# RATIO OF THE DEUTERON AND PROTON YIELDS IN THE PHOTODISINTEGRATION OF Au$^{197}$

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The ratio of the yields of photodeuterons and photoprotons has been measured for gold irradiated with bremsstrahlung of maximum energy 70 Mev. This ratio equals 0.14 ± 0.07. The protons and deuterons were identified by grain counting in emulsions over the last 90 $\mu$ of their range.

IN a series of papers on the photodisintegration of nuclei a rather high deuteron yield has been reported.[1-7] In these investigations it was also found that for low and medium photon energies the deuteron yields fluctuate strongly from element to element. A theoretical interpretation of these results is however frustrated by the lack of a sufficient amount of data.

The aim of the present work is the determination of the ratio of the deuterium yield to the proton yield from gold under irradiation with bremsstrahlung of maximum energy of 70 Mev. As the detector nuclear emulsions of type NIKFI Ya-2 were utilized. The particle masses were determined by the well known method of grain counting.[7]

## EXPERIMENTAL METHOD

The gold target was irradiated inside a multiplate chamber. The experimental arrangement is shown schematically in Fig. 1. The chamber consisted of a cylindrical brass vessel with a cover plate and with two nipples. The entrance nipple was placed in a constant magnetic field to clear the beam of electron and positron contamination. The chamber was evacuated to 2.5 × 10$^{-2}$ mm Hg pressure. The target was a gold foil 99.1 mg/cm$^2$ thick. It was placed at an angle of 40° with respect to the photon beam. An area of 1.7 × 2.2 cm$^2$ was irradiated. Bremsstrahlung with a maximum energy of 70 Mev was utilized. The relative dose of the irradiation was measured with an ionization chamber placed in the photon beam. The reaction products were registered in nuclear emulsions type NIKFI Ya-2 of thickness 200 $\mu$ placed at 90° with respect to the beam. The particles entered the emulsions with a mean angle of 15°. The camera was surrounded by heavy lead shield. The exposed plates were developed with a metol hydro-

quinon developer. The developing was controlled by the temperature of the developer. The scanning was performed with an MBI-2 microscope with a 90 × objective and a 10 × ocular. The horizontal projection of the tracks was measured with an ocular scale graduated 1.23 $\mu$ per division. The micrometer with which the vertical track projections were determined had a graduation of 1 $\mu$ per division. The tracks between 90 and 500 $\mu$ long which entered the emulsions were selected for measurement if their direction indicated that they came from the illuminated region of the target. Furthermore, 89 tracks of recoil protons were found and the characteristic grain distributions were obtained from these. They were selected such that they began and terminated within the emulsion and had a track length of at least 90 $\mu$. The grains in the last 90 $\mu$ of these tracks were counted twice each. The average of these two counts was taken to be the true number. Additionally the grains on the last 45 $\mu$ of each recoil proton track were counted.

The ends of the tracks of the photoparticles and of the recoil protons were inclined 0° to 40° to the surface of the emulsion. If the grain numbers were determined similarly in all tracks, one would obtain a smaller count in the steeper tracks compared with the more horizontal ones, because the number of optically nonresolvable grain pairs
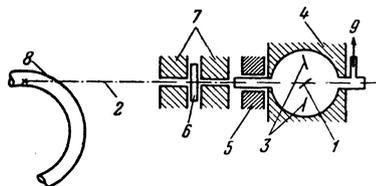


FIG. 1. Experimental arrangement. 1—target, 2—γ-ray beam, 3—nuclear emulsions, 4—lead shielding, 5—sweeping magnet pole pieces, 6—monitor, 7—lead collimators, 8—synchrotron, 9—to the pump.

increased with increasing track steepness. In order not to distort the results, all measurements* were reduced to an inclination of 15°. The correction curves were obtained from the recoil-proton tracks since they were uniformly distributed in inclination.

The surface of an emulsion is usually more fully developed than the interior. Therefore the grain density of tracks near the surface was greater than of those near the backing. To correct for this effect all grain counts were reduced to the middle of the emulsion. The necessary corrections were also obtained from the proton recoil tracks, which were distributed uniformly in depth. The grain count obtained by the same observer may differ at different times (drift).[7] To establish this subjective factor in the course of determining the stabilized grain count, the number of grains was counted for 64 recoil proton tracks. The grain count was repeated a short time afterwards. A possible drift was eliminated by alternating grain counts on photoparticle tracks with counts on proton recoil tracks, thus establishing checkpoints.
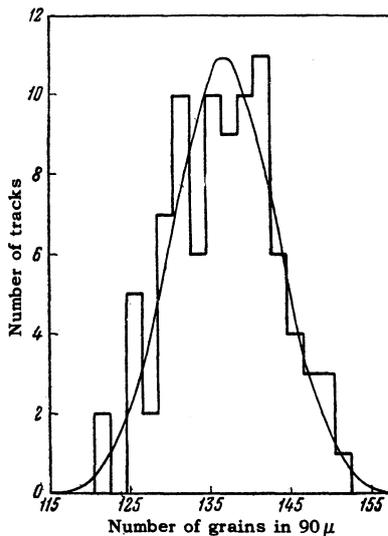
FIG. 2. Distribution of recoil protons as a function of the number of grains in the last $90\,\mu$ of the track. The smooth curve is the normal distribution.

Figure 2 shows the distribution of the number of grains of the last $90\,\mu$ of the proton recoil tracks. The mean grain count of this distribution is $N^p_{90\mu}$ 136.8; its standard deviation is $\sigma^p = 0.56\sqrt{N^p_{90\mu}}$.

The indicated deviation is not in disagreement with the value $\sigma \approx 0.7\sqrt{N}$ which has been proposed by Hodgson.[8] It is known that for singly charged particles[9]

$$N_R = mF\,(R\,/\,m)$$

and thus

$$N^d_{90\,\mu} = 2N^p_{45\,\mu},\qquad(1)$$

where R is the residual range, m the particle mass, $N_R$ the grain number in the residual range R, and p and d denote the respective particles. One can thus obtain the mean number of grains in the last $90\,\mu$ of deuteron track from the number of grains of the last $45\,\mu$ of the proton track, by means of (1). Such a distribution is shown in Fig. 3. From the mean proton grain count $N^p_{45\mu} = 72.7$ we thus obtain for the deuterons $N^d_{90\mu} = 145.4$.
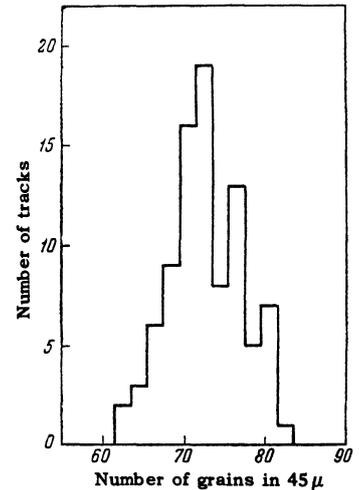
FIG. 3. Distribution of the tracks of recoil protons as a function of the number of grains in the last $45\,\mu$ of the track.

Like in reference 7, it was assumed that the number of grains on the last $90\,\mu$ of the proton tracks forms a normal distribution with a mean value $N^p_{90\mu}$ and a standard deviation $\sigma^p = 0.56 \times \sqrt{N^p_{90\mu}}$. The observed distribution was checked by means of the well known $\chi^2$ test and was found to fully agree with this hypothesis. The smooth curve in Fig. 2 shows the calculated normal distribution. It was further assumed that the grain number of the deuteron tracks also forms a normal distribution with mean value $N^d_{90\mu}$ and standard deviation $\sigma^d = 0.56\sqrt{N^d_{90\mu}}$.

The ratio $(N^d/N^p) = 1.06$ thus obtained for plates developed in a metol-hydroquinon developer is rather low. Under these circumstances it was not possible to resolve single protons from deuterons. It was therefore necessary to represent the experimentally observed distribution in the best possible manner by a sum of two normal distributions. This was done by the method of least squares.[11] The analysis was performed in the following manner. The experimental distribution obtained from 180 photoparticles was plotted as a histogram (Fig. 4). The ratio of the number of photoprotons to the total number of photoparticles was then assigned several values $\theta$, and the corresponding number of photoprotons and photoneutrons was determined. Then the corresponding normal distributions were computed[10] with account

of the known characteristic distributions, and both distributions were added. Finally the sum of the squares of the differences between the distribution so determined and the points of the histogram was computed. The most probable value was found to be $\theta = 0.878$. The corresponding individual distributions are shown as the dashed curves in Fig. 4 while their sum is plotted as the full curve. The uncertainty of $\theta$ was obtained from the magnitude of the sum of the squared deviations of the calculated from the observed distribution. It was found that for $\theta = 0.878$, $\Delta\theta = \pm 0.057$. It is possible for systematic errors to occur when the corrections for track stopping depth and inclination are applied to the grain count. Such errors can occur if there exist small differences between the angular and stopping depth distributions of the photoprotons and the recoil protons. This error will not exceed 0.5% for the photoprotons and will be $\leq 0.4\%$ for the photodeuterons.

## RESULTS AND DISCUSSION

The ratio of the yield of deuterons of energy 7 — 14 Mev to that of protons of energy 5 — 11 Mev was found in the present experiment to be

$$Y(\gamma, d) / Y(\gamma, p) = 0.14 \pm 0.07.$$

The indicated error was calculated from the above given value $\Delta\theta$. The small systematic errors in the determination of the grain number of the photoproton and photodeuteron tracks and the background of approximately 5% were not taken into account. In addition to the 180 tracks making up the histogram of Fig. 4 there had been found three further tracks of lengths between $90\,\mu$ and $100\,\mu$. They had grain counts of 117, 108, and 114. They were considered to be photoproton tracks and were included in obtaining the final result. It was assumed that the possible contribution of triton tracks was negligible.

Evidently, a rather high yield ratio was obtained. It is interesting to note that also in the case of sulfur and copper the obtained deuteron yields are rather high for irradiation with bremsstrahlung of $E_{\gamma\,max}$ around 70 Mev.[2,4] They are several times greater than those obtained with bremsstrahlung of $E_{\gamma\,max} \approx 30$ Mev.[3,7]

The energy distribution of photoprotons from gold[12] has a sharp rise between 8 and 10 Mev with the maximum at 10.5 Mev. The computations performed in reference 12 according to the statistical theory and to the direct photoemission were not able to explain these facts. From the evaluation of the photodeuteron yield of this work we can conclude that these facts are not related to deuterons, since otherwise there would have had to be observed a significantly higher photodeuteron yield.
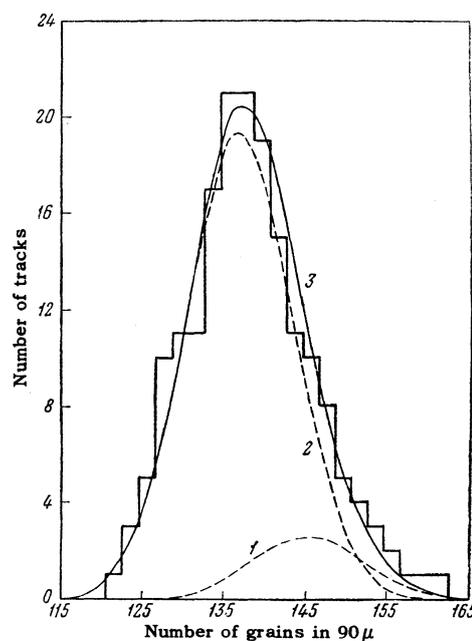


FIG. 4. Distribution of the tracks of photoparticles as a function of the number of grains in the last $90\,\mu$ of the track. 1 — normal distribution of photodeuterons, 2 — normal distribution of photoprotons, 3 — sum of both.

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