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ENERGY AND ANGULAR DISTRIBUTIONS OF PROTONS FROM THE REACTION $Ca^{40}(\gamma, p)K^{39}$ *AT* $E_{\gamma\,max} = 22$ MeV

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The energy and angular distributions of protons from the reaction $Ca^{40}(\gamma, p)K^{39}$ are obtained at $E_{\gamma\,max} = 22$ MeV. Fine structure is observed in the energy distribution. The experimental results are discussed in terms of Wilkinson's theory and of the compound nucleus resonance theory.

1. INTRODUCTION

IT has been reported previously[1] that fine structure has been observed in the energy distribution of protons emitted in the reaction $Ca^{40}(\gamma, p)K^{39}$ when irradiated with bremsstrahlung of $E_{\gamma\,max} = 85$ MeV. That experiment was performed at the synchrotron of the Physico-technical Institute of the U.S.S.R. Academy of Sciences. A fine structure in the photoproton energy distribution has been also found in other studies of photonuclear reactions in light nuclei.[2-4] The study of the fine structure in the energy distribution and the angular distribution of the different proton groups yields more detailed and unambiguous information concerning the mechanism of the interaction of photons with nuclei and concerning the nuclear levels.

Ca^{40} is apparently one of the more interesting cases for the study of the fine structure in the photoproton energy distributions. It lies at the boundary between light and medium heavy nuclei and is the third doubly "magic" nucleus. The level spacing in magic (and even more so in doubly magic) nuclei is considerably larger than in nearby nonmagic nuclei. The first excited state in the residual nucleus of the reaction $Ca^{40}(\gamma, p)K^{39}$ lies relatively high (~ 2.5 MeV). All these peculiarities facilitate considerably the detailed study of this reaction. Furthermore, this reaction can be treated theoretically since the levels in nuclei with one hole in a closed shell, like K^{39}, can be computed.[5] We decided therefore to study this reaction in greater detail.

In the present work we give the results obtained for the reaction $Ca^{40}(\gamma, p)K^{39}$ with $E_{\gamma\,max} = 22$ MeV. This energy is of interest since on the one hand it encompasses a large part of the giant resonance and on the other hand the situation evidently is not affected by photons of energy above the giant resonance.

2. EXPERIMENTAL SETUP AND METHOD

The experiment was performed employing nuclear emulsion techniques. This method gives a high resolution in the determination of the energy of the reaction products - about 1.5% at a proton energy of 4 MeV.[6] Furthermore, it allows us to utilize a large solid angle and to observe the full angular distribution at once in a single experiment.

The experimental setup is shown in Fig. 1. The photon beam of the synchrotron passes through a collimator, a thin-walled aluminum ionization chamber serving as the monitor, a second collimator, and a sweeping magnet before it falls on target 1 in the center of the experimental chamber. The photoplates carrying the emulsion were precisely held in location by special holders in the experimental chamber. They encompassed the angles from 20° to 160° in increments of 10° or 20°. To eliminate the background from nuclear reactions on air and to avoid proton energy losses on the way from the target to the emulsions the chamber was evacuated to $\sim 10^{-2}$ mm Hg during the irradiation.

The final preparation of the calcium target foil ($10\ mg/cm^2$) was performed under dried gasoline. The gasoline film protected the target from contamination during its placement in the chamber until the evacuation. To maintain the purity of the target until the completion of the experiment, some $CaCl_2$ was placed inside the experimental chamber.

The irradiation dose was determined with the monitor. Its response was calibrated by means of a thick-walled copper ionization chamber with an effective depth of 16 mm, which was placed behind

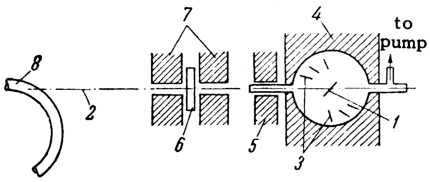

FIG. 1. Diagram of experimental setup; 1 – target, 2 – photon beam, 3 – nuclear emulsions, 4 – lead shield, 5 – poles of sweeping magnet, 6 – monitor, 7 – lead collimators, 8 – synchrotron.

the experimental chamber. The response of the latter chamber was in turn calibrated by means of a quantameter.[7] All the dose-measuring apparatus was built by S. P. Kruglov.

The data were obtained in two steps. First the emulsions were area scanned and the coordinates of the proton track beginnings were noted (using 300 × microscope magnification). Then the tracks that originated in the irradiated portion of the target were selected and measured. The horizontal projection of these tracks was measured in the usual way; the depth of the end of the track was measured by means of a special micrometer with 1 μ divisions (microscope magnification 1350 ×). This way the scanning losses were kept negligibly small (< 1%) while the precision of the measurements was maintained high (~1.5%) and the data collection was considerably accelerated.

The energy of the photoprotons was obtained from their range using a known experimentally-determined energy-range relation for the NIKFI-Ya2 emulsion. In order to introduce a more accurate correction for the energy loss in the target, the energy-range relation was calculated for calcium for proton energies up to 15 MeV. The energy of the photoprotons and the corrections due to energy loss in the target were not determined for each particular track individually. Tables were prepared in advance giving the track length limits for photoprotons between 0 and 15 MeV in steps of 0.1 MeV taking the corrections into account. In the preparation of these tables particular attention was paid to avoid the introduction of artificial breaks in the energy distributions of the photoprotons by the interval boundaries. To that end the energy-range relations were smoothed including the first derivatives both for the emulsion and for calcium.

The obtained histograms of the photoproton energy distributions were treated by the method of Ferreira-Valoshek.[8] This is a useful and simple treatment which decreases considerably the fluctuations in the energy distributions. One can judge from a curve obtained this way, with high confidence, whether a fine structure exists.

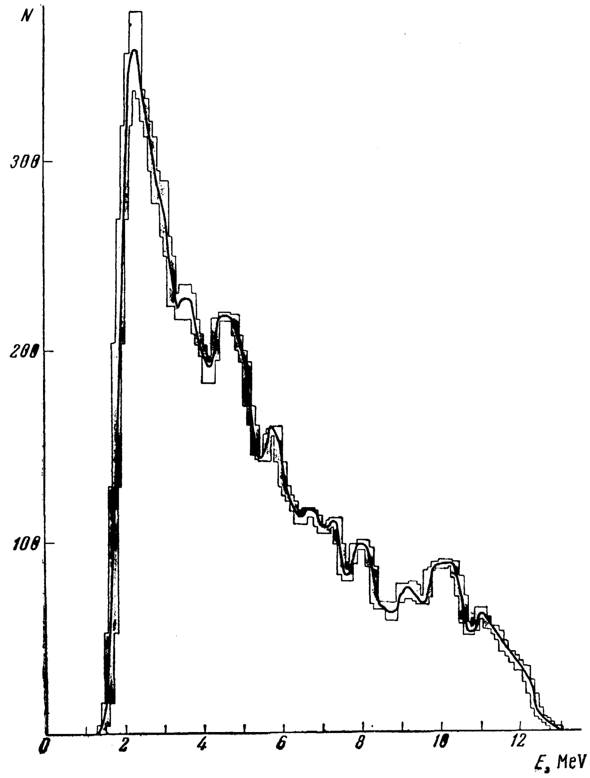

FIG. 2. Energy distribution of the protons.

The solid angles subtended by the photoplates with respect to the irradiated portion of the target were determined by computation. The procedure of this calculation has been described by one of the authors.[9]

The parameters of the expressions for the angular distributions were obtained by the least squares method.

The background was determined in a special investigation. It turned out to be less than 1% for protons with energy larger than 3 Mev.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In the experiment 12 photoplates were investigated. They corresponded to protons emitted from the target at the angles 20, 40, 50, 60, 70, 80, 90, 100, 110, 120, 140, and 160° relative to the photon beam. A total of 5270 tracks was measured. The energy distribution of the protons is shown in Fig. 2. Below 3 MeV the energy distribution cuts off because tracks of less than 10 μ length were omitted, and due to the large background and the stopping of a fraction of the protons in the target. One sees that in the energy distribution two proton groups clearly stand out: one group at 4.2 – 5.4 MeV with the peak at 4.65 MeV, the other at 9.5 – 10.8 MeV with the peak at 10.2 MeV. Although the group with energies above 10.8 MeV is less

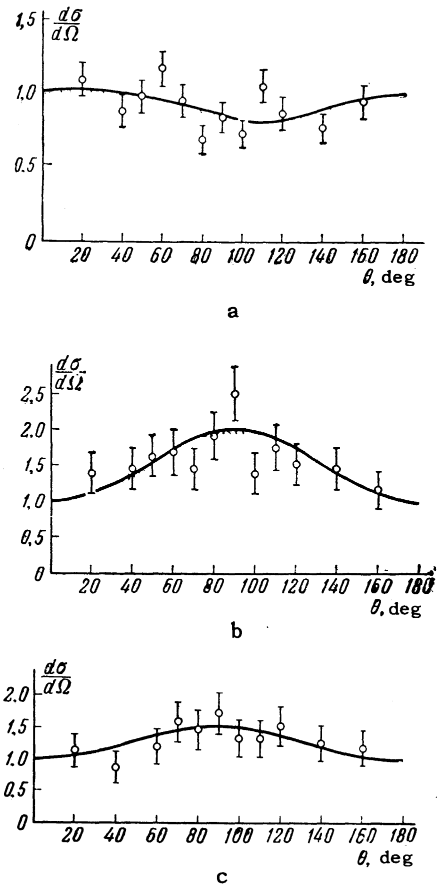

FIG. 3. Angular distributions of protons with the following energies: (a) 4.2–5.4 MeV; (b) 9.5–10.8 MeV; (c) above 10.8 MeV.

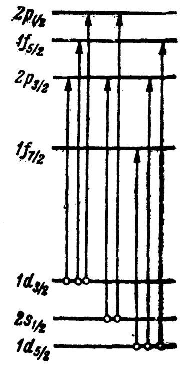

FIG. 4. Single-particle E 1 transitions.

pronounced we shall discuss it, too. The angular distributions of these three proton groups are given in Fig. 3a, b. c.

The energy and angular distributions were compared with the results of Wilkinson's theory[10] and of the resonance theory of the compound nucleus.[11]

The angular distribution of the first proton group can be expressed in the form

$$d\sigma / d\Omega = 1 - 0{,}146 \sin^2\theta\,(1 - 1{,}17 \cos\theta),$$

it is essentially isotropic, however. This group is strong and is evidently associated with electric dipole photon absorption. According to Wilkinson one does not obtain such a distribution in direct-resonance transitions. This group is evidently associated with collective transitions into an excited state of K^{39}. This assumption explains well the prominence of this group and its angular distribution.[11]

The proton group at 9.5–10.8 MeV shows up clearly in all energy distributions obtained with $E_{\gamma\,max}$ = 22 MeV and higher. It is absent at $E_{\gamma\,max}$ = 19 MeV, an energy which would suffice if the group were associated with a transition leading to the ground state of K^{39}. The angular distribution of this group is well represented by an expression of the type

$$d\sigma/d\Omega = 1 + \sin^2\theta.$$

All these facts are in agreement with the assumption that this proton group is associated with the direct resonance transition $1d_{5/2} \rightarrow 1f_{7/2}$ (see Fig. 4). According to Nilsson[12] the $1d_{5/2}$ level is approximately 3 MeV lower than the level $1d_{3/2}$ and thus the proton binding energy of the $1d_{5/2}$ level is 11.3 MeV. In order to emit 10.2-MeV protons from the $1d_{5/2}$ level one needs 21.5-MeV photons. This explains the absence of this proton group at $E_{\gamma\,max}$ = 19 MeV even though Nilssons values evidently are somewhat high.

The clear emergence of this group is also aided by the circumstance that the $1f_{7/2}$ level is well separated from the other levels and that the outgoing photons have l = 3.

Although the proton group with energies above 10.8 MeV does not show up clearly in the energy distributions, it nevertheless can be considered to be due to the direct resonance transitions $1d_{3/2} \rightarrow 2p_{3/2}$ and $2s_{1/2} \rightarrow 2p_{3/2}$. Its angular distribution (see Fig. 3c) is of the form

$$d\sigma/d\Omega = 1 + 0.48 \sin^2\theta.$$

At $E_{\gamma\,max}$ = 22 MeV the angular distribution of these protons is more isotropic than the expression which one would calculate according to Wilkinson

$$d\sigma/d\Omega = 1 + 2.5 \sin^2\theta.$$

This obviously is associated with the exceedingly large number of photons corresponding to the transition $1d_{3/2} \rightarrow 2p_{3/2}$.

In conclusion, we wish to express our deep gratitude to Professor A. P. Komar and to the staff of the x-ray and γ-ray laboratory for making available their facilities to perform this work and for many discussions and suggestions.

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53