a detailed measurement of p—H^3 scattering in the proton energy region E < 1 Mev.

This work was carried out with the participation of A. N. Volkov, A. M. Klabukov, and I. V. Shtranikh who developed and adjusted the electronic equipment of the slowing-down-time spectrometer. A description of this equipment will published elsewhere.

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Note added in proof (June 26, 1957). The measurements of the ratio of the cross sections for $Li^6(n, \alpha)$ and $He^3(n, p)$ were repeated with better statistics and under conditions which made systematic errors less likely. The results are in agreement, within the limits of errors, with the data presented in Fig. 5; the more accurate values of the parameters α and β are the same: $\alpha_{He} - \alpha_{Li} = \left(3.5 {}^{+0.8}_{-0.5}\right) \times 10^{-2}$ kev$^{-1/2}$, $\beta_{He} - \beta_{Li} = \left(2.8 {}^{+1.5}_{-1}\right) \times 10^{-3}$ kev^{-1}. These limits shown include the root mean square statistical error and an estimate of the limits of systematic errors. The course of the cross section is described satisfactorily by the Breit-Wigner formula with the following parameters for the resonant state: the contribution of a $J = 0^+$ state in the $He^3(n, p)$ cross section for thermal neutrons is $x = (94 \pm 6)\%$; if x is taken to be 94% then $-E_r \approx 250$ kev, while for $x = 100\%$, $-E_r = 500 - 1000$ kev; $\Gamma_{p0} | E_r | \approx 2.1$.

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2