SOVIET PHYSICS JETP VOLUME 16, NUMBER 4 APRIL, 1963

PHOTONEUTRONS FROM In^{115}

É. S. ANASHKINA

A. F. Ioffe Physico-technical Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor May 9, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 1197-1201 (October, 1962)

The energy and angular distributions of photoneutrons from In^{115} are obtained in irradiation by γ-bremsstrahlung at $E_{\gamma \max} = 28$ MeV. The registration was with NIKFI-Ya2 nuclear photographic emulsions. The contribution of the resonance photoeffect came out to $(45 \pm 10)\%$. The angular distribution of photoneutrons in the range 1.0—11.0 MeV is anisotropic. The total yield of photoneutrons in the energy range 0—11.0 MeV is $(1.72 \pm 0.6 \times 10^{-3}$ neutrons/mole-MeV-cm^2.

THE energy distributions of photoneutrons were investigated with the aid of nuclear photoemulsions for Co^{59}[1], Au^{197}[2], Rh^{103}, Ca^{40}, V^{51}, Y^{89}[3], Cu^{64}[4], Ta^{181}, Cr^{52}[5], Bi^{209}[6,7], and Pb^{207}[8].

The form of the experimental curves obtained in these investigations suggests that an additional maximum exists in some of the elements in the region 4—6 MeV. The presence of such a maximum is related[9] with the contribution of the neutrons emitted as a result of interaction between the quanta and individual nucleons on the nuclear shells ("resonant" neutrons). The additional maximum is observed most pronouncedly in the photoneutron spectrum corresponding to the "difference" spectrum between the experimental one and that calculated from statistical theory. The energy distribution, calculated from the statistical theory, was compared by the author with the experimental ones, starting from the assumption that all the neutrons with energy ≤ 2 MeV were emitted as a result of "evaporation" from the compound nucleus. Then in the region ≥ 4 MeV one observed an excess in the experimental number of neutrons above the calculated value (10—16% relative to the total yield), which cannot be explained on the basis of the statistical theory. The angular distributions of the photoneutrons were measured for a large number of nuclei at $E_n \geq 5$ MeV with the aid of threshold detectors, and at $E_n = 1.0—10$ MeV using nuclear emulsion[10]. For many nuclei, an anisotropy was observed in the angular distribution, which varied on going from one nucleus to another. The appreciable anisotropy could likewise not be explained from the point of view of the statistical theory. In connection with the foregoing uncertainties in the interpretation of the energy and angular distributions of the photoneutrons, we undertook a study of the mechanism of the (γ, n) reaction for In^{115}.

EXPERIMENTAL SETUP

The indium target was irradiated with γ bremsstrahlung at $E_{\gamma \max} = 28$ MeV from the synchrotron of the A. F. Ioffe Physico-technical Institute of the U.S.S.R. Academy of Sciences.

The number of neutrons emitted from the target was determined from the number of recoil protons registered in type NIKFI-Ya2 emulsion 400 μ thick. We present some quantities characterizing the formulation of the experiment:

Content of In^{115} isotope, %	95.77
Target (spherical), g	21
Total γ-ray flux, MeV/cm^2	1.14×10^{13}
Investigated area of emulsion, cm^2	39.88
Total number of measured tracks	3892
Ratio of background to effect, %	22

The target and the photographic plates were secured on a light aluminum support in such a way that the target was located at the center of the beam. The plates measuring 3 × 5 cm were located 18 cm from the target. The neutrons knocked out by the γ quanta from the lead wall of the collimator were moderated to an energy ≤ 0.5 MeV in a paraffin block placed in front of the setup. This reduced the scattered neutron background. The intensity was monitored with an aluminum ionization chamber. During the time of the experiment, absolute measurements were made of the γ-ray flux using a standard ionization chamber calibrated with the aid of a calorimeter[11].

To establish the dependence of the proton range in the NIKFI-Ya2 emulsion on the energy, the emulsion was calibrated against neutrons from

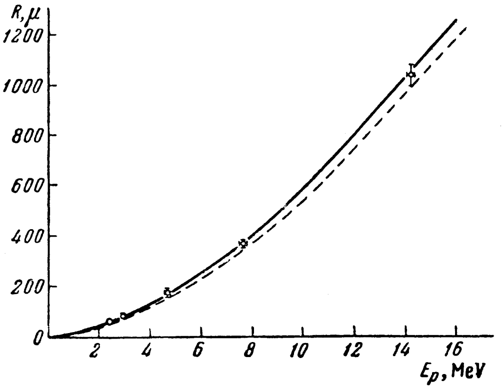

FIG. 1. Dependence of the proton range in NIKFI-Ya2 on the energy. The dashed curve is the analogous dependence for the Ilford-G5 emulsion.

the (d, d) and (d, T) reactions with energies 2.47 and 14.2 MeV[12] and against neutrons from a Po-Be source. The moderating ability of the emulsion was also calculated (see Fig. 1) starting from measurements of the AgBr content and of the emulsion density, and taking account of the fact that the slowing down ability of the emulsion is equal to the sum of the gelatin and of the silver halide[13]. The range is then determined from the relation

$$\frac{1}{R_{\mathrm{AgBr}}} = \frac{f}{f_s}\left(\frac{1}{R_s} - \frac{1-f_s}{R_g}\right) + \frac{1-f}{R_g},$$

where R_{AgBr} is the range in AgBr, f is part of the volume of the investigated emulsion occupied by the AgBr, f_s is part of the volume of standard emulsion occupied by the AgBr, R_s is the range in standard emulsion, and R_g is the range in gelatin.

The standard emulsion used was Ilford-G5, for which Barkas et al[13] measured the emulsion density and the range-energy ratio in the interval 0—70 MeV. The obtained curve for the dependence of the proton range on the energy (solid curve in Fig. 1) differed from the similar curve (dashed curve in Fig. 1) for the Ilford-G5 emulsion by three to four percent in the proton energy interval 1.0—11.5 MeV.

RESULTS AND DISCUSSION

The experimental data are shown in Figs. 2—4. Figure 2 shows that the obtained angular distribution of the photoneutrons has appreciable anisotropy. According to the statistical theory, for a nucleus with high ground-state spin ($S_0 = 9/2$) the contribution of the anisotropic part does not exceed 8—10%[14]. It can be assumed that the anisotropic part of the angular distribution is attributed to the presence of a "resonant" photoeffect[9].

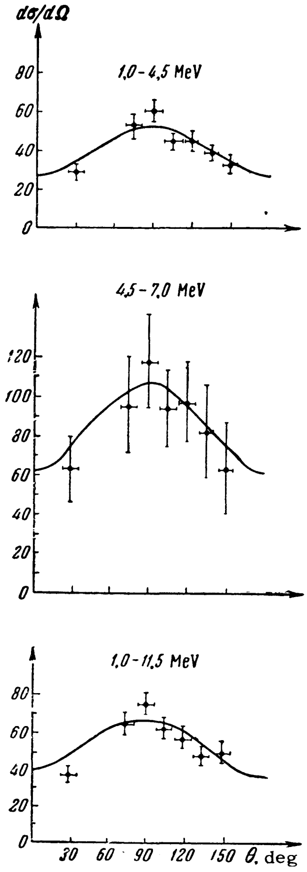

FIG. 2. Angular distribution of photoneutrons from In^{115}. The curves correspond to the calculations by the Wilkinson model.

Calculation based on the shell model (Fig. 2) yields the following angular dependence for the energy interval 1—11.0 MeV, which is in satisfactory agreement with the experimental data:

$$J(\theta) = 1 + 0.68 \sin^2 \theta.$$

Figure 3 shows lines whose slope characterizes the "temperature" of the nucleus. The experimental value obtained (curve 1) does not coincide with the data for the "nuclear temperature" at the same average excitation energy, known from other experiments (Fig. 2); thus, for example, the (n, n′) reaction yielded a value 0.66 ± 0.07 MeV. This confirms the assumption made regarding the impossibility of explaining the mechanism of the (γ, n) reaction at a neutron energy ≤ 4.5 MeV from the point of view of the statistical theory alone.

Figure 4 shows therefore a comparison between the experimental energy spectrum of the neutrons with the spectrum calculated using two different models, evaporation and shell. Curve 1 corresponds to the photoneutron spectrum for the reactions (γ, n) + (γ, 2n), calculated by statistical theory at a level density $W(E) = \exp(\sqrt{2aE})$, where $a = 1.6\,(A_{\mathrm{core}} - 40)^{1/2}$.

Curve 2 shows the neutron spectrum corresponding to "resonant" emission, calculated by the shell

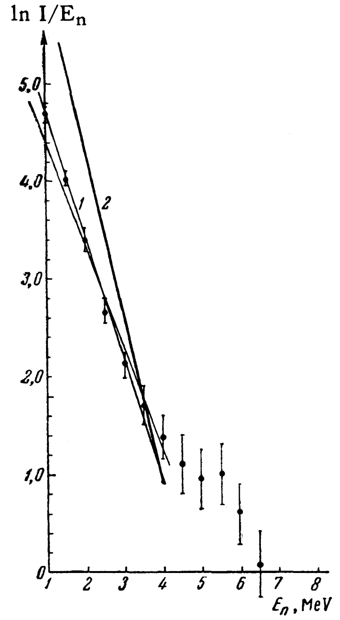

FIG. 3. "Temperature" of the In^{114} nucleus.

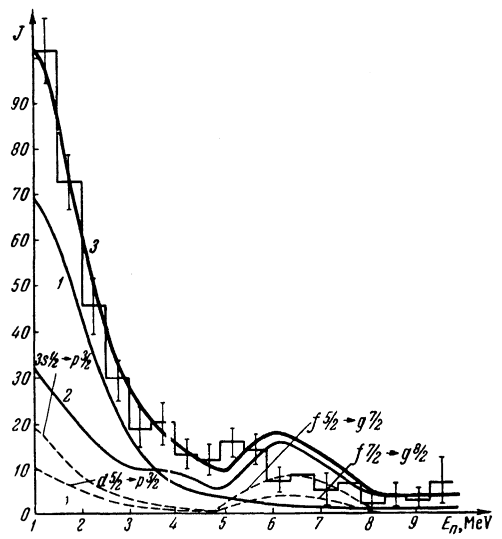

FIG. 4. Energy distribution of the In^{115} photoneutrons. Curve 1 – spectrum obtained in the "evaporation" theory; curve 2 – calculated spectrum obtained with the Wilkinson model; curve 3 – spectrum corresponding to the sum of both processes.

theory. The Nilsson level scheme was used in the calculations and all the dipole transitions possible in the excitation of the In^{115} nucleus were considered ($V_0 = 56$ MeV). The spectra corresponding to the most intense dipole transitions are shown in Fig. 4 by dashed lines: $s_{1/2} \rightarrow p_{3/2}$; $d_{5/2} \rightarrow p_{3/2}$; $f_{5/2} \rightarrow g_{7/2}$; $f_{7/2} \rightarrow g_{9/2}$. Curve 2 is a result of adding these spectra.

The discrepancy between the calculated value of the maximum and the experimental one at 5.5 MeV is within the limits of the calculation accuracy. The ratio of the process corresponding to curves 1 and 2 in Fig. 3 was chosen such that the summary curve can account satisfactorily for the experimental data. The contribution of the "resonant process" is equal here to (45 ± 10) percent. This value agrees, within the accuracy of the estimate, with the results of the analysis of the angular distributions of the photoneutrons, in which the contribution of the anisotropic part to the total photoneutron yield (~ 36%) must be regarded as the lower limit of the contribution of the "resonant" photoeffect, since this mechanism can partially cause also an isotropic angular distribution.

The error in the number of neutrons includes the statistical error in the determination of the geometrical correction for the probability of the proton leaving the emulsion and the uncertainty in the cross section for the scattering of the neutrons by the protons in the emulsion.

We have also measured the absolute photoneutron yield in the energy interval 0–1.5 MeV, which was found to be $(1.72 \pm 0.6) \times 10^{-3}$ neutron/mole-MeV-cm^2.

On the basis of all the foregoing we can conclude that the statistical theory cannot explain satisfactorily the mechanism of the reaction occurring even in the energy region ≤ 4.5 MeV. To explain the energy and angular distributions it is necessary to assume in addition to the statistical process also a direct "resonant" emission of the neutrons. It must be noted that the probability and the energy distribution of the dipole transitions in the calculation strongly depend on the chosen level scheme and on the depth of the nuclear potential well. For an exact calculation it is necessary to take into account the two-particle correlation of the nucleons in the nucleus.

In conclusion I am deeply grateful to the synchrotron crew for operating the synchrotron, and the entire staff of the laboratory of Professor A. P. Komar for a discussion of the experimental data. I thank A. Z. Dolginov for continuous interest in the work and N. V. Sopov for help.

---

[1] Emma, Milone, Rubbino, Jannelli, and Messanares, Nuovo cimento **22**, 135 (1961).

[2] R. F. Askew and A. P. Batson, Nucl. Phys. **20**, 408 (1960).

[3] A. Agodi and S. Cavallaro et al, Proc. of the 1958 Paris Conf. on Nucl. Phys.

[4] P. R. Byerly and W. E. Stephens, Phys. Rev. **81**, 473 (1951).

[5] Cortini, Milone, Rubbino, and Ferrero, Nuovo cimento **17**, 365 (1960).

[6] Emma, Millone, Rubbino, and Malvano, Nuovo cimento **17**, 365 (1960).

[7] Zatsepina, Lazareva, and Pospelov, JETP **32**, 27 (1957), Soviet Phys. JETP **5**, 2 (1957).

[8] M. E. Toms and W. E. Stephens, Phys. Rev. 108, **77** (1957).

[9] D. H. Wilkinson, Physica **22**, 1039 (1956).

[10] F. Tagliabue and J. Goldemberg, Nucl. Phys. **23**, 144 (1961).

[11] S. P. Kruglov, Dissertation, 1961.

[12] É. S. Anashkina, PTÉ, No. 4, 148 (1961).

[13] Barkas, Barrett, Cuer, Heckman, Smith, and Ticho, Nuovo cimento **8**, 185 (1958).

[14] V. V. Daragan, in collection Yadernye reaktsii pri malykh i srednikh energiyakh (Nuclear Reactions at Low and Medium Energies), AN SSSR, 1958, p. 476.

Translated by J. G. Adashko
211