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RADIATIVE THERMAL NEUTRON CAPTURE BY HELIUM-3

Submitted to ЯФ

Алфименков В.П. и др. E15 - 12380

Радиационный захват тепловых нейтронов гелием-3

В работе сообщаются результаты экспериментального и теоретического исследования радиационного захвата тепловых нейтронов гелием-3. Измерения выполнены по методу времени пролета на импульсном реакторе ИБР-30 с применением газовой мишени ^{3}He и детектора NaI(Tl). Выполнены расчеты нейтронного эффективного сечения с использованием простейших, гауссовых волновых функций основных состояний ^{3}He и ^{4}He. Из сравнения экспериментального и теоретического результатов получена оценка примеси состояния "смешанной симметрии" в ядре ^{4}He.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1979

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Radiative Thermal Neutron Capture by Helium-3

The results of experimental and theoretical investigation of the radiative thermal neutron capture by ^{3}He are reported. The measurements were performed by the time-of-flight method at the pulsed reactor IBR-30 with the ^{3}He gaseous target and NaI(Tl) detector. The effective cross section of the (n,γ) reaction followed by magnetic dipole radiation was calculated with the Gauss wave functions of the ground states of ^{3}He and ^{4}He. A comparison of experimental and theoretical results allowed to estimate the admixture of the "mixed symmetry" state in the ^{4}He nucleus.

The investigation has been performed at the Laboratory of Neutron Physics, JINR.

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1. INTRODUCTION

Radiative neutron capture investigations with light nuclei ^{1}H, ^{2}H, ^{3}H are closely connected with the nucleon-nucleon interaction problem and may give direct information about the wave functions of few-body systems. By now theoretical and experimental radiative thermal neutron capture study was carried out only for hydrogen and deuterium. Experimental data on the interaction of neutrons with ^{3}He nucleus was very poor. In a short communication [1] the cross section value $\sigma_{n\gamma} = 60 \pm 30\,\mu b$ for thermal neutrons was given, but our latest n^{3}He results [2] obtained for a wide energy range (1-70 keV) made it doubtful. This was the reason for extending our n^{3}He investigations to a thermal neutron energy range. The experiment in this energy range is difficult to perform due to a very small value of the investigated cross section comparing with ^{3}He(n, p) competing ones.

From theoretical point of view one is eager to understand why the radiative capture cross section of thermal neutrons decreases going from proton to two and three nucleon target. The known value of thermal neutron cross section for ^{1}H, ^{2}H and ^{3}He is equal to 334, 0.6 and 0.06 mb [1], respectively. Quantitative analysis for deuterium is given in [3,4] and in [5] one may find a qualitative explanation for helium-3. The authors there operate with the wave functions symmetry selection rules for M1 transitions taking place in the thermal neutron energy range in few nucleon systems studied. The radiative capture under investigation is due to small components of the total wave function. These components, known as mixed symmetry wave functions, are discussed in chapter 2 in the frame of a simple formalism without isotopical spin. There also is obtained the theoretical formula for the cross section of radiative neutron capture by ^3He with M1 transition. In chapter 3 there is described the method and reported the results obtained for effective cross sections. The value of thermal cross section is smaller than that given in /1/. In the last chapter conclusions made for wave functions of the ground states of ^3He and ^4He are discussed.

2. THEORY

2.1. Structure of the ^3He and ^4He wave functions

The wave functions of ^3He and ^4He ground states ($L=0$, $s=1/2$, $J=1/2$ for ^3He and $L=0$, $s=0$, $J=0$ for ^4He) can be written basing on /5/ in the form:

$$\psi^{m}_{^3He}(\tilde{12},3) = b^{s}\phi^{s}_{^3He}(\bar{123})S^{a,m}_{^3He}(\tilde{123}) + b^{a}\phi^{a}_{^3He}(\tilde{123})S^{s,m}_{^3He}(\bar{123}), \tag{1}$$

$$\psi_{\alpha}(\tilde{12},\tilde{34}) = c^{s}\phi^{s}_{\alpha}(\bar{1234})S^{a}_{\alpha}(\tilde{1234}) + c^{a}\phi^{a}_{\alpha}(\tilde{1234})S^{s}_{\alpha}(\bar{12},\bar{34}),$$

$$m = \pm 1/2$$

if consideration is restricted to the case of s-states of ^3He and ^4He (which correspond only to central nucleon-nucleon interaction). Here $|b^s|^2 + |b^a|^2 = 1, |c^s|^2 + |c^a|^2 = 1$, particles 1 and 2 are the protons, 3 and 4 are the neutrons, signs $-$ and $\sim$ and indices s and a are used to mark symmetry and antisymmetry in the permutation of identical particles. Total wave functions are evidently antisymmetrical in respect to the permutation of identical nucleons. The second component of the ψ function with antisymmetrical space and symmetrical spin functions is the mixed symmetry function. The ^3He wave function introduced in /6/ using the isospin formalism has the form:

$$\psi_{^3He} = b_1 f_s(\overbrace{123})S^{a}_{^3He}(\tilde{123}) + \frac{b_3}{\sqrt{2}} f_{1m}(\bar{123})S^{a}_{^3He}(\tilde{123}) +$$

$$+ \frac{b_3}{\sqrt{2}} f_{2m}(\tilde{123})S^{s}_{^3He}(\bar{123}) - b_2 f_a(\widetilde{123})S^{s}_{^3He}(\bar{123}) = \tag{2}$$

$$= b_1 S^{a}_{^3He}(\tilde{123})\left(f_s + \frac{b_3}{b_1\sqrt{2}} f_{1m}\right) + \frac{b_3}{\sqrt{2}} S^{s}_{^3He}(\bar{123})\left(f_{2m} - \frac{b_2}{b_3}\sqrt{2} f_a\right),$$

where the mixed symmetry components f_{1m} and f_{2m} are symmetrical or antisymmetrical with respect to the permutation of particles 1 and 2 and are different from the main component $f_s(123)$ symmetrical with respect to all the three particles. Comparing formulas (1) and (2) we can derive a simple connection between the functions and coefficients in these two approaches:

$$b^s = b_1,\ b^a = b_3/\sqrt{2},\ \phi^{s}_{^3He}(\bar{123}) = f_s + \frac{b_3}{b_1\sqrt{2}} f_{1m},$$

$$\phi^{a}_{^3He}(\tilde{123}) = f_{2m} - \frac{b_2}{b_3}\sqrt{2} f_a .$$

This relationship becomes simplier $\phi^{a}_{^3He}(\tilde{123}) = f_{2m}$ if as usual one takes $b_2 = 0$, being correspondent to the absence of the component f_a antisymmetrical with respect to the space components of all the particles.

In many calculations (for instance, of the radiative neutron capture with E1 transition) the ϕ^a component can be neglected but in the case of radiative neutron capture with M1 transition this component is very important. Wave functions $\phi^{a}_{^3He}$ and ϕ^{a}_{α} which will be used in further chapters we can write following /6,7/ in the form

$$\phi^{a}_{^3He} = n_t \left\{ e^{-t^2(r_{21}^2 + r_{31}^2) - t_1^2 r_{23}^2} - e^{-t^2(r_{12}^2 + r_{32}^2) - t_1^2 r_{31}^2} \right\},$$

$$\phi_\alpha^a = n_\alpha \{ e^{-\alpha^2(r_{12}^2+r_{14}^2+r_{32}^2+r_{34}^2)-\alpha_1^2(r_{13}^2+r_{24}^2)} -$$

$$- e^{-\alpha^2(r_{21}^2+r_{24}^2+r_{31}^2+r_{34}^2)-\alpha_1^2(r_{23}^2-r_{14}^2)} \}, \quad (3)$$

$$\vec{r}_{ij} = \vec{r}_i - \vec{r}_j .$$

We can carry out the exponent development over degrees $\alpha - \alpha_1$ and $t - t_1$ under assumption that the values of α, α_1 and t, t_1 are about equal:

$$\phi_{^3He}^a = N_t e^{-t^2(r_{21}^2+r_{31}^2+r_{23}^2)} (r_{31}^2 - r_{23}^2), \quad (3')$$

$$\phi_\alpha^a = N_\alpha e^{-\alpha^2(r_{12}^2+r_{13}^2+r_{14}^2+r_{23}^2+r_{24}^2+r_{34}^2)} (r_{23}^2+r_{14}^2-r_{13}^2-r_{24}^2),$$

in which N_t and N_α are the normalization constants obtained from

$$\int |\phi_{^3He}^a|^2 d\vec{r}_{31} d\vec{r}_{32} = 1, \quad \int |\phi_\alpha^a|^2 d\vec{r}_{31} d\vec{r}_{32} d\vec{u} = 1,$$

$$\vec{u} = (\vec{r}_1 + \vec{r}_2 + \vec{r}_3)/3 - \vec{r}_4 .$$

2.2. Theoretical estimation of the thermal neutron cross section $\sigma_{n\gamma}$ (^{3}He)

We consider the radiative neutron capture of ^{3}He as a direct process similar to n,γ reaction for proton and deuterium targets. The ^3He+n system at $L=0$ in the case of s-wave neutrons may have $J=0$ (singlet channel) or $J=1$ (triplet channel). The ground state spin of the formed ^{4}He nucleus has spin $J=0$. The radiative capture is possible only in the triplet channel (M1 transition $1^+ \to 0^+$) since the $0^+ \to 0^+$ - transition is forbidden. The wave function of the

system in the triplet state can be written in the form /5/:

$$\psi_m^f(\tilde{12},\tilde{34}) = b^s[\phi_{^3He}^s(\tilde{123})R(123,4) - \phi_{^3He}^s(\tilde{124})R(124,3)] *$$

$$* T_m^a(\tilde{1234}) + b^a[\phi_{^3He}^a(\tilde{123})R(123,4)T_m^s(\tilde{1234}) - \quad (4)$$

$$- \phi_{^3He}^a(\tilde{12},4)R(124,3)T_m^s(\tilde{1243})],$$

$$m = -1, 0, 1.$$

The triplet spin wave functions T^m in formula (4) obtained from the ^{3}He and free neutron spin functions are given in /5/. The function of the relative motion of helium-3 and the neutron with a zero orbital momentum normalized over a unit energy interval is:

$$R(123,4) = \sqrt{\frac{2}{\pi}} \frac{p}{\hbar} \left(\frac{3M}{4p\hbar}\right)^{1/2} \frac{\sin(p \cdot u/\hbar)}{u \cdot p/\hbar} \frac{1}{\sqrt{4\pi}}, \quad (4')$$

$$\vec{u} = (\vec{r}_1 + \vec{r}_2 + \vec{r}_3)/3 - \vec{r}_4 ,$$

where p is the momentum of the neutron. The cross section we seek for can be found by calculating the α-particle desintegration cross section and by using the detailed balance relation:

$$\sigma_{\gamma n} = \frac{4\pi^2 E_\gamma}{\hbar c} \sum_m |\langle f|\hat{M}|i\rangle|^2, \quad (5)$$

$$\sigma_{n\gamma} = \frac{E_\gamma^2}{3Mc^2E} \sigma_{\gamma n},$$

here $\hat{M} = [\mu_p(\sigma_z^1 + \sigma_z^2) + \mu_n(\sigma_z^3 + \sigma_z^4)] \frac{e\hbar}{2Mc}$ is the conventional operator of the dipole magnetic momentum, $\langle f|\hat{M}|i\rangle$

is the matrix element of the M1 transition between ^4He ground state and triplet state of the $^3He + n$ system, $E_\gamma = |B| + E$ is the energy of gamma quanta, E is the total kinetic energy in the center of mass system, B is the binding energy of the neutron in ^4He nuclei. The way $\hat{M}$ operator affects the spin wave function gives, as is shown in /5/, the following selection rule: transition is allowed only between the two wave function components with symmetrical spin functions S_α^s and $T_{m=0}^s$, i.e., between the components with antisymmetrical wave functions, the matrix element in (5) being equal to:

$$< \psi_0^b |\hat{M}| \psi_\alpha > = \frac{8}{3} b^a c^a (\mu_p - \mu_n) \int \phi_\alpha^a \phi_{^3He}^a R \, d\vec{r}_{13} d\vec{r}_{23} d\vec{u}. \quad (5')$$

Calculation of this matrix element using wave functions (3') and (4') gives us the following formula for the ^3He radiative thermal neutron capture cross section:

$$\sigma_{n\gamma} = 350 \frac{e^2}{(\hbar c)^2} (\mu_p - \mu_n)^2 \frac{E_\gamma^3}{(Mc^2)^{3/2} \sqrt{E_n}} \frac{\alpha^7 t^{10}}{(\alpha^2 + \frac{3}{4} t^2)^{10}} (c^a b^a)^2 e^{-\frac{M E_n}{4 \hbar^2 \alpha^2}} \quad (6)$$

where E_n is the kinetic energy of the neutron in the laboratory system of coordinates.

Experimental value of the cross section together with its theoretical estimation allow one to make a conclusion about the values of coefficients b^a and c^a.

3. EXPERIMENT

3.1. Experimental procedure

Our measurements were carried out by the time-of-flight method at the pulsed reactor IBR-30 at a 15 m flight path. The average power of the pulsed reactor was rather low (20 kW), but pulsed mode of operation allowed us to restrict the role of cosmic background which is essential in the measurements of such small cross sections.

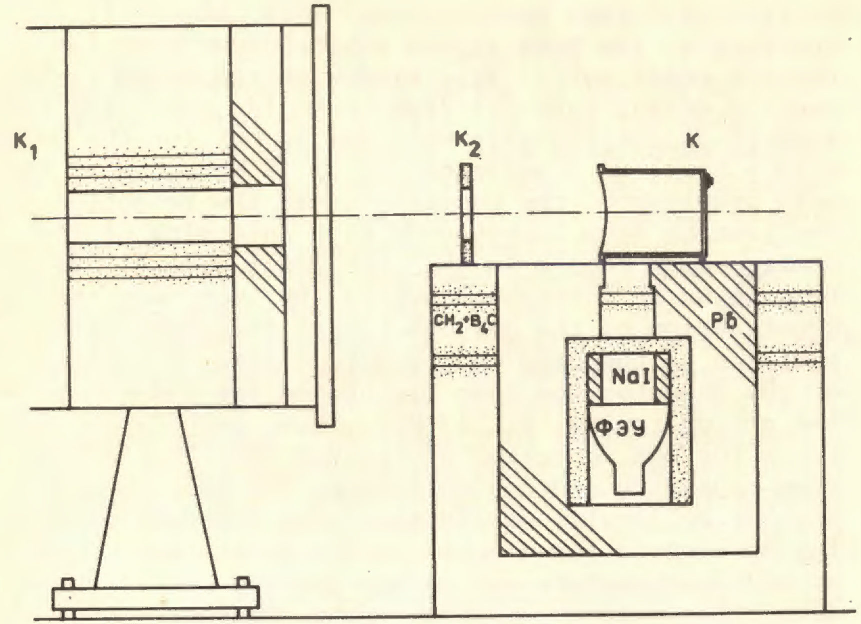

Fig. 1. Experimental lay-out for the measurement of the effective cross section of radiative thermal neutron capture ^3He.

The experimental lay-out is shown in fig. 1. The neutron beam 14 cm in diameter was formed by the main and additional collimators. A cylindrical aluminium container 17 cm in diameter and 20 cm long had a 15 μm lavsan entrance window and was filled with the ^3He gas at a pressure of 730 torr. This container was installed in the neutron beam so that its back wall was not seen directly from the detector. The NaI(Tl) detector ø 10 cm x 10 cm was placed at an angle of 90° with respect to the neutron beam and at a distance of 28 cm from its axis. The detector was shielded with lead and parafin with boron carbide. The channel in the lead shielding between the crystal and the target was also filled with parafin with boron carbide. Photomultiplier pulses were analysed with the amplitude analyzer in the time window synchronized with the reactor power pulse. This window corresponded to the neutron energy interval from 10 to 140 meV. Also the time-of-flight analysis was carried out for the pulses with a level of discrimination of 18 MeV. One of the main problems of the experiment was the reduction on the neutron beam background. High intensity of the neutron beam needed in the experiment was followed by pile up of background pulses. By improving the construction of the gaseous target container, its position on the beam and by more careful shielding of the detector, the beam background was removed from the energy region $E_\gamma > 17$ MeV. Thus, acceptable conditions for the detection of γ-rays ($E_\gamma = 20.6$ MeV) from radiative neutron capture by ^3He were created. Another difficulty was to take into account correctly the background inavoidable in the experiment. Background measurements during the pumping out of ^3He from the container would be wrong. Neither scattering nor absorption in ^3He could not be taken into account and a contribution of the background from the container back wall (in working conditions the target plays the role of a screen) would be much higher. That is why the background was measured with the container filled with ^4He, and a screen from equivalent ^6LiF absorber was placed in front of the back wall. It gave us an upper background limit, since neutron absorption by ^6Li is accompanied by the radiative capture process. The low limit was obtained in the measurements with investigated ^3He target and boron filter in front of the K_2 collimator. The cross section value $\sigma_{n\gamma}$ was obtained from the formula:

$$N_\gamma(E) = \frac{\sigma_{n\gamma}}{\sigma_t} \Pi(E)(1 - e^{-n\sigma_t(E)}) B \epsilon_\gamma \frac{\Delta\Omega}{4\pi} . \qquad (7)$$

Here N_γ is the number of detector counts above the background in a given neutron energy interval, n is the target thickness, $\Pi(E)$ is the integral beam intensity, ϵ_γ is the detector efficiency of γ-quanta.

The ϵ_γ value was calculated as in /2/ using a known pulse height distribution and the cross section data for interaction of γ-rays with the NaJ(Tl) crystal. B - factor is the shielding attenuation factor for γ-rays. In fact the ratio of the capture cross section $\sigma_{n\gamma}$ to a well known absorption cross section was measured, since σ_t for the ^3He, in practice, is equal to σ_{np}. This ratio should be independent of thermal neutron velocities.

The intensity of the beam was determined by two methods: the measurements with a thin counter in the direct beam (^3He pressure in this counter was 10^{-2} torr) and the measurement of incoherent neutron scattering from the vanadium target with the help of the calibrated boron counter. The results of these two measurements in the thermal neutron energy range are in agreement within 15%: Π (10-140 meV) = 3.5×10^8 s^{-1}

3.2. Results of the effective cross section $\sigma_{n\gamma}$ measurements

The amplitude spectrum of the NaJ(Tl) detector pulses for 65 hours of measurement is presented in fig.2. Energy calibration was done using the following lines: 11.4 MeV (neutron capture by ^{10}B), 7.7 MeV (neutron capture by Al) and 4.43 MeV from the Po-Be neutron source. For energies higher than 17 MeV the effect due to radiative neutron capture by ^3He is observed. From these data, using formula (7) and $\sigma_t(^3He) = 5327$ barn the cross section

$$\sigma_{n\gamma}(0.025) = 29 \pm 3 \ \mu b \qquad (8)$$

was obtained. Here the systematical error of measurement mainly due to uncertainties of $\Pi \epsilon_\gamma$ value is indicated. The statistical one is equal to 15%.

The time-of-flight method gave us a possibility of estimating the energy dependence of $\sigma_{n\gamma}$. The time spectrum of pulses corresponding to energies higher than 18 MeV in fig. 2 is shown in fig. 3. The cosmic

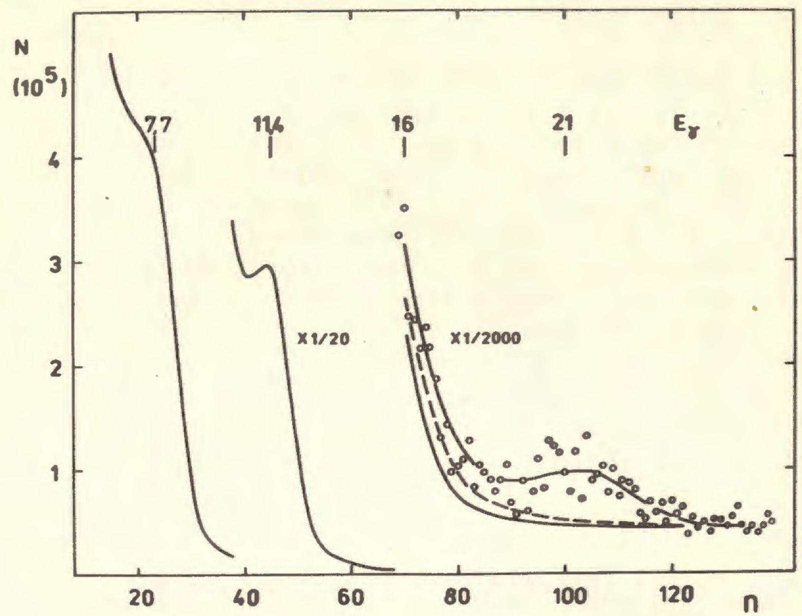

Fig. 2. Amplitude spectrum (points) obtained with the ^{3}He target on the neutron beam. Figures above indicate the value of E_{γ} in MeV: N, the number of counts per channel after 65 hours of measurements; n, the number of the channel of the amplitude analyzer. The dashed line and the lower solid line are the upper and low limit, respectively, of the background.

background level is given by a dashed curve and the quantity $\Pi(E)(1-e^{-n\sigma t})$, by a solid line. This quantity was normalized to the effect measured in the maximum above the cosmic background. The experimental points being in agreement with the solid curve is an additional confirmation of the fact that the pile up contribution in the energy region $E_{\gamma} > 18$ MeV is small.

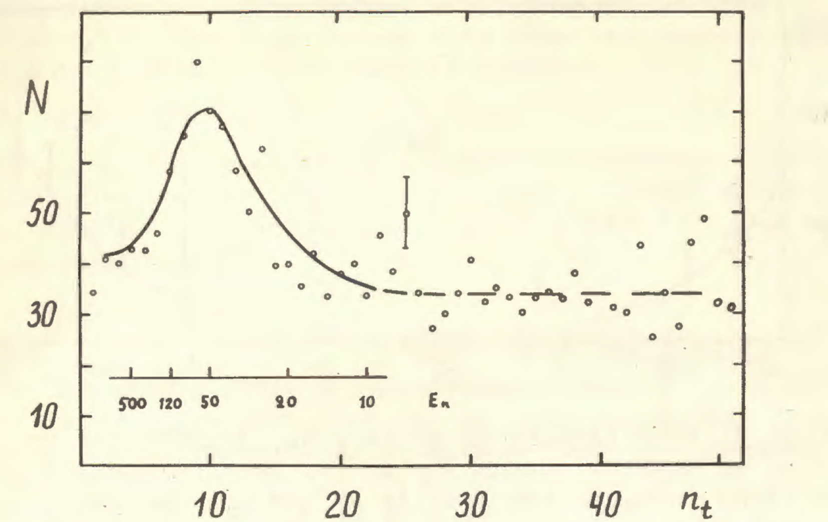

Fig. 3. Part of experimental time-of-flight spectrum. N is the number of counts per channel after 38 hours of measurements in the amplitude window E_{γ}=18-24 MeV, n_t is the number of the channel of the analyzer 512 μsec wide. Figures give neutron energy E_n in meV.

The energy dependence of the cross section estimated basing on these data is shown in fig. 4. The statistical accuracy of experimental points here is not better than 30% due to shorter measuring time and the fact of dividing the spectrum into parts. The value $\sigma_{n\gamma}$ (0.025 eV) discussed above is indicated by a cross. The energy dependence of the cross section for low energy region is in agreement with the known $1/v$ law for the reaction cross section. The data of /2/ for keV energy region are shown also. They correspond to the $\sqrt{E_n}$ dependence expected for p-neutrons. The solid line is the theoretical estimation for the cross section

$$\sigma_{n\gamma}(E_n) = c(M1)E_n^{-1/2} + c(E1)E_n^{1/2}$$

normalized to the experimental result $\sigma_{n\gamma} = (19 \pm 3)\ \mu b$ at a thermal point in the low energy region and to theoretical value in keV energy region discussed in /2/.

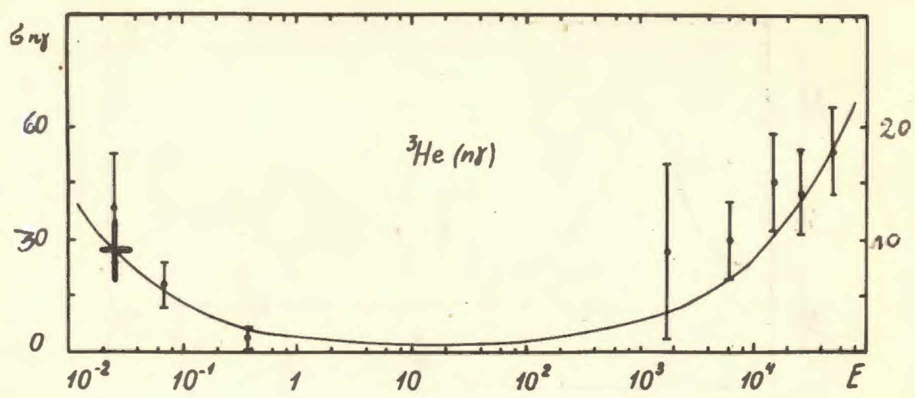

Fig. 4. Effective cross section $\sigma_{n\gamma}$ in μb as a function of neutron energy E_n in eV. Open points and a cross indicate the results of the present paper, black points - paper [2], solid curve - calculation.

4. CONCLUSIONS

The radiative thermal neutron capture cross section measured in this work for ^{3}He is smaller than 60 ± 30 μb given in [1]. The difference can be likely explained by the influence of fast neutrons on the results of measurements [1] with a target placed in the reactor core.

In present paper and in ref. [2] the first data about the energy dependence of $\sigma_{n\gamma}(^3He)$ cross section in the region $E < 1$ eV and $1 < E < 70$ keV were obtained. Using these data the energy dependence of $\sigma_{n\gamma}$ in the intermediate energy range was predicted. In the energy interval 5-50 eV the minimal value of cross section (about 0.7 μb) is expected.

For the theory of few nucleon systems most interesting are the conclusions about the wave functions of the ground states of ^{3}He and ^{4}He following our work. Comparing theoretical (6) and experimental (8) results one may estimate a value of $(c^a b^a)^2$. This estimation

depends on a and t values. Many authors believe that $a^{-1} = t^{-1}$, but the values they take are ranging from 2.6 to 5.25 f. In our case it gives:

$$0.3\sigma_{n\gamma} \le (c^a \cdot b^a)^2 \le 3\sigma_{n\gamma}.$$

Here $\sigma_{n\gamma}$ is given in barns. Using theoretical [10,11] and experimental [7,9] results one can adopt a value of $(b^a)^2 \approx 2\%$ for ^{3}He. Then with $a^{-1} = t^{-1} = 3.65$ f [8] we can find for ^{4}He:

$$(c^a)^2 \approx 0.14\%.$$

This estimation is in agreement with the results [11] on ^{4}He binding energy calculation, where a value of $(c^a)^2 = 0.1 \div 0.2\%$ was obtained. It is curious that even such a small contribution of mixed symmetry states into an s-state of the ^{4}He nucleus gives an experimentally observed cross section $\sigma_{n\gamma}(^3He)$.

In our calculation similar to papers [4,5,6] the orbital momenta of ground states of ^{3}He and ^{4}He were taken equal to zero. The states with $L = 2$ must be taken into account in a more careful consideration. The role of these states is discussed in [11,12] in connection with the binding energy and form factor calculations. The admixture of a state with $L = 2$ is 4-8% for ^{3}He and 6-12% for ^{4}He. An assumption that $L = 0$ is justified in our case, since the matrix element of M1 transition between $L = 0$ and $L = 2$ states equals zero, and between $L = 2$ states is very small. It should be noted that the value of $(c^a)^2$ will appear to be even smaller, if one takes into account the transitions between the states with $L = 2$, since a part of the experimentally observed $\sigma_{n\gamma}$ value should be ascribed to these transitions and not to those between S-states of mixed symmetry.

This paper does not consider the role of meson exchange interaction as it is done in several other papers on nD capture. Careful consideration of S-components appeared to be sufficient for the explanation of the results of the experiment in the case of n^{3}He capture process. Theoretical estimates here are

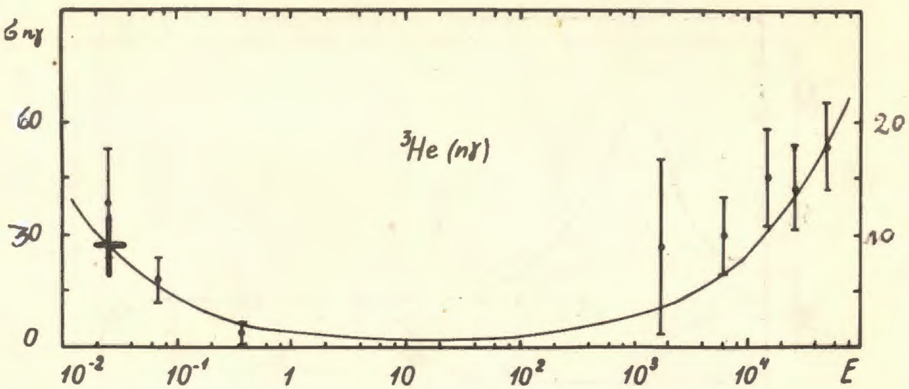

Fig. 4. Effective cross section $\sigma_{n\gamma}$ in μb as a function of neutron energy E_n in eV. Open points and a cross indicate the results of the present paper, black points - paper /2/, solid curve - calculation.

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Here $\sigma_{n\gamma}$ is given in barns. Using theoretical /10,11/ and experimental /7,9/ results one can adopt a value of $(b^a)^2 = 2\%$ for ^3He. Then with $a^{-1} = t^{-1} = 3.65$ f /8/ we can find for ^4He:

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In our calculation similar to papers /4,5,6/ the orbital momenta of ground states of ^3He and ^4He were taken equal to zero. The states with $L = 2$ must be taken into account in a more careful consideration. The role of these states is discussed in /11,12/ in connection with the binding energy and form factor calculations. The admixture of a state with $L = 2$ is 4-8% for ^3He and 6-12% for ^4He. An assumption that $L = 0$ is justified in our case, since the matrix element of M1 transition between $L = 0$ and $L = 2$ states equals zero, and between $L = 2$ states is very small. It should be noted that the value of $(c^a)^2$ will appear to be even smaller, if one takes into account the transitions between the states with $L = 2$, since a part of the experimentally observed $\sigma_{n\gamma}$ value should be ascribed to these transitions and not to those between S-states of mixed symmetry.

This paper does not consider the role of meson exchange interaction as it is done in several other papers on nD capture. Careful consideration of S-components appeared to be sufficient for the explanation of the results of the experiment in the case of n^3He capture process. Theoretical estimates here are approximate. More accurate analysis of radiative neutron absorption by ^3He by using modern methods of the theory of few-nucleon system (i.e., with the help of Faddeev-Jakubovsky equations) is much desired. The results of it should be of course followed by more precise measurements of $\sigma_{n\gamma}(^3He)$.

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