Radiative capture of He^3 neutrons in the energy interval 1–70 keV

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First measurements are reported of the effective cross section of radiative capture of He^3 neutrons in the energy interval 1–70 keV. The resultant energy dependence of the cross section is compared with theoretical predictions.

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The radiative capture of He^3 neutrons is directly related to the four-nucleon problem, a topic actively pursued by theoretical nuclear physicists. However, this problem remained, until recently, virtually untouched by experimentalists. The differential cross section $\sigma(90^\circ) = 5^{+2}_{-1}$ μbarn/sterad at $E_n \approx 4$ MeV was measured,[1] and $\sigma_{n\gamma} = 60 \pm 30$ μbarn was measured for thermal neutrons,[2] although the later work was unpublished. These experiments are difficult because of the small value of the cross section, although the high value of γ-ray energy (20.58 MeV) equalling the binding energy of a neutron in He^4 is helpful.

In our experiments the neutron source was the IBR-30 pulsed reactor operating in the booster regime concurrently with the LUE-40 linear electron accelerator. Measurements were conducted using the time-of-flight method over a 33.2-m base by means of a NaI (Tl) detector with 10-cm diameter and 10-cm thickness, placed at 90- and 45°-angles with the beam. Time-of-flight analysis of pulses after discrimination

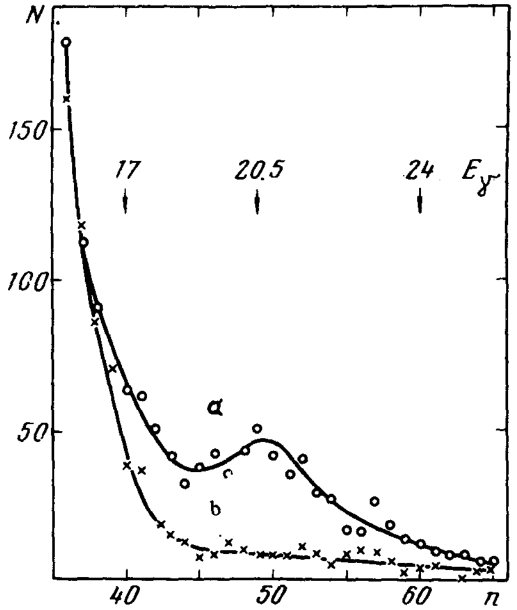

FIG. 1. a—γ-ray spectrum in the reaction He^3 (n,γ) obtained by means of NaI(Tl) crystal at an angle of 90° with the beam; N—number of readouts per channel during 48-hour period of measurements; n—amplitude analyzer channels. b—background spectrum after He^3 substitution with graphite sample, indentical to He^3 with respect to scattering. Numbers indicate energy in MeV.

with a threshold of 16 MeV was performed and the pulse amplitude spectrum was recorded concurrently (in a time window corresponding to interval E_n from 4 to 70 keV). Liquid He^3 in a container was used as a target, its area being 30 cm^2 and thickness $n = 3 \times 10^{22}$ nuclei/cm^2. A screen made of paraffin (10 cm), boron carbide (4 cm), and lead (1 cm) was placed between target and detector. Signal and background measurements were alternated over an 8-hour period. Spectra shown graphically in Fig. 1 show clear evidence for gamma radiation from He^3 radiative neutron capture in the neutron energy range in question.

The value of cross section σ (90°) and its energy dependence were obtained on the basis of a relationship for a thin sample, which in our case holds with greater than 15% accuracy at an energy of 10 keV:

$$N(E_i E_f) = \sigma(90^\circ, \bar{E})\Pi(\bar{E})\epsilon_\gamma n B[1 + a(E_f \infty)]\Delta\Omega ,$$

where $N(E_i E_f)$ is the number of detector readouts in the given interval $(E_i E_f)$ with an average value of neutron energy $\bar{E}$; $\pi(\bar{E})$ is the neutron beam intensity during measurements, determined by means of calibrated boron and helium counters; ϵ_γ is the calculated detector efficiency; n is sample thickness; B is coefficient of attenuation of γ rays by the screen; a is correction factor that describes the contribution of faster neutrons to $N(E_i E_f)$. The latter is introduced through calculations, proceeding from the exponential form of the spectrometer resolution function, known energy dependence of neutron flux, and probable dependence of $(E_n)^{1/2}$ for $\sigma_{n\gamma}$ (He^3). As regards ϵ_γ, the correctness of its value was checked earlier,[1] and was reconfirmed in our calibrated measurements of the known partial width of direct transition (9.0 MeV) in the case of neutron capture in nickel. The calibration uncertainty of ϵ_γ constitutes the basic error

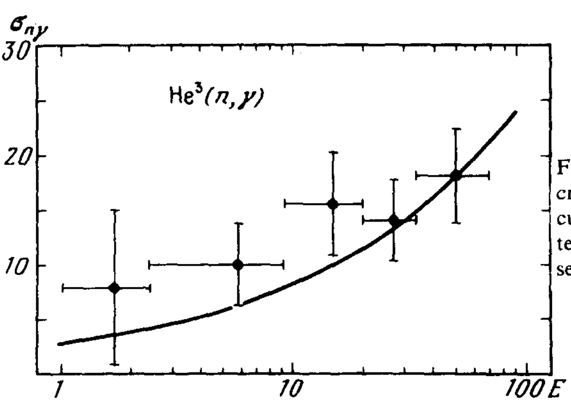

FIG. 2. Energy dependence of the effective cross section $\sigma_{n\gamma}(He^3)$: points—experiment, curve—theoretical prediction discussed in the text, E—neutron energy in keV, $\sigma_{n\gamma}$—cross section in μbarn.

in determining the cross section. The radiative capture cross section shown in Fig. 2 was determined from the relationship $\sigma_{n\gamma} = \frac{8}{3}\pi\sigma(90°)$ which is suitable for the case of angular distribution that corresponds to the function $\sin^2\theta$. In our case this dependence is indicated by the measured relationship of γ-ray intensities at 90 and 45° angles equal to 1.8 ± 0.20. The results obtained are the first for this range of energies.

When discussing these results it should be borne in mind that the first excited 0^+ level of He^4 does not take part in the given process due to the forbidden 0^+—0^+ transitions. Direct capture in the triplet state for the s-neutrons (M1-transition) is also eliminated in view to its $1/v$ energy dependence. Therefore, the most probable interpretation of results is p-wave capture which allows the E1-transition, in contrast to the s-wave capture. The theoretical calculations[3] for the inverse helium photodisintegration reaction—carried out within the framework of perturbation theory, assuming a direct E1-transition and central nucleon-nucleon forces—yield $\sigma_{n\gamma} \sim (E_n)^{1/2} \times (20.58 + 3E_n/4)^3 \exp(-3E_n/4\epsilon)$ which reduces to th simple depndence $(E_n)^{1/2}$ in the measured interval (here $\epsilon \approx 6$MeV, i.e., of the order of the binding energy for one nucleon). The absolute normalization of the theoretical curve in Fig. 2 was carried out on the basis of numerical calculations,[4] using a boundary condition model for the continuous spectrum, at the 22 MeV point and using the detailed balance ratio $\sigma_{n\gamma} = \sigma_{\gamma n}\, 4E_\gamma^2/9mc^2E_n$. The experimental results agree with the theoretical value of cross section obtained in this manner. However, subsequent refinement of the experiment is desirable, as are also continued calculations in the given energy range from a common theoretical viewpoint. It appears also necessary to repeat the thermal neutron experiment since the results of measurements[2] involving a sample in the active region of the reactor may have been affected, in principle, by the fast neutrons.

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