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Angle-Energy Distribution of Photoneutrons from Bi

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The angle-energy distribution of photoneutrons emitted from bismuth bombarded by x-rays with a maximum energy E_{max} = 18.9 mev has been investigated using nuclear emulsions. The energy distribution obtained includes a large number of energetic neutrons which cannot be explained in terms of the statistical theory.

IN the existing studies of photoneutron angular distributions[1-6], simultaneous measurements of the distribution over angle and energy have not been carried out. In Refs. 1-3, a threshold-detector method was employed; in Refs. 4-6, a scintillation counter was used to detect neutrons with energies above a definite level. In the present work, nuclear emulsions have been used to study the energy distribution of photoneutrons from bismuth, emitted at various angles with respect to the x-ray beam. The measurements were carried out at the 30 mev synchrotron of the Physical Institute , Academy of Sciences, using a maximum x-ray energy E_{max} = 18.9 mev.

In Fig. 1 is shown the arrangement of the sample and the emulsion during irradiation. The bismuth sample, a disc 40 mm in diameter and 5 mm thick (4.91 gm/cm^2), was set up on a light aluminum holder at the center of a collimated x-ray beam. To reduce the neutron background, the collimator was made of graphite and aluminum; a large paraffin block (80 × 80 × 60 cm) with a longitudinal channel, 50 mm in diameter in the direction of the x-ray beam, was placed between the collimator and the sample. NIKFI Ya-2 photoemulsions, 400 μ thick, (3 × 5 cm) were placed at a distance of 16 cm from the center of the sample at angles of 30°, 90°, 150°, and 270° with respect to the x-ray beam. The disposition of the sample and emulsion was chosen (Fig. 1) so as to maintain a uniform solid angle for all emulsions. The uncertainty in the neutron direction due to the finite dimensions of the sample and emulsion was, on the avarage, about 3°.

The x-ray dose was measured with a thin-walled integrating ionization chamber placed in the x-ray beam between the collimator and the paraffin block (the overall thickness of the electrodes and screen, made from aluminum foil, was 300 μ).

To measure the background, the Bi sample at the center of the beam was replaced by a graphite disc 40 mm in diameter and 0.92 gm/cm^2 thick. The number of neutrons in the beam scattered by the graphite disc and by the bismuth sample was the same. The average value of the background

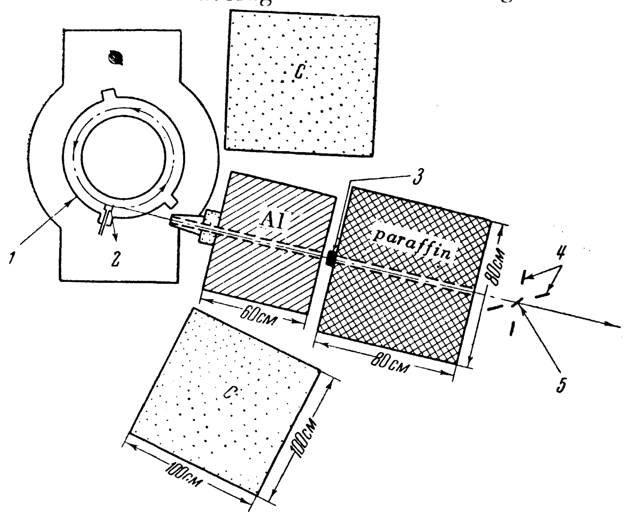

FIG. 1. Arrangement of the sample and emulsion during irradiation: *1* — synchrotron chamber; *2* — external synchrotron target; *3* — thin-walled monitor; *4* — emulsion; *5* — sample.

ranged from 10 to 16 percent as a function of angle.

The developed emulsions were scanned with a MBI-2 microscope with a magnification of 60 in the objective and 5 in the ocular. Only those recoil protons which were scattered at small angles with respect to the direction of neutron motion were recorded. The maximum detection angle in the plane of the undeveloped emulsion was 15°; the maximum in the vertical direction was 24°. Using this selection of tracks the measured proton energy was, on the average, about 8.8 percent smaller than the neutron energy. In converting from the measured recoil-proton spectrum to the photoneutron spectrum, in addition to this correction, corrections were introduced to take account of the energy dependence of the (n-p) scattering cross-section and errors due to tracks which passed out of the emulsion. The range-energy relation for protons was taken from Ref. 7. Less than 9 percent of the Bi photoneutrons were scattered in the sample.

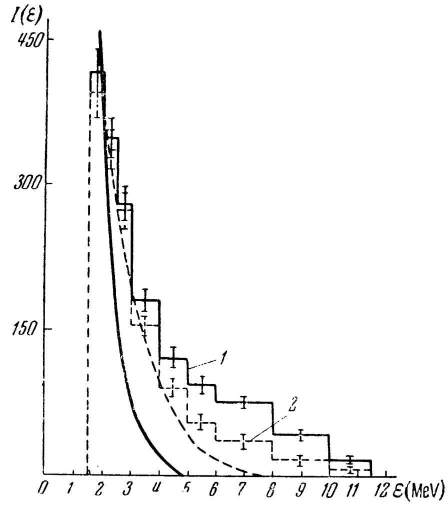

FIG. 2. Energy distribution of photoneutrons from Bi.

After background corrections, the number of protons recorded in the emulsions at angles of 30°, 90°, 150° and 270° was 2605. In Fig. 2 are shown the photoneutron energy spectra, $I(\epsilon)$, obtained at the angles indicated. Histogram *1* represents the energy distribution of neutrons emitted at right angles to the x-ray beam (90° and 270°). Within the error limits, the neutron spectra at 30° and 150° are identical. Histogram *2* represents the summed spectrum for 30° and 150°. Both spectra which are presented are normalized to the same scanned area on the emulsion. The solid curve and the dashed curve refer to neutron energy distributions computed on the basis of the statistical theory, using two different level densities,

$$\omega_1 = C \exp [3.35 (A - 40)^{1/2} (E - E_n - \varepsilon)]^{1/2}$$

and

$$\omega_2 = C \exp [0.7 (A - 40)^{1/2} (E - E_n - \varepsilon)]^{1/2},$$

(C is a constant, A is the mass number, E is the excitation energy, E_n is the binding energy of the neutron and ϵ is the energy of the emitted neutron). The cross-sections for the (γ, n) and $(\gamma, 2n)$ reactions in Bi were taken from Ref. 8. A Schiff spectrum was assumed for the γ-radiation. No account was taken of the change in the x-ray spectrum due to transmission through the Bi sample nor of inelastic neutron scattering in the sample. The introduction of these corrections should tend to increase the relative number of neutrons at the high energies.

Neither spectrum computed on the basis of the statistical theory coincides with the energy distribution observed for the photoneutrons from Bi. The experimental neutron spectra agree roughly with the spectrum calculated using the level density ω_2 only in the region from 1.5 mev to approximately 4 mev. Above 4 mev histograms *1* and *2* exhibit a considerable number of neutrons the yield of which, according to the evaporation model, should be virtually zero. Similar results have been obtained by Byerly and Stephens[9] and Price[3] investigating photoneutrons emitted at 90° to the x-ray beam in photo-disintegration of copper (E_{max} = 24 mev) and bismuth (E_{max} = 22 mev). The number of neutrons with energies above 4 mev is noticeably greater at 90° and 270° than at 30° and 150°. In the Table are shown the relative neutron yields for different energies at 30°, 90° and 150°. It is apparent from this Table that the anisotropy over angle increases sharply with increasing neutron energy. If it is assumed that the neutron yield for energies below 1.5 mev corresponds to that expected on the basis of the statistical theory, neutrons emitted anisotropically with respect to the x-ray beam amount to 8.8 percent of the total number of photoneutrons. It would appear that the data must be analyzed in terms of two different interactions between the γ-quanta and nuclei: the absorption of γ-quanta with the production of a compound nucleus and subsequent evaporation, and a direct photo-effect.

In Fig. 3 the following curve has been plotted for neutrons emitted at right angles to the γ-quanta direction: neutron energy is plotted along the abscissa axis and the function $\ln [I(\epsilon)/\epsilon]$ is plotted

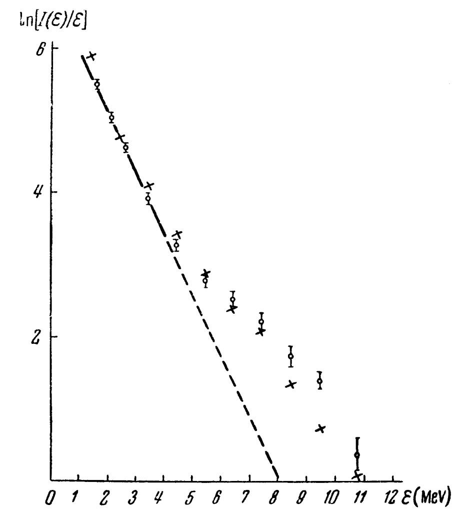

FIG. 3. Spectrum of photoneutrons emitted from Bi at right angles to the direction of the x-ray beam. The crosses refer to the spectrum calculated in accordance with the Courant model.

Relative neutron yields at different energies at 30°, 90° and 150° to the direction of the x-ray beam (per unit solid angle)*.

Energy interval, mev.	30°	90°	150°
1.5—4	0.88 ± 0.04	1 ± 0.04	0.97 ± 0.04
4—7	0.77 ± 0.08	1 ± 0.09	0.66 ± 0.09
7—11	0.17 ± 0.07	1 ± 0.08	0.26 ± 0.06
4—11	0.52 ± 0.06	1 ± 0.06	0.47 ± 0.06
1.5—11	0.74 ± 0.03	1 ± 0.04	0.79 ± 0.04

* The neutron yield at 90° is taken as unity. The errors shown are statistical errors.

along the ordinate axis. The straight segment up to 4 mev yields an average temperature $T = 1.1$ mev. Using a mean excitation energy of about 13 mev, the temperature should be 0.7 mev. The higher value of the temperature is obviously connected with the fact that some of the neutrons with energies below 4 mev are emitted by virtue of a direct interaction. At an energy of approximately 4 mev, above which the neutron yield is obviously due only to the direct photo-effect, a sharp break is observed. The crosses refer to values of $\ln[I(\epsilon)/\epsilon]$ for a neutron spectrum computed under the assumption that the γ-quantum absorbed by the nucleus transfers all of its energy to the ejected neutron. According to Courant[10], in this case the cross-section for the absorption of γ-quanta goes as $\sigma_\gamma \sim 1/E^3$. The value of $\ln[I(\epsilon)/\epsilon]$ computed on this basis is in satisfactory agreement with the experimental data. Other calculations, carried out under the assumption of a small level density at small excitation energies of the residual nucleus, do not yield this type of behavior.

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