INVESTIGATION OF 15 TO 65-Mev PROTONS PRODUCED IN THE PHOTODISINTEGRATION OF ALUMINUM AND NICKEL

E. B. BAZHANOV, Iu. M. VOLKOV, and L. A. KUL' CHITSKII

Leningrad Physico-Technical Institute

Submitted to JETP editor February 27, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 322-327 (August, 1958)

The angular distributions of photoprotons from aluminum and nickel were investigated for a peak bremsstrahlung energy $E_{\gamma max} = 85$ Mev, and the energy distributions of photoprotons from Al were obtained at angles of 30°, 90° and 130° for $E_{\gamma max} = 90$ Mev. The results are discussed from the point of view of the interaction of γ rays with nuclei through the quasi-deuteron mechanism.

1. SHORT DESCRIPTION OF THE EXPERIMENT

THE present work is a continuation and development of the work, the results of which were published in an earlier short note.[1] The investigation of the angular and energy distributions of protons was carried out with the 100-Mev synchrotron of the Physico-Technical Institute. The arrangement of the apparatus used in the experiment described below is shown in Fig. 1. Products of photonuclear

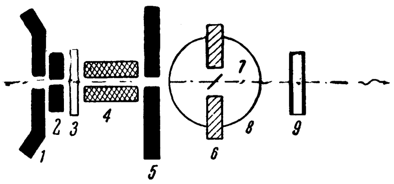

FIG. 1. Arrangement of the apparatus. 1) shielding wall of Pb, 2 and 5) lead collimators, 3) monitor, 4) magnet to clean the beam, 6) telescopes, 7) target, 8) table, 9) standard chamber.

reactions are registered by two scintillation telescopes, each consisting of two counters. A short description of the telescope arrangement and counting scheme was given in reference 1. The telescopes could be turned in the horizontal plane through the desired angle θ relative to the direction of the γ-rays to an accuracy of better than ± 1°. A target of the desired material was placed in the center of the table. In the study of the proton angular distribution, cylindrical targets were used. These were made of foils of thickness 110 μ for aluminum and 50 μ for nickel.

The diameter of the cylindrical targets was 1.6 cm and the diameter of the beam cross section at the point at which the targets were placed was 2.2 cm. In studying the proton energy spectra, flat targets of area more than twice the beam cross section were used. The thickness of the aluminum target was 150 μ. In taking the angular distributions at 60, 75, 90 and 120°, the distance from the center of the target to the crystal of the first counter was 16.7 cm. At angles 25° and 40°, the telescopes were moved outwards to a distance of 23.7 cm. In order to combine data obtained at small and large angles, measurements at 60° were carried out with the telescopes in both positions, and the data were then correspondingly normalized.

In counting heavy charged particles, one must pay special attention to the possibility of counts coming from the sum of pulses from several electrons incident on the telescope within the resolving time of the counting system. The probability of such a count increases with increasing atomic

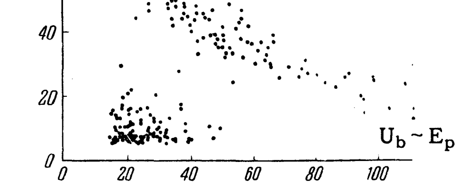

FIG. 2. Illustration of the resolving power of the telescopes: separation of heavy charged particles and electrons in the case of Au at angle 90°; U_f and U_b are the magnitudes of the pulses from the front and back counters, respectively.

number of the element, and also increases in going to small angles relative to the γ-ray beam. The construction chosen for the telescope made it possible to separate the contributions from heavy charged particles and electrons. To determine this, the pulses from both counters were fed after amplification into a double-beam oscilloscope (type OK17M), the horizontal sweep of which was triggered by pulses from the coincidence circuit to which the outputs of both counters of the telescope were connected. Pulses on the screen of the oscilloscope were photographed. Figure 2 illustrates the capabilities of the telescope with respect to the separation of particles emitted from gold at 90°. The abscissa is the amplitude of the pulse (in relative units), proportional to the energy loss of the particle in the crystal of the rear counter. The ordinate is the amplitude of the pulse, proportional to the energy loss of the same particle in traversing the thin crystal of the front counter of the telescope. The lower left group of points corresponds to pulses from electrons; the upper group of points to heavy charged particles. The pulse of an α particle of energy 8.78 Mev from Th C′ is shown by the cross. Using a differential pulse-height analyzer on the rear counter and several integral discriminators on the front counter, it is easy to separate off the electrons, taking here several proton energy intervals.

In this experiment the different types of heavy charged particle were not separated, although a special check, carried out with a telescope of similar construction, but with higher resolving power[2] which made it possible to distinguish between protons and deuterons, showed that the contribution of deuterons in the elements studied was less than 5% for the proton energies counted, and could not change the experimental results essentially. The contribution of tritons and α particles was in general negligible.

2. INTRODUCTION OF CORRECTIONS, ESTIMATES OF ERRORS

In the preliminary processing of results of the measurements of the energy spectra of protons, the data were reduced to 1-Mev proton-energy intervals by dividing the total number of counts in the energy interval of acceptance of a given channel of the pulse-height analyzer by the width of the interval in Mev.

The number obtained could be ascribed to the mean energy of the interval, E_m, defined as the arithmetic mean of the limits E_1 and E_2, only after introduction of several corrections which took into account the decreasing nature of the spectrum with increasing photon energy. The correction factor α_1 can be calculated from

$$\alpha_1 = E_{cp}^{-\delta}(E_2 - E_1)(1-\delta)/(E_2^{1-\delta} - E_1^{1-\delta}). \qquad (1)$$

This formula was obtained under the assumption that the proton spectrum is described by the law $n(E_p) = kE_p^{-\delta}$, which, for the comparatively narrow proton energy intervals used ($\Delta E_p/E_p \approx 20\%$), is a completely satisfactory approximation. In addition to this, it is necessary to correct for the loss in energy of the protons in going through the target. If we count protons with energies in the interval $E_1 - E_2$ ($E_1 < E_2$), defined at the entrance to the telescope, then some protons with energies near to E_1 will be lost because of the finite thickness of the target and, at the same time, some protons with energies slightly larger than E_2 will be included. The correction factor α_2 can be determined by a numerical integration which splits the target into a number of layers, in each of which a power law for the change in proton spectrum with energy is assumed for a small energy interval. The total correction factor for the aluminum target of thickness 150 μ was 13% for a proton energy E_p = 15.4 Mev, 1% for E_p = 36.7 Mev, and 6% for E_p = 49.8 Mev.

The dependence of the total corrections on the magnitude of δ was very weak. Changing δ by a factor of 3 or 4 changed the correction, in absolute value, by less than 20%.

Corrections for multiple scattering and nuclear absorption, estimated for the crystal of the front counter, amounted to only a fraction of a per cent and were not introduced.

The maximum value of $\Delta\theta$, characterizing the angular resolution of the telescope, was ± 6.5°. In the practical case, as an estimate showed, about 75% of the protons went within the angular limits ± 3.5°.

The background in various experiments was equal to 15% on the average, although at small angles it increased to 25 or 30%, depending on the proton energy.

Both the relative and absolute measurements of the total energy of the γ rays traversing the target were carried out with an apparatus devised by Kruglov.[3] An aluminum ionization chamber with front wall of thickness 4 mm, connected to a stable beam integrator, served as monitor. The stability of operation of the monitor was ~ 2%. Absolute measurements were carried out using a thick-walled copper standard chamber, calibrated by the calorimetric method.[4] The accuracy of absolute calibration for the maximum bremsstrahlung energy, $E_{\gamma max} = (90 \pm 5)$ Mev, was 4%.

The energy spectra of protons from Al were given below in units $cm^2 \times 10^{30}$/sterad-Mev-Q. The relative mean square error, taking into account statistical errors, the mean square error in the number of effective quanta Q, the error in definition of the solid angle, and a series of others, constituted 16% for 30-Mev protons.

3. EXPERIMENTAL RESULTS AND DISCUSSION

(a) Angular Distributions of Protons from Aluminum and Nickel

The angular distributions obtained for several proton energy intervals at maximum bremsstrahlung energy $E_{\gamma max} = 85 \pm 5$ Mev are given in Figs. 3 and 4. A general characteristic of the distributions is the rise of the anisotropic parts and the increased shift of the maxima of the angular distributions with increasing proton energy.

In order to clarify the role of the quasi-deuteron interaction mechanism of γ rays with Al and Ni nuclei, it is of interest to compare the data obtained with the angular distributions of protons from the photodisintegration of the deuteron. Levinger[5] employed the theoretical cross sections for photodisintegration of the deuteron calculated in references 6 and 7 which, as is well known,[8,9] diverge from the experimental data for γ-ray energies exceeding 50 Mev. We used the experimental curves of the cross section for photodisintegration of the deuteron obtained by Allen[8] and Whalin et al.[10] transposed to the laboratory system. The solid curves

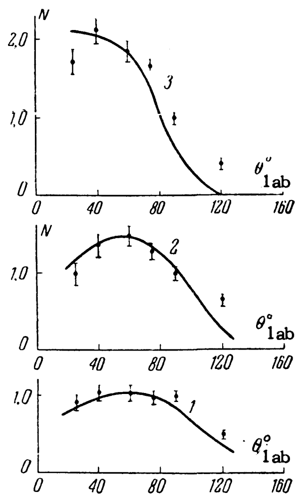

FIG. 3. Angular distributions of photoprotons from Al. The solid curves give the results of calculation. Only statistical errors are shown. 1) E_p = 13.7-17.5; 2) E_p = 17.5-21.5; 3) E_p = 21.5-41.0 Mev.

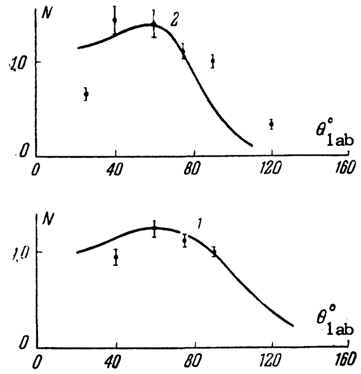

FIG. 4. Angular distributions of photoprotons from Ni. The solid curves give the results of calculation. Only statistical errors are shown. 1) E_p = 13.7-21.5; 2) E_p = 21.5-33.3 Mev.

in Figs. 3 and 4 were constructed by calculating the integral proportional to the yield of protons $Y(\Delta E_p)$ with energies corresponding to interval $\Delta E_p = E_{p2} - E_{p1}$,

$$Y(\Delta E_p) \sim \int_{E_\alpha}^{E_\beta} N_\gamma(E_\gamma)\,\sigma_d(E_\gamma)\,dE_\gamma. \quad (2)$$

Here $N_\gamma(E_\gamma)$ is the number of γ rays of energy E_γ in the bremsstrahlung spectrum (using the spectrum of Schiff), E_α and E_β are the energies of γ rays corresponding to the production of protons of energies E_{p1} and E_{p2}, respectively. The connection between the γ-ray energy and proton energy is determined by the well-known kinematical relation

$$E_\gamma = 2E'_p / \left(1 - \frac{E'_p}{M} + \frac{p}{M}\cos\theta\right), \quad (3)$$

which follows from the conservation laws. Here $E'_p = E_p + E_B$, $\sigma_d(E_\gamma)$ is the cross section for photodisintegration of the deuteron for a γ ray of energy E_γ and a given angle θ_{lab}. The results of the calculation were obtained by numerical integration under the assumption that the residual nucleus is left in the ground state. The curves obtained were normalized so that they coincided with the experimental points at $\theta_{lab} = 60°$ for all proton-energy intervals.*

In the case of aluminum, the complete agreement of the calculated curves with the experimental points is striking. This serves to indicate the essential contribution of the quasideuteron mechanism for the interaction of γ rays with the Al

*In the corresponding graphs presented in the report to the Conference on Nuclear Reactions at Low and Medium Energies (Moscow, November 1957), the comparison was less precise. These curves gave the change in the cross section for deuteron photodisintegration $\sigma_d(E_p)$ with the angle θ_{cm} for protons of energy E_p corresponding to the mean energy of the energy interval chosen.

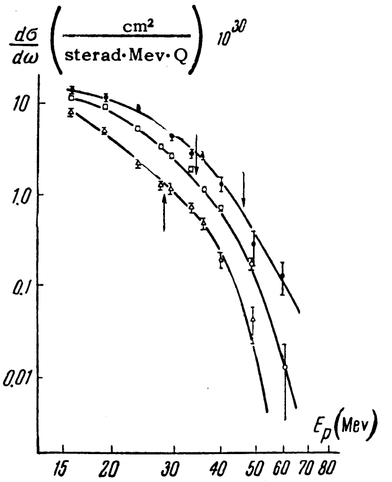

FIG. 5. Energy distributions of photoprotons from Al for various angles, $E_{\gamma max}$ = 90 Mev. Only statistical errors are shown. ● – θ = 30°; ○ – θ = 90°; Δ – θ = 130°.

nucleus. The deviations of the experimental points from the calculated curves in the interval from 21.5 to 41.0 Mev at small and large angles can be understood if one takes account of the fact that in the production of protons of a given energy E_p, quanta of significantly higher energy are needed in the case of the quasi-deuteron mechanism than in the case of the direct photoeffect, and this difference increases with increasing angle θ. The bremsstrahlung spectrum of the γ rays falls with energy and is limited by $E_{\gamma max}$. Thus, for comparatively large proton energies, the relative contribution of the direct photoeffect should increase. This effect should first of all show up at large angles. It should be noted that if the angular distribution of protons from the direct photoeffect is described by a law well approximated by $a + b \sin^2 \theta (1 + c \cos \theta)^2$ and has a maximum shifted to larger angles than in the calculated curves shown in Fig. 3, then a 20 to 30% contribution from the direct photoeffect is sufficient to obtain agreement with experiment for all angles.

For nickel, the agreement with the calculated curves is worse. Especially noticeable is the sharp fall in the points at small angles. It is possible that the contribution from the direct photo effect (or some other mechanism) is larger.

(b) Energy Spectrum of Protons from Aluminum

The energy spectra of protons from Al, taken at angles θ_{lab} = 30, 90, and 130° for $E_{\gamma max}$ = 90 ± 5 Mev are given in Fig. 5.

Starting from the idea of the quasi-deuteron mechanism of interaction, one would expect the slope to increase with angle. The determination of the slopes of the spectra in their initial parts is difficult, because the spectra change their slope smoothly and can only approximately be described by the power law $n(E_p) \sim E_p^{-\delta}$. The table lists the approximate values of δ, and for comparison, also values of the slopes for energy spectra of protons from the photodisintegration of deuterium, calculated from the data of references 8 and 9.

θ	δ	
	Al	D
30°	2.1	2.3
90°	2.8	2.6
130°	3.2	2.8

It can be seen from the deuteron data that one should not expect a strong change with θ in the slopes of the energy spectra of protons from aluminum.

The arrows in Fig. 5 indicate the positions of the kinematical cutoffs, determined by Eq. (3), taking the minimum binding energy of the proton in Al to be 8.2 Mev. Sharp changes were not observed in the spectra at energies near the kinematical cutoff. The relatively smooth, but increasing rate of drop (instead of a sharp drop) of the spectra can be caused, on the one hand, by the momentum distribution of protons inside the nucleus, and, on the other hand, by the fact that the direct photoeffect, in this region of energies, can contribute relatively more. The shift in the position of the kinematical cutoff with changing angle shows up possibly only in the fact that the spectra of the higher-energy protons drop off more strongly with the angle than at low energies, and that as the angle increases, this drop begins at lower energies.

In Fig. 6 the experimental spectrum of protons from Al at θ = 90° is compared with the energy spectrum calculated as done by Levinger.[5]

In the calculations (curve 1) we employed the experimental spectrum of protons in the photodis-

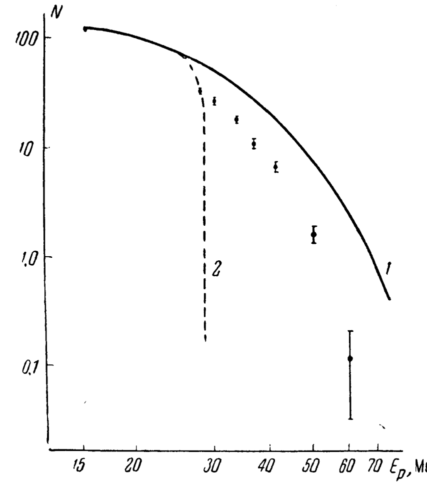

FIG. 6. Comparison of the experimental energy spectrum of photoprotons from Al with the one calculated for θ = 90°.

integration of deuterium, the spectrum of γ rays of Schiff with $E_{\gamma max} = 90$ Mev, and a Gaussian distribution of nucleon momenta in the nucleus, with parameter $E_0 = 10$ Mev. Curve 2 gives the spectrum with the momentum distribution disregarded.

The experimental curve falls more sharply at high energies than the calculated one.

Taking into account the possibility of the role of the direct photoeffect increasing for high protor energies in our experiments, where the γ-ray spectra was limited by $E_{\gamma max} = 90$ Mev, we can probably explain the results of the experiment satisfactorily. Choice of a more sharply falling momentum distribution also improves the agreement with experiment.

Thus, the qualitative features of the proton energy spectra, obtained at various angles in Al, and also comparison of the angular distributions of protons for Al and Ni with curves calculated from the quasi-deuteron model, indicate that the quasi-deuteron mechanism of interaction may give a substantial contribution in the case of Al. At the same time it is also very probable that the direct photoeffect also gives an important contribution.

[1] Bazhanov, Volkov, Komar, Kul'chitskii and Chizhov, Dokl. Akad. Nauk SSSR **113**, 65 (1957), Soviet Phys. "Doklady" **2**, 107 (1957).

[2] Bazhanov, Volkov, Komar, Kul'chitskii, Chizhov, and Iavor, Report at the Conference on Nuclear Reactions at Low and Medium Energies, Moscow, November, 1957 (in press).

[3] S. P. Kruglov, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1060 (1957); Soviet Phys. JETP **6**, 817 (1958).

[4] S. P. Kruglov, J. Tech. Phys. (U.S.S.R.) (in press).

[5] J. S. Levinger, Phys. Rev. 84, 43 (1951).

[6] L. I. Schiff, Phys. Rev. **78**, 733 (1950).

[7] J. F. Marschall and E. Guth, Phys. Rev. **78**, 738 (1950).

[8] L. Allen, Phys. Rev. **98**, 705 (1955).

[9] Aleksandrov, Delone, Slovokhotov, Sokol, and Shtarkov, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 614 (1957), Soviet Phys. JETP **6**, 472 (1958).

[10] Whalin, Schriever, and Hanson, Phys. Rev. **101**, 377 (1956).

Translated by G. E. Brown
62