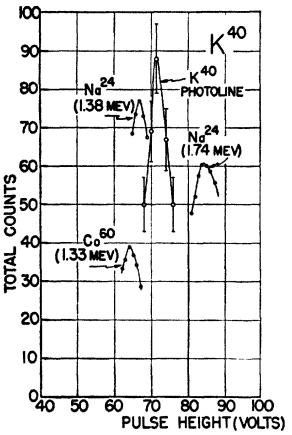


FIG. 15. The photo-line of $K^{40}$ and $Na^{24}$ and $Co^{60}$ calibration lines. The source strength was less than $10^{-9}$ curie. The data were taken in about five hours. The $K^{40}$ energy is 1.48±0.02 Mev.

of the pulses in $K^{40}$ show that there is no other gamma-ray present with an intensity greater than about 10 percent of the 1.48-Mev line. Our success with the photographs of oscilloscope patterns suggests that this technique will be valuable for work with weak sources since it serves the purpose of a multichannel discriminator. Densitometer traces we have made of gamma-ray patterns resemble the discriminator curves very closely. For initial spotting of gamma-ray lines this technique will probably not be surpassed.

We are greatly indebted to Drs. Dean Cowie and P. Abelson of the Carnegie Institution of Washington for supplying us with sources of $Ga^{66}$. We wish to thank Drs. E. P. Tomlinson and J. L. Simons for sources of $Au^{198}$.

PHYSICAL REVIEW VOLUME 80, NUMBER 4 NOVEMBER 15, 1950

# Photo-Disintegration Cross Sections of Deuterium and Beryllium for the Gamma-Rays of Sodium 24 and Gallium 72

ARTHUR H. SNELL, E. C. BARKER, AND R. L. STERNBERG
*Oak Ridge National Laboratory, Oak Ridge, Tennessee*

(Received June 22, 1950)

Photo-neutron yields from spheres of $D_2O$ and Be containing $Na^{24}$ and $Ga^{72}$ gamma-ray sources were measured by spatial integration of induced foil activities in a large paraffin block. A standard neutron source was used to calibrate the apparatus.

The $Ga^{72}$ and $Na^{24}$ sources were subsequently dissolved, and their radioactive strengths were measured by beta-counting of aliquots. The data so obtained, when combined with the known wall thickness of the spheres led to the following results after the application of appropriate corrections:

(1) Photo-disintegration cross section of D at 2.76 Mev: $14.3\times10^{-28}$ cm²
(2) Photo-disintegration cross section of Be at 2.76 Mev: $6.74\times10^{-28}$ cm²
(3) Cross section of D at 2.50 Mev multiplied by intensity of 2.50 Mev line in quanta per $Ga^{72}$ beta-emission: $2.81\times10^{-28}$ cm²
(4) Sum of cross sections of Be at 1.84, 2.20 and 2.50 Mev weighted according to respective gamma-intensities in $Ga^{72}$: $2.16\times10^{-28}$ cm²

These results are believed accurate within 8 percent. Agreement with theory is discussed for both D and Be.

## I. INTRODUCTION

THE measurements to be described in this paper were made in 1945–46. At that time a rather complete survey of photo-neutron yields was envisaged. Since circumstances have prevented the completion of such a survey, we describe here our study of the yields from $Na^{24}$ and $Ga^{72}$. The results may be of interest inasmuch as very little has been published on this subject. Comparable work which has come to our attention is that of Russell, Sachs, Wattenberg, and Fields[1] and Wilson, Collie, and Halban.[2]

It is easy to see from first principles that if a gamma-emitting radioactive source is placed in a small spherical cavity in the center of a sphere of beryllium or heavy water, the number of photo-neutrons emitted per second will be given by

$$S=QN(\Sigma_i\alpha_i\sigma_i) \quad (1)$$

where $Q$ is the number of radioactive transformations taking place per second within the source, $N$ is the wall thickness of the spherical shell expressed in terms of the number of Be or D atoms per square centimeter, $\alpha_i$ is the relative intensity (i.e., the mean number of quanta per radioactive transformation) of the $i$th gamma-ray above the photo-neutron threshold for beryllium (1.67 Mev) or deuterium (2.235 Mev), and $\sigma_i$ is the $(\gamma, n)$ cross section at the energy of the $i$th gamma-ray. This expression will hold so long as there is negligible neutron and gamma-ray absorption in the spherical shell. We are here concerned with the experimental measurement of the $\Sigma_i\alpha_i\sigma_i$. In the case of $Na^{24}$ this leads to a value for the photo-dissociation cross sections at 2.76 Mev,

[1] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).
[2] Wilson, Collie, and Halban, Nature **163**, 245 (1949), and supplementary communication from Professor Halban.

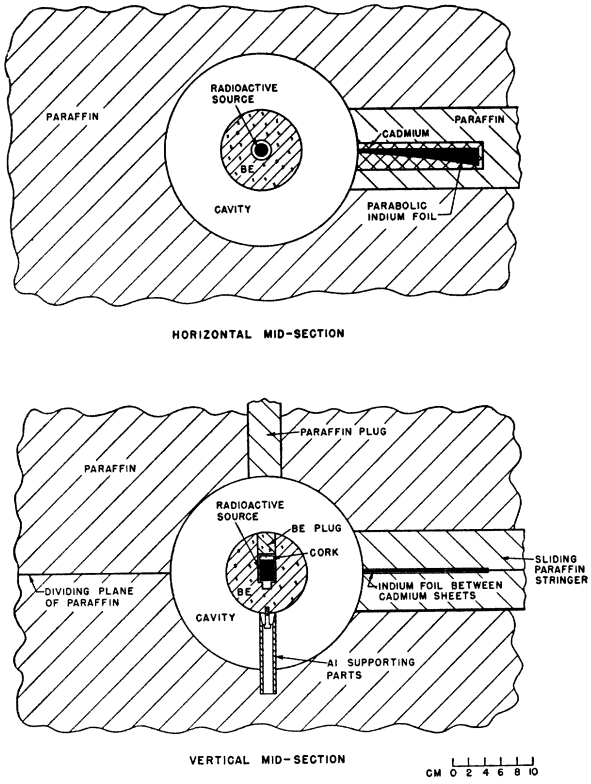


FIG. 1. Experimental arrangement used for measuring photo-neutron yields. The beryllium sphere was chosen for indication in the sketch, but the $D_2O$ sphere was nearly the same size and had similar geometry. The 2-g Ra source placed in the beryllium sphere, without the covering plug, constituted the standard (photo-neutron) source used for calibration purposes.

and in the case of $Na^{24}$ a direct comparison with theory is possible. Even for the more complicated decay scheme of $Ga^{72}$ comparison with theory can be instructive, although it is less satisfactory because of the difficulty of measuring the $\alpha$'s with precision.

## II. EXPERIMENTAL

The radioactive sources consisted of several grams of NaF or $Ga_2O_3$ contained in Lusteroid tubes and activated in the Oak Ridge Nuclear Reactor to a strength of a few tenths of a curie. They were first placed in the beryllium and heavy water spheres, and the photo-neutron outputs were measured; they were then dissolved, and aliquots were taken for absolute beta-counting. For a closer discussion, we shall describe severally the measurements of $N$, $Q$, and $S$.

### The Spheres

The beryllium sphere had an average diameter of 10.05 cm and departed from sphericity by less than 0.10 cm along various diameters. A radial recess 2.22 cm in diameter and 6.36 cm deep permitted the insertion of the radioactive source (Fig. 1). After the source was in place, a beryllium plug was inserted over it so as to complete the shell. Let us call $(10.05-2.22)/2=3.91$ cm the "nominal" wall thickness. This is not the correct wall thickness to use in our formula because of two factors: first, the source cavity was cylindrical rather than spherical, so that some kind of average wall thickness had to be determined; second, the source was of finite extent, so that the $\gamma$-rays did not in general proceed along radii but rather had slightly longer paths in the metal. Both of these effects were estimated graphically; the former involved a reduction of the nominal wall thickness by a factor 0.92 and the latter an increase by a factor 1.04, together yielding a final value 3.75 cm. The weight of the sphere without plug was 911.2 g, whence the mean density of the metal was 1.78. Thus the wall thickness $N$ in terms of atoms per $cm^2$ was $4.46\times10^{23}$.

The $D_2O$ sphere was contained in a shell spun of brass $\frac{1}{2}$ mm thick. It was slightly smaller in diameter than the beryllium sphere, and had an entrant brass tube to contain the radioactive source, with a covering cap containing about 6 g of $D_2O$. The nominal wall thickness of $D_2O$ was 2.86 cm. Corrections were again determined graphically. The cavity shape correction reduced the nominal wall thickness by a factor 0.889 and the finite source size correction increased it by a factor 1.03; thus the final value was 2.62 cm, whence $N=1.75\times10^{23}$. The weight of $D_2O$ in the sphere was close to 270 g.

## III. THE NEUTRON MEASUREMENTS

The photo-neutron sources were placed in a paraffin pile and the space-integrated radioactivity induced in cadmium-covered indium foils was compared with that induced by a calibrated neutron source of known intensity. In the actual experimental arrangement, (Fig. 1) each source was placed at the center of a spherical cavity, 24 cm in diameter, centered in the paraffin. The whole paraffin pile measured $54\times48\times32$ inches; it had been built by the Metallurgical Laboratory group under L. Szilard, and it was fortunately available to us for this work. Rather than measure the indium resonance activity distributions explicitly to compare the (activity$\times r^2$) integrals, we cut parabolic indium foils and laid them between sheets of cadmium, 0.020 inch thick, in the equatorial plane of the paraffin geometry. The width of any element of the foil was then proportional to the square of the radial distance of that element from the center of the total geometry, and the narrow end of the foil came to the boundary of the cavity in the paraffin. The foils had to be about 15 cm long in order to cover the region containing the indium resonance neutrons. After irradiation, the foils were removed and wrapped in a standard way about a thin-walled Geiger counter.

The standard source happened also to be a photo-source, consisting of a capsule containing 1935 mg of radium bromide placed in our beryllium sphere, without the beryllium plug. The absolute neutron output of this combination could be derived by comparisons that had

been made with the following three independently standardized Ra—Be sources:

(1) A source known as Source *I* in the Metallurgical Laboratory literature. This source had been calibrated absolutely by Anderson *et al.*[3] by a method depending on the calculation by diffusion theory of the slow neutron flux emerging from a pile of pure graphite with the source buried in it. Source *I* had been compared[4] with another Ra—Be source known as Source *II*, which in turn had been compared with our standard photo-source by Bernstein *et al.*[5] The results were: for Source *II*, $12.8\times10^6$ neutrons per second, and for our photo-source, $4.09\times10^6$ neutrons per second.

(2) Source *II* had been independently absolutely calibrated by Agnew *et al.*[6] in a water tank containing boron. The result, $14.0\times10^6$ neutrons per second, was somewhat higher than the above figure obtained by comparison with Source *I*, and led through the same intercomparison by Bernstein to the figure $4.48\times10^6$ neutrons per second by our photo-source.

(3) A Los Alamos source known as No. 44. Absolute standardization of this source had been carried out carefully by Walker[7] (result: $5.90\times10^6$ neutrons per second) and comparison with our Ra—Be photo-source was possible through two linkages. In the first place, Bernstein[5] had compared our Ra—Be photo-source with a Ra—B source known as No. 37, and Walker had compared No. 37 with No. 44. Walker's result for No. 37 was $4.28\times10^6$ neutrons per second, and this led through Bernstein's comparison to a strength of $4.13\times10^6$ neutrons per second for our photo-source.

The second comparison arose through the fact that Bernstein had also intercalibrated sources 37 and *II*; therefore the chain 44→37→*II*→(Ra—Be photo-source) could be set up. Using Walker's figure of $4.28\times10^6$ for No. 37, Bernstein's comparison gave $12.9\times10^6$ neutrons per second for Source *II*, in close agreement with the graphite pile calibration mentioned in paragraph (1) above. The derived strength for our photo-source was $4.12\times10^6$ neutrons per second.

As a final figure for the strength of the Ra—Be photo-source substandard, we have chosen $4.17\times10^6$ neutrons per second. This result comes from weighting the calibration of source No. 44 slightly more favorably than the earlier calibrations of Sources *I* and *II*.

## IV. THE RADIOACTIVE SOURCE STRENGTHS

After the radioactive sources had been dissolved, the solutions were stirred thoroughly and two or three aliquots consisting of about $10^{-6}$ of the total were taken volumetrically. These samples were then evaporated on thin backing, and counted under a mica-window counter. The counting efficiency was determined by means of a separated $UX_1$ sample for which a specific activity of 724 disintegrations per minute per milligram was assumed. Suitable corrections were evaluated and applied for window absorption, backscatter, counting loss, and counts arising from the gamma-rays.

## V. TREATMENT OF DATA AND RESULTS

Several different parabolic indium foils were used, and each was calibrated by three separate activations with the Ra—$\gamma$—Be standard source ($4.17\times10^6$ neutrons per sec.) If a fraction, $k$, of the neutrons from the source is absorbed in the foil, and if the beta-particles are counted with an efficiency $E_f$, then $E_fk$ is given by (saturation activity of foil in counts per sec.)/$4.17\times10^6$. Thus $E_fk$ was determined for the various foils; the values had a spread over a range of 4 percent in the neighborhood of $7.77\times10^{-6}$.

Now if we take the zero of time at the instant of starting the exposure of the parabolic indium foil to the photo-neutron sources under investigation, application of the laws of radioactive decay yields without approximation the following expressions for $\Sigma_i\alpha_i\sigma_i$ in terms of the parameters of the experiment:

$$\sum_i \alpha_i\sigma_i=\frac{1}{E_fk}\left(\frac{E_\beta A}{N}\right)\left(\frac{\lambda_f-\lambda_s}{\lambda_s}\right)\times\left\{\frac{e^{-\lambda_s t_2}-e^{-\lambda_s t_3}}{(e^{-\lambda_f t_a}-e^{-\lambda_f t_b})(e^{-\lambda_s t_1}-e^{-\lambda_f t_1})}\frac{N_f}{N_A}\right\}. \quad (2)$$

The symbols hitherto undefined have the following meanings: $\lambda_f$ and $\lambda_s$ are the decay constants of the indium foil and the radioactive source respectively, $A$ is the aliquot fraction, $E_\beta$ is the efficiency of counting the beta-particles of the aliquot, $t_1$ is the time of the end of the exposure of the indium foil (60 min. throughout), $t_2$ is the time of the start of the aliquot count and $t_3$

TABLE I. The figures in column 2 give results uncorrected for gamma-ray absorption and neutron slowing down in the spheres. Column 5 gives the results corrected for these effects as explained in the text. Columns 3 and 4 give the numbers of independent foils activated and aliquots taken and counted. Column 6 gives standard yields as derived from the figures of column 5, and column 7 gives comparable figures obtained by other workers.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Photo-source | $\Sigma_i\alpha_i\sigma_i$ before correction | Number of parabolic foils activated | Number of aliquots counted | $\Sigma_i\alpha_i\sigma_i$ after correction | Standard yield* | Standard yield (Russell *et al.*) |
| Na—Be | $6.02\pm0.04\times10^{-28}$ cm² | 7 | 7 | $6.74\pm0.04\times10^{-28}$ cm² | $14.1\times10^4$ | $14\times10^4$ |
| Na—$D_2O$ | $13.4\pm0.2$ | 6 | 8 | $14.3\pm0.2$ | 27.0 | 29 |
| Ga—Be | $1.83\pm0.02$ | 7 | 7 | $2.16\pm0.03$ | 4.5 | 5.9 |
| Ga—$D_2O$ | $2.58\pm0.04$ | 7 | 7 | $2.81\pm0.04$ | 5.3 | 6.9 |

* Neutrons per second per curie of radioactive material situated 1 cm from 1 g of deuterium or beryllium.

[3] Anderson, Fermi, Roberts, and Whitaker, MDDC 880, unpublished.
[4] M. D. Whitaker and J. H. Roberts, Metallurgical Laboratory Report CP-10, unpublished.
[5] S. Bernstein, private communication.
[6] Agnew, Anderson, Miller, Roberts, Whitaker, and Wollan, MDDC 878, unpublished.
[7] R. L. Walker, MDDC 414, unpublished.

TABLE II. Summary of knowledge of the gamma-rays of $Ga^{72}$ above the Be($\gamma$, $n$) threshold.

| Gamma-ray energies | | Gamma-ray intensities ($\alpha_i$)* | | $\sigma$(Be) Theor. | $\alpha_i\sigma$(Theor.) | |
|---|---|---|---|---|---|---|
| MZK | Haynes | MZK | Haynes | Guth and Mullin | MZK (ref. 10) | Haynes (ref. 11) |
| 1.81 Mev | 1.87 Mev | 0.102 | 0.078±0.02 | $7.5\times10^{-28}$ cm$^2$ | $0.76\times10^{-28}$ cm$^2$ | $0.59\times10^{-28}$ cm$^2$ |
| 2.18 | 2.21 | 0.33 | 0.33 ±0.05 | 5.4 | 1.78 | 1.78 |
| 2.50 | 2.51 | 0.154 | 0.265±0.04 | 5.8 | 0.89 | 1.54 |
| | | | | $\Sigma_i\alpha_i\sigma_i$ (Theor.): | $3.43\times10^{-28}$ cm$^2$ | $3.91\times10^{-28}$ cm$^2$ |

* Quanta per $Ga^{72}-Ge^{72}$ radioactive transformation.

is the time of its conclusion ($t_3-t_2=10$ min. throughout), $N_A$ is the total number of beta-counts registered in the interval $t_3-t_2$ from the aliquot, $t_a$ (5 min. throughout) and $t_b$ (55 min. throughout) are the beginning and conclusion times of the foil count measured from the *end* of the activation of the indium foil, and $N_f$ is the number of foil counts observed in the interval $t_b-t_a$. Usually, $t_2$ was less than two half-lives of the radioactive source.

In a typical experiment two or three foils were activated from one of the sources placed in one of the spheres, after which the source was transferred to the other sphere and two or three more foils were activated. After dissolving the source two or three aliquots were taken. For a given photo-source Eq. (2) was applied to all of the possible foil-aliquot combinations, and the resulting values of $\Sigma_i\alpha_i\sigma_i$ were averaged with equal weight. The whole procedure was carried through for three or four freshly pile-irradiated radioactive sources. For example, in the case of Na$-D_2O$ three $Na^{24}$ samples were used from which a total of six foils were activated and eight aliquots were counted. The possible foil-aliquot combinations per $Na^{24}$ source added to give a total of sixteen determinations of $\Sigma_i\alpha_i\sigma_i$—not all independent, but all approximately equally reliable. The mean of these sixteen "determinations" is listed in column 2 of Table I, together with its "probable error" as derived from the spread of the individual values.

## VI. CORRECTIONS

There are several corrections which clearly should be considered for the values of $\Sigma_i\alpha_i\sigma_i$ thus obtained. All of these are in the direction of increasing $\Sigma_i\alpha_i\sigma_i$. They are as follows:

### A. Absorption of the $\gamma$-Rays in the Sphere

Our spheres were sufficiently large to make this a correction worth stating explicitly. If one assumes in a spherical geometry a wall thickness ($R_2-R_1$) and allows for the Compton absorption of the gamma-quanta in the material of thickness ($r-R_1$) inside of a shell at thickness $dr$ and radius $r$, one obtains instead of (1) the following expression for the photo-neutron source strength:

$$S=QN\,\Sigma_i\{1-\exp[-\mu_i(R_2-R_1)]\}(\alpha_i\sigma_i/\mu_i)$$

Where $\mu_i$ is the total Compton absorption coefficient in cm$^{-1}$ for the $i$th gamma-ray. This derivation assumes that any scattering of the original gamma-quantum will remove it from the picture so far as photo-neutron generation is concerned. Actually, it is seen that only a few percent of the quanta make either a Compton or a nuclear collision, so that the chance that any one of them will make a subsequent nuclear collision is negligible. Also there is a good chance that the original collision will reduce the energy of the quantum below the ($\gamma$, $n$) threshold. The assumption is therefore justified. The correction factors thus evaluated for $\Sigma_i\alpha_i\sigma_i$ are as follows: for Na$-D_2O$, 1.05; for Na$-$Be, 1.11; for Ga$-D_2O$, 1.06; for Ga$-$Be, 1.14.

### B. Absorption of the Gamma-Rays in the Radioactive Source

Here the assumption was made that the average path length traversed by the gamma-quanta in the cylindrical radioactive sources was equal to the radius of the source. This was close to 1 cm. On this basis, the correction factors to be applied to were as follows: for NaF sources, 1.01; for $Ga_2O_3$ sources, 1.02.

### C. The Slowing Down of Neutrons to below Indium Resonance before Escaping from the Sphere

Here we have adopted the corrections evaluated by Bernstein. In his work, using a radium gamma-source in the $D_2O$ and Be spheres, the neutron distribution in the paraffin had been determined with cadmium-covered indium foils. These distributions, in terms of foil activity $\times r^2$, were extrapolated according to a purely $r^2$-decrease across the cavity in the paraffin to the outer surface of the sphere, and thence taken to decrease linearly to zero at the center of the sphere. The fragment of area under the foil activity $\times r^2$ curve thus obtained within the boundary of the sphere was compared with the total area under the curve as it extended into the paraffin. When allowance was made for the difference in slowing down density in the material of the sphere and the paraffin, it was thus estimated that 1 percent of the neutrons were slowed to indium resonance within both the beryllium and $D_2O$ spheres. Although these corrections were evaluated for a radium source, we have applied them without change to our various source-sphere combinations.

### D. Parasitic Capture of Neutrons above the Indium Resonance Level in the Source Material and, in the Case of the $D_2O$, in the Brass Shell of the Sphere

This we take to be negligible. One of the advantages of using the indium resonance activations instead of thermal activations is simply the great reduction in this effect.

Column 3 of Table I gives our values of $\Sigma_i \alpha_i \sigma_i$ after the application of these corrections.

## VII. ERRORS

The probable errors of the means of the individual "determinations" of given in Column 5 of Table I show that the data are quite good so far as internal consistency is concerned. With regard to absolute values, systematic errors contribute the main uncertainties. In all, the probable precision of the various parts of the measurement can be summarized thus:

| | |
|---|---|
| (1) Counting errors, as judged from the scatter of the data | 1% |
| (2) Absolute calibration of Ra—Be photo-source substandard | 6% |
| (3) Systematic errors in absolute beta-count of aliquots | 4% |
| (4) Wall thickness uncertainty | 2% |

Thus the over-all absolute precision can be estimated as probably about 8 percent. Clearly the relative values will be considerably more accurate, in that item 2 will not be involved, and 3 would be expected to be reduced.

In the case of the gallium, three separate $Ga_2O_3$ sources were activated, and each of these was used in the $D_2O$ and in the Be. Consequently the ratio (standard yield in Be)/(standard yield in $D_2O$) should be especially accurate,[7a] because errors in the radioactive source strength determination are not involved; the only errors should be those of items 1 and 4. In this respect it is gratifying to note excellent agreement with the same ratio as derived from the work of Russell *et al.* (Table I), where it should also be particularly accurate for like reasons. Unfortunately our work with sodium involved only one source used both in $D_2O$ and in Be; there were in addition two other sources used only in $D_2O$ and two more used only in Be. Thus the Be/$D_2O$ yield ratio is not expected to be so accurate as in the case of gallium. This may be part of the reason for the fact that the agreement with Russell *et al.* is also not as good; however, it is doubtful whether the disagreement can be considered significant inasmuch as their stated precision for the Be/$D_2O$ yield ratios is 7 percent, and ours (for Na) is probably 3 or 4 percent.

## VIII. DISCUSSION

We shall divide the discussion of our results into four paragraphs, of which the latter two are predominantly concerned with comparison with theory.

(1) *Sodium*—Since there is widespread agreement[8] that one 2.76 Mev gamma accompanies each beta-transition in $Na^{24}$, and since there is a negligible number of cross-over transitions with the cascading 1.38 Mev gamma,[9] we can drop our $\alpha_i$ notation and accept the figures 14.3 and $6.74 \times 10^{-28}$ cm$^2$ as our results for the photo-disintegration cross sections respectively of deuterium and beryllium at 2.76 Mev.

(2) *Gallium*—The rather complicated decay scheme of $Ga^{72}$ has been studied by Mitchell, Zaffarano, and

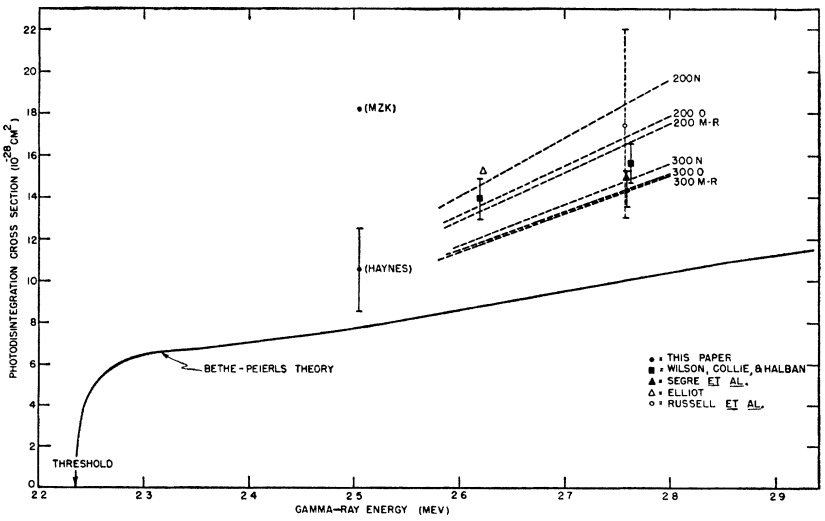


FIG. 2. Cross-section data on the photo-disintegration of the deuteron. The dashed lines are drawn through the points at 2.62 and 2.76 Mev as calculated theoretically by Hansson and Hulthén; the figures 200 and 300 refer to the assumed meson mass, and *N*, *O* and *M-R* refer, respectively, to calculations based upon the neutral meson theory, no interaction in the $^3P$ state, and the Møller-Rosenfeld theory. The experimental points attributed to Elliott and Segrè have been quoted by Wattenberg [A. Wattenberg, "Photoneutron Sources," Preliminary Report No. 6, Nuclear Science Series, Division of Mathematical and Physical Sciences, National Research Council]; the former has also been quoted by Sargent [B. W. Sargent, National Research Council of Canada, Division of Atomic Energy, Report PD-206, unpublished.]. The two points at 2.50 Mev are derived according to discrepant measurements of the intensity of this gamma-ray in $Ga^{72}$ (see text).

[7a] The term "standard yield" is defined in the footnote for Table I.

[8] References to $Na^{24}$ include among others: J. Itoh, Proc. Phys. Math. Soc. Japan **23**, 605 (1941); Elliot, Deutsch, and Roberts, Phys. Rev. **63**, 386 (1943); H. Maier-Leibnitz, Zeits. f. Physik **122**, 233 (1944); K. Siegbahn, Phys. Rev. **70**, 127 (1946); Cook, Jurney, and Langer, Phys. Rev. **70**, 985 (1946); E. C. Barker, Phys. Rev. **71**, 453 (1947).

[9] Bishop, Wilson, and Halban, Phys. Rev. **77**, 416 (1950).

Kern[10] and by Haynes.[11] The results for the lines above the beryllium $(\gamma, n)$ threshold are summarized in columns 1 to 4 of Table II. The intensity values are based in both cases on the assumption that every $Ga^{72}$ beta-emission is followed sooner or later by a gamma-quantum in the 0.835 Mev line. The 2.50 Mev quantum is the only one above the deuterium threshold, so that in this case we can deduce corresponding cross section values. Using our $\alpha\sigma$ value $2.81\times10^{-28}$ cm$^2$ from Table I one obtains, in fact, photo-disintegration cross section values of $18.2\times10^{-28}$ cm$^2$ on the MZK intensity[10] and $10.6\times10^{-28}$ cm$^2$ on the Haynes intensity.[11] Comparison with other results (Fig. 2) shows that the former figure seems improbably high, while the latter figure appears reasonable even if inaccurate.

(3) *Deuterium*—In order to see how the present measurements agree with previous experimental results and with theory, the published data on the total photo-disintegration cross section of deuterium in this energy range have been assembled in Fig. 2. In this figure, dashed straight lines have been drawn joining the points calculated by Hansson and Hulthén[12] for 2.62 and 2.76 Mev, with (1) a meson mass of 200 $m$, $(N)$ on the neutral meson theory; $(0)$ on the assumption of no interaction in the $^3P$ state; and $(M-R)$ on the Møller-Rosenfeld theory; and (2) with a meson mass 300 m and the same respective theoretical bases $N$, $0$ and $M-R$.*

A glance at the figure shows that the experimental results agree rather well with the modern theory, but that they are not yet sufficiently accurate for a critical comparison. It is also clear that it will be difficult in this energy region to obtain experimental results accurate enough to favor definitely one or other of the alternates $N$, $0$ or $M-R$. Hansson and Hulthén have implied that for comparisons of this accuracy the theory might also be due for refinement. All that can be said at this time is that our result at 2.76 Mev seems to join others in favoring a meson mass greater than 200 m.

(4) *Beryllium*—Our cross section $6.74\times10^{-28}$ cm$^2$ at 2.76 Mev is in good agreement with the results of Russell *et al.*[1] and of Segrè and also Elliot as quoted by Guth and Mullin.[13] Guth and Mullin have treated the photo-disintegration of $Be^9$ theoretically on the basis of a model consisting of a $Be^8$ core plus an orbital neutron, and have succeeded in showing that a combination of $P-S$ and $P-D$ transitions can lead to a threshold maximum-minimum curve for the dependence of the cross section on gamma-ray energy in agreement with the type of variation found experimentally. The well depth describing the interaction of the $Be^8$ core with the orbital neutron appears in the theory as an adjustable parameter. Taking the published theoretical curve at its face value, one finds that with good agreement with experiment at 2.76 Mev, the cross sections at the $Ga^{72}$ gamma-ray energies are as listed in the fifth column of Table II. The following two columns combine these cross sections with the MZK[10] and the Haynes[11] intensities to yield $\alpha_i\sigma_i$ values which on addition yield the sums 3.43 and $3.91\times10^{-28}$ cm$^2$ for comparison with our photo-neutron result (Table I) $2.16\times10^{-28}$ cm$^2$. There is, therefore, a discrepancy between theory and experiment so far as the summed results are concerned. Considering especially the evidence from deuterium that the Haynes intensity for the 2.50 line is approximately right, one is faced with a rather strong implication that the Guth-Mullin curve lies too high in the region below 2.76 Mev.

We are much indebted to S. Bernstein for advice, equipment and information, without which these measurements would have been much more time-consuming. We wish also to thank M. E. Rose for theoretical consultations, L. D. Norris for help in the absolute beta-counting, and the Subcommittee on Neutron Standards (Division of Mathematical and Physical Sciences, National Research Council) for information on the intercalibration of neutron sources. Correspondence with A. Wattenberg, H. Halban, L. G. Elliott, and R. L. Walker on various aspects of the work is gratefully acknowledged.

[10] Mitchell, Zaffarano, and Kern, Phys. Rev. **73**, 1424 (1948).
[11] S. K. Haynes, Phys. Rev. **74**, 423 (1948).
[12] I. F. E. Hansson and L. Hulthén, Phys. Rev. **76**, 1163 (1949).
[13] E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949).

* *Note added in proof:* I. F. E. Hansson has just published (Phys. Rev. **79**, 909 (1950)) the results of an extension of the Hansson-Hulthén computations, so that theoretical cross sections are now available for the $Ga^{72}$ gamma-ray energy. For the sake of completeness we shall quote his figures for the total photo-disintegration cross section of the deuteron at 2.52 Mev, with binding energy 2.237 Mev. They are as follows, in units $10^{-28}$ cm$^2$: 200-$N$, 11.82; 200-$O$, 11.14; 200-$MR$, 10.96; 300-$N$, 10.13; 300-$O$, 9.96; 300-$MR$, 9.96.

The reader should also be aware that an extensive experimental investigation of the photo-disintegration cross sections for the gamma-rays of $Ga^{72}$, ThC″ and $Na^{24}$ has recently been completed by Hedgran, Siegbahn, du Toit, Bishop, Collie, Halban, and Wilson (Phys. Rev., in publication).