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PHOTODISINTEGRATION OF A^{40}

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The photodisintegration of A^{40} induced by bremsstrahlung of 70 Mev peak energy was investigated with a cloud chamber. The relative yields of the different reactions were found, as well as the integrated cross section of the (γ, p) reaction. The angular and energy distributions of the photoprotons from argon were determined.

INTRODUCTION

OVER the last years, several papers have been published concerning the photodisintegration of A^{40}.[1-3] A^{40} is of medium atomic weight and has a high abundance (99.6%) in the natural isotopic mixture. Owing to this fact and to the circumstance that the (γ, p) threshold in A^{40} (12.44 Mev) is more than 2 Mev higher than the (γ, n) threshold (10.25 Mev) an investigation of the photoreactions in this element is of interest.

The (γ, n) and (γ, p) yields in A^{40} were studied in reference 2. It turned out that the yield of the (γ, p) process was greater than the yield of the (γ, n) process. At a γ-ray energy of 19.5 Mev, the ratio $\sigma(\gamma, p)/\sigma(\gamma, n)$ becomes > 1 and continues to increase with increasing photon energy. This is hard to explain from the point of view of the statistical theory of nuclear reactions. In reference 3, the energy and angular distributions of photoprotons were investigated by means of nuclear emulsions. While the energy spectrum of the emitted protons agrees rather well with the predictions of the statistical theory, the angular distributions obtained in reference 3 show a pronounced anisotropy that is difficult to explain.

The present work was undertaken to investigate further the photodisintegration of A^{40} and to confirm the earlier results. In our experiments we used a cloud chamber containing argon gas. This allowed us to find all cases of photodisintegration where charged particles were emitted. The cloud chamber was irradiated with bremsstrahlung of 70 Mev peak energy from the synchrotron of the Physico-Technical Institute of the Academy of Sciences, U.S.S.R.

THE CLOUD CHAMBER AND ITS FILLING

The present experiment was performed with a fast-action cloud chamber. A description of the chamber and of the auxiliary apparatus has been given earlier.[4] The working volume of the chamber has a diameter of 30 cm and a depth of 7 cm. The chamber was located in a magnetic field of strength H = 6300 oersteds. The collimated x-ray beam from the synchrotron had a diameter of 4 cm. The x-ray beam entered the cloud chamber through a thin aluminum window placed in its side wall. The tracks were photographed with a stereo camera which was used also to project the tracks during the analysis.

In the argon experiment, the cloud chamber was filled with a mixture of argon and helium ($N_A = 0.69\ N_{He}$). The pressure of this mixture was 950 mm Hg. This mixture was chosen because of the following reasons.

(1) The construction of the chamber requires an operating pressure slightly larger above atmospheric. By adding helium to the argon, the track length of the emitted charged particles could be increased by a factor of almost two. This increase in the track lengths of the recoil nuclei is of great importance in identifying (γ, p) and (γ, pn) reactions.

(2) The helium in the chamber gas mixture was used in the present work as a monitor to obtain the irradiation dose. This was its main function.

The photoreactions on helium differ very much from those on argon (and on the oxygen and car-

Yields of the different reactions of the photodisintegration of A^{40}

Reaction	Number of cases	$\int_0^{70}\sigma dE$, Mev-bn
(γp)	474	0.35 ± 0.1
(γpn)	43	≈ 0.035
$(\gamma\alpha)$ and $(\gamma\alpha n)$	102	≈ 0.07
stars	10	≈ 0.007
(γn)	—	0.23

bon contained in the condensing vapors of the chamber). The cross sections of the different photoreactions in helium are known and have been repeatedly checked.[5-7] Thus one can determine the absolute yields of the different reactions by relating them to the yields of reactions in helium without having to utilize auxiliary apparatus to determine the γ-radiation intensity.

YIELDS OF THE PHOTONUCLEAR REACTIONS

All possible photoprocesses involving the emission of charged particles were registered by the cloud chamber.

As a result of a (γ, n) process on argon, the recoil nuclei produce short heavily ionizing tracks. In most cases the track lengths do not exceed 1 to 2 mm. At the same time, the electrons and positrons in the chamber produce a background which makes it difficult to determine the total number of the (γ, n) reactions. The (γ, n) reaction therefore was not studied further.

The reactions (γ, p) and (γ, pn) have a characteristic appearance in the cloud chamber. They consist of a proton track of rather weak ionization with a heavy short track of the recoil nucleus at its start. Such tracks are denoted in the literature as "flags." The (γ, p) and (γ, d) reactions were not separated in the present experiment. The (γ, p) and (γ, pn) reactions were identified by kinematical considerations. In the center-of-mass system, the proton and the recoiling nucleus form an angle of 180°. In the laboratory system the reaction products have an additional forward velocity due to the momentum of the absorbed photon, and the emission angle is reduced. However, even in the most favorable case (photon energy close to the peak energy; recoil nucleus in a very highly excited state) the angle does not decrease by more than 15 to 18°. Furthermore, the proton, recoil nucleus, and the photon are obviously coplanar. In the (γ, pn) reaction the proton can be emitted in an arbitrary direction with respect to the recoil nucleus. Obviously the error in the determination of the relative yield of the (γ, pn) reaction is confined to the cases in which the neutron is emitted with very low energy relative to the proton energy, or in which the neutron is emitted almost in the same direction as the proton. It is also confined to the fraction of cases in which the recoil nucleus has such a short track, that it is difficult to determine the direction of its motion.

The reactions (γ, α) and $(\gamma, \alpha n)$ are similar to the described proton "flags". However, they can be easily identified by the considerable ionization density of the α-particle tracks, and also by the track length of the recoil nuclei. It must be noted that it is much more difficult to discriminate between the (γ, α) and $(\gamma, \alpha n)$ reactions than between the (γ, p) and (γ, pn) reactions. This is caused by the relatively small momentum carried by the neutron, compared to the momentum of the α-particle. The neutron has therefore a relatively small influence on the angle between the α-particle and the recoil nucleus.

All photodisintegrations resulting in emission of three or more charged particles were counted as "stars."

The condensing vapor consisted of a mixture of 70% ethyl alcohol and 30% water, leading also to photoprocesses on O and C. The corresponding processes on argon, oxygen, and carbon could not be distinguished in our experiment, except for a small number of (γ, p) flags which happened to be favorably oriented. In order to account for the background due to these reactions, an auxiliary experiment was performed where the cloud chamber was filled only with helium but had the same content of condensing vapors and otherwise identical conditions. The yields of the different reactions on O and C were determined in relation to the (γ, p) reaction in helium. They then were corrected for the change of the partial pressure of helium in the helium-argon mixture and used to determine the number of corresponding reactions in argon (relative to the known number of helium (γ, p) flags in the helium-argon mixture). Under the actual conditions of the experiment, the background reactions of the (γ, p) and (γ, pn) type amounted to 15% of the (γ, p) and (γ, pn) reactions in argon. The values of the relative yields of the different photoreactions on argon are given in the table.

By comparing the numbers of (γ, p) reactions in argon and in helium, the integrated cross section of the (γ, p) reaction in argon was determined in the following manner. To eliminate errors associated with vertical tracks, only those argon and helium flags were counted whose tracks did not make an angle greater than 65° with the horizontal plane. It was found that there were 67 helium (γ, p) flags and 474 argon flags of the same type (after subtracting the background flags due to the water and alcohol vapors). The value of the integrated (γ, p) cross section of helium for a photon peak energy of 70 Mev (0.034 Mev-bn) was taken from references 5 to 7. Then the integrated cross section of argon, for a photon peak energy of 70 Mev, turns out to be 0.35 Mev-bn. This does not agree with the result of reference 2, which apparently is much too large.

It is of interest to compare the experimentally-determined total integrated photon absorption cross section with the theoretical predictions. According to Levinger and Bethe,[8] this quantity equals 0.83 Mev-bn, assuming that the fraction of exchange forces is $x = 0.5$. From the experiment we have the value 0.69 Mev-bn. This can be taken to be in good agreement with the theoretical value, since in this range of atomic numbers the experimental values of the integrated absorption cross section are in general slightly smaller than the theoretical ones calculated with $x = 0.5$.[9] The integrated cross sections of the different processes in argon are given in the table.

The integrated cross section for the (γ, n) reaction was taken from reference 10.

THE ENERGY DISTRIBUTION OF THE PHOTOPROTONS

The energies of the protons were determined in the following ways: (1) from the curvature of the tracks in the magnetic field, (2) from the track length of the recoil nucleus [for the (γ, p) reactions], (3) from the range of the proton track in the chamber for small proton energies, and (4) very crudely from the visually-determined ionization density. In practice the measurement was performed in each case with all methods applicable to the particular case, except for the fourth method, which was used only as an order-of-magnitude check.

The precision of the measurement of the track curvature is limited by the multiple scattering of protons of a few Mev in the chamber gas. This has been considered, for example, in reference 11. Furthermore, in general the curvature can be determined sufficiently well only for tracks which are so oriented as to have a visible length of 10 to 15 cm. The second method can be used only for (γ, p) reactions, where a unique correlation exists between the energy of the proton and the energy (and consequently also the range) of the recoil nucleus. One sees from Table I that the main photoproton yield comes from (γ, p) reactions, and only $\sim 10\%$ is due to the (γ, pn) reaction. Therefore, (2) was the main method used in the present experiment.

The energy spectrum of photoprotons from A^{40} was determined up to a proton energy of 15 Mev. The corresponding range of the recoil nucleus for the condition of our experiment was ~ 0.14 cm. Most photoprotons from argon have energies up to 8 or 10 Mev. The number of protons with energies > 10 Mev, i.e., with a recoil range > 0.1 cm, is relatively small. Since protons of equal energy produce much larger recoils if they are emitted from carbon and oxygen than from argon, one has to determine the contribution of the background nuclei to recoils of ranging from 0.1 to 0.15 cm. It was found in the auxiliary experiment with the pure helium filling that most photoprotons from C and O had recoil ranges > 0.1 cm (referred to the larger stopping power of the helium-argon mixture). In fact, the number of (γ, p) reactions in O and C with a recoil range up to 0.15 cm does not exceed 10% of all reactions of this kind. Since the total number of (γ, p) reactions of O and C is only $\sim 10\%$ of the argon reactions, the contribution of background protons to the high-energy tail of the protons from argon is unimportant in the 10 to 15 Mev range.

No range-energy relation for Cl^{39} ions is known in the literature. Assuming that the energy dependence of the range of Cl^{39} differs from that of A^{40} by less than the uncertainties of the present experiment, one can use the known range-energy relation for A^{40}.[12] A check on the curvatures and ranges of the corresponding protons gave a satisfactory agreement.

The recoil-nuclei ranges were approximately determined by projecting the photographs. They were more precisely determined under the microscope, taking the inclination of the track into account. To avoid errors connected with large inclinations, both the curvatures and the ranges were determined only for tracks which made an angle of not more than 45° with the horizontal plane. The accuracy of the measurement of the track lengths of the recoils was 0.1 mm.

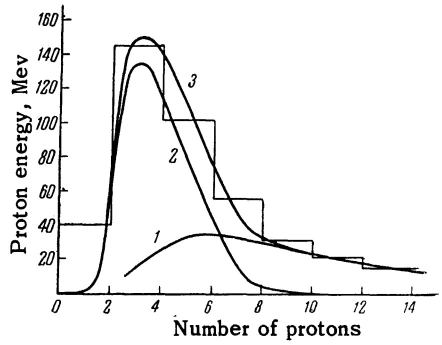

FIG. 1. Energy distribution of photoprotons from argon: 1 – distribution calculated from the theory of the direct photoeffect; 2 – distribution calculated from the statistical theory of nuclear reactions; 3 – total theoretical energy distribution of photoprotons; histogram – experimental results.

The energy distribution obtained for photoprotons from argon is given by the histogram of Fig. 1. The other curves in Fig. 1 show the spectra as given by the statistical theory of nuclear reactions and by Courant's theory[13] of the direct photoeffect. The spectrum of evaporation photoprotons is given[14] by

$$I(\varepsilon)\,d\varepsilon = \varepsilon\sigma_c(\varepsilon)\,e^{-\varepsilon/T}d\varepsilon \int\limits_{B_p+\varepsilon}^{E_{\gamma m}} N_\gamma(E)\,\sigma_{\gamma n}(E)\,dE.$$

The following values were assumed for the parameters entering this expression: nuclear temperature T = 1 Mev; proton binding energy in A^{40}, $B_p = 12.44$ Mev[2]; cross section $\sigma_{\gamma n}(E)$ for the reaction $A^{40}(\gamma, n)A^{39}$ as a function of the energy of the photons, E, was taken from reference 15; the bremsstrahlung spectrum $N_\gamma(E)$ with peak energy E = 70 Mev was taken from reference 16. The energy distributions of the "direct" photoprotons was calculated from the formula

$$I(\varepsilon)\,d\varepsilon = f(\varepsilon)\,d\varepsilon \int\limits_{B_p+\varepsilon}^{E_{\gamma m}} N_\gamma(E)\,E^{-3}dE,$$

where $f(\epsilon)$ is the penetrability of the coulomb barrier.

The calculated energy distributions agree well with the experimental photoproton spectra if one assumes a ratio of the direct to evaporation yields of 1 : 1, 2. It should also be mentioned that there exist many photoprotons from the (γ, p) reaction of A^{40}, with energies between 15 and 30 Mev, which are not included in the histogram of Fig. 1.

ANGULAR DISTRIBUTIONS OF PHOTOPROTONS

The inclinations of the photon tracks to the horizontal plane and the angles θ between the proton tracks and the directions of the x-ray beam were determined by projecting the photographs. The errors of this method do not exceed 2°. Tracks with inclination angles up to 45° were used for the angular distributions. The tracks thus selected were grouped in bands 20° wide. The distribution obtained was then expressed per unit solid angle by applying appropriate angle-dependent factors which were assumed to be constant in any particular angular band. The obtained angular distribution of photoprotons from A^{40} with energies 2 to 15 Mev in the laboratory system is shown as a histogram in Fig. 2. The ordinate is in relative units. The statistical errors are also indicated. An analogous histogram from preliminary experiments was given earlier,[17] but was not reduced to yield per unit solid angle.

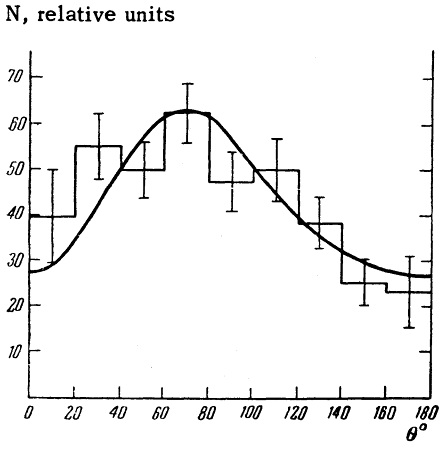

FIG. 2. Angular distribution of photoprotons, from argon with energies of 2 to 15 Mev. The histogram is the result of analysis of 406 proton tracks. The number of tracks shown has been referred to unit solid angle.

The forward shift of the maximum in the angular distribution cannot be explained by the momentum of the incoming photon, since the transformation to center-of-mass coordinates is unimportant for such a heavy nucleus as A^{40}.

The solid curve drawn in Fig. 2 has the form

$$I(\theta) = A + B(\sin\theta + p\sin\theta\cos\theta)^2,$$

with A = 27, B = 30, and p = 0.5. The parameter p is connected with the ratio of dipole to quadrupole absorption of photons, $\sigma_Q/\sigma_D = p^2/5$. Thus, in our case, the quadrupole absorption amounts to ~ 5% of the dipole absorption.

The angular distribution of photoprotons from argon obtained in reference 3 with bremsstrahlung with 22.5 Mev peak energy has its maximum near 70°, like our Fig. 2.

CONCLUSIONS

The experimental results on the photodisintegration of A^{40} obtained in the present work are not in disagreement with the results of most papers devoted to the investigation of the photonuclear reactions of medium weight nuclei.[14,18-20] The dipole character of the photon absorption of A^{40} nuclei is corroborated by comparing the experimental integrated absorption cross sections with the theoretical predictions, as well as by the angular distribution of the photoprotons. The anomalously large photoproton yield compared with the photoneutron yield is not as sharp as indicated by the results of reference 2. It can be explained in part by the large contribution of the direct photoprotons, which follows from the comparison of the experimental photoproton spectrum of argon with theoretical predictions. At γ-energies of up to 70 Mev essentially there occur in argon two competing reactions, (γ, p) and (γ, n), with approximately equal integrated cross sections and with a small contribution from (γ, α), $(\gamma, \alpha n)$ and (γ, pn) reactions.

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290

SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 6 DECEMBER, 1958

ENERGY SPECTRUM AND ANGULAR DISTRIBUTION OF π^+ MESONS PRODUCED ON CARBON BY 660-Mev PROTONS

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The energy spectrum of π^+ mesons produced by 660-Mev protons on carbon was measured at five angles from 19°30′ to 65°. The absolute cross-sections $d\sigma_+/d\Omega$ were also measured. In the c.m.s. of the two colliding nucleons, the mean π^+ meson energy was found to be independent of the angle of emission, and equal to 100 Mev. Conclusions are drawn concerning the angular distribution of π^+ mesons; the total cross-section for their production on carbon by 660-Mev protons has been found to be $(46.7 \pm 5.1) \times 10^{-27}\,\mathrm{cm}^2$. The probability of π^+-meson production in p — p collisions in the carbon nucleus is half the analogous probability for free p — p collisions.

1. INTRODUCTION

THE production of charged π mesons on carbon by 660-Mev protons was investigated for various angles of observation in several experiments.[1-4] Meshcheriakov et al. measured the relative energy spectrum of π^+ and π^- mesons at 24°.[1] Energy spectra and absolute yields of π^+ mesons[2] and π^- mesons[3] were studied at 45°. Analogous information on mesons of both signs was obtained for 90° as well.

In the present work, we have studied the energy