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Yields of Neutrons from Photo-Neutron Sources*

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The number of neutrons emitted per second per curie from ten photo-neutron sources was determined, and they are listed in Table I. Absolute values of yields and cross sections may be in error by 27 percent, but relative values are more reliable. The photo-disintegration cross section for deuterium, $\sigma_D(\gamma,n)$, is found to be 16×10^{-28} cm^2 at 2.76 Mev. $\sigma_{Be}(\gamma,n)$ is found to be 7×10^{-28} cm^2 at 2.76 Mev, and is greater than 9.7×10^{-28} cm^2 at 1.67 Mev. The more reliable ratios of $\sigma_{Be}(\gamma,n)/\sigma_D(\gamma,n)$ are found to be 0.43 at 2.76 Mev and 0.30 at 2.50 Mev.

The curve of $\sigma_{Be}(\gamma,n)$ *versus* energy must pass through at least one maximum and one minimum in the range 1.63 Mev to 2.76 Mev.

The number of 2.7-Mev photons per disintegration of Mn^{56} is estimated to be about 1 percent. These photons are probably due to direct transitions to the ground state from the known excited levels of Fe^{56}.

1. INTRODUCTION

IN order to facilitate the planning of experiments employing photo-neutron sources, measurements were undertaken to determine the yield of neutrons from some of the sources employed at the Argonne National Laboratory.[1,2] As no further work is being done along these lines at the present time, it was considered desirable to make these data available to others despite the fact that more refined measurements should be made.

The number of neutrons produced per curie of radio-isotope was observed to vary by large factors in the photo-disintegration of beryllium and deuterium.[1] One cause of this variation is that the cross section for the (γ,n) reaction depends upon the energy of the photons. A detailed discussion of the theoretical dependence of the deuterium cross section, $\sigma_D(\gamma,n)$, is given by Bethe and Bacher.[3] A more recent calculation at one energy is given by Rarita and Schwinger.[4] However, previous experimental determinations[5–7] have yielded values lower than that calculated by Rarita and Schwinger.[4]

The only theoretical prediction that has been made of the dependence of $\sigma_{Be}(\gamma,n)$ on the energy of the photons is that of Mamasachlisow.[8] Determinations of $\sigma_{Be}(\gamma,n)$ using the γ-rays from the radium chain and from ThC″ are summarized by Houtermans and Bartz.[9]

* This document is based on work performed under Contract Number W-31-109-eng-38 for the Atomic Energy Project at the Argonne National Laboratory.

[1] Wattenberg, Fields, Russell, and Sachs, Phys. Rev. **71**, 497, 508 (1947).

[2] D. J. Hughes and C. Eggler, Phys. Rev. **72**, 902 (1947).

[3] H. Bethe and R. Bacher, Rev. Mod. Phys. **8**, 125 (1936).

[4] W. Rarita and J. Schwinger, Phys. Rev. **59**, 436 (1941).

[5] H. Halban, Comptes rendus **206**, 1170 (1938).

[6] G. A. R. Graham and H. Halban, Rev. Mod. Phys. **17**, 297 (1945).

[7] Chadwick and Goldhaber, Proc. Roy. Soc. **A151**, 479 (1935).

[8] V. I. Mamasachlisow, Physik. Zeits. Sowjetunion **10**, 214 (1936).

[9] F. G. Houtermans and I. Bartz, Physik. Zeits. **44**, 167 (1943).

A second cause for the variation of the number of neutrons emitted per second per curie of radio-isotope is that the majority of radio-isotopes employed have complex decay schemes. Na^{24} was the only radio isotope used that seemed to have a reliably established simple disintegration scheme.[10,11] According to this scheme one 2.76-Mev photon is emitted per disintegration. Therefore the yields of neutrons from sources employing Na^{24} are the only ones that can be readily converted into cross sections for photo-disintegration.

2. YIELDS

Experiment

The sources employed in these measurements were of the same shape and size as those previously described[1,2] and are shown in Fig. 1. The photon emitting radio-isotopes were activated in the Heavy Water Pile of the Argonne National Laboratory.

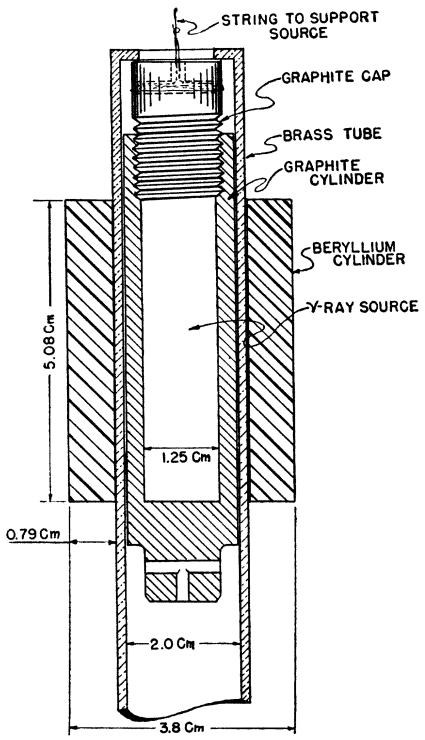

FIG. 1. Photo-neutron sources used in determining yields. For sources employing deuterium, an identically shaped thin-walled brass cylinder of heavy water was substituted for the beryllium.

To determine the absolute number of neutrons emitted by these sources, a comparison was made with a Ra-(α,n)-Be source whose neutron yield had been determined.[12] The comparison was made with the aid of a "long counter" (i.e., a BF_3 counter embedded in a large cylinder of paraffin). The "long counter" was constructed in the same manner as the one studied by A. O. Hanson and designated as type No. 3.[13] Hanson's work indicated that such a "long counter" had a neutron detecting efficiency that was approximately independent of the energy of the neutrons above 0.1 Mev.

The number of neutrons emitted by the photo sources was compared with that from the Ra-(α,n)-Be source with the sources at a distance of one meter from the face of the "long counter." The apparatus was six feet above the floor in a large room; the room. scattering and counter background were determined. Measurements were made in cycles at counting rates between 200 and 1000 counts per minute. A total of at least 10,000 counts was taken in each measurement.

In order to determine the number of curies of radio-isotope, the activity of the γ-ray sources was calculated from the isotopic neutron activation cross sections given in column 3 of Table I and measurements of the neutron flux in which the photon sources were irradiated. The neutron flux was measured by means of small gold foils.[14]

3. RESULTS

The results obtained with the sources shown in Fig. 1 are listed in the fifth column of Table I. Corrections have been applied to take account of the following: (a) the time of irradiation and the decay of the sources; (b) the self-shielding of the sources during their activation in the Pile; (c) the room scattering and background present during the "long counter" measurements; (d) the distribution of the neutrons from the sources not being spherically symmetrical because of shape and finite thickness of the sources (this correction was determined experimentally); (e) the known

[10] L. G. Elliott, M. Deutsch, and A. Roberts, Phys. Rev. **63**, 386 (1943).
[11] K. Siegbahn, Phys. Rev. **70**, 127 (1946).
[12] F. Seidl and S. Harris, Rev. Sci. Inst. (in press).
[13] A. O. Hanson, Los Alamos Declassified Report No. 59.
[14] A. Wattenberg and D. Sachs, to be published in the Plutonium Project Record.

TABLE I. Yields of neutrons from photo-neutron sources.

Sources	½ life	Neutron activation cross section* (in barns)	γ-rays energies[1,2] (in Mev)	Number of neutrons second—curie sources shown in Fig. 1	Number of neutrons second—curie "standard sources"**
$Na^{24}+D_2O$	14.8 hrs.	0.41	2.76	2.7×10^6	29.0×10^4
$Na^{24}+Be$	14.8 hrs.	0.41	2.76	2.4×10^6	14.0×10^4
$Mn^{56}+D_2O$	2.6 hrs.	10.7	2.7 ± 0.2	0.029×10^6	0.31×10^4
$Mn^{56}+Be$	2.6 hrs.	10.7	1.81, 2.13, 2.7	0.50×10^6	2.9×10^4
$Ga^{72}+D_2O$	14 hrs.	1.3	2.50	0.64×10^6	6.9×10^4
$Ga^{72}+Be$	14 hrs.	1.3	2.50 and ?	1.04×10^6	5.9×10^4
$In^{116}+Be$	54 min.	150.0	1.8, 2.1	0.14×10^6	0.82×10^4
$Sb^{124}+Be$	60 days	1.1	1.67	3.2×10^6	19.0×10^4
$La^{140}+D_2O$	40 hrs.	7.0	2.50	0.062×10^6	0.68×10^4
$La^{140}+Be$	40 hrs.	7.0	2.50	0.041×10^6	0.23×10^4

* These are activation cross sections for the periods indicated in column 2 for the energy distribution of neutrons that exists in a Pile. The cross sections for Mn, Ga, In, and Sb are from L. Seren, Phys. Rev. **72**, 881 (1947); the cross sections for Na and La are from A. Wattenberg and G. Thomas, to be published in the Plutonium Project Record. The method employed is that described by Anderson, Fermi, Wattenberg, Weil, and Zinn, Phys. Rev. **72**, 16 (1947).

** See section on Results for description of "standard source."

variation of the efficiency of the "long counter" below 0.1 Mev.[13]

In order to calculate cross sections and to make the data more useful to others who will undoubtedly use sources of a different size and shape, the number of neutrons per second per curie has been calculated for a "standard source" (that is, a source of one curie of activity placed at a distance of one centimeter from one gram of target material). The values obtained for the "standard sources" are listed in column 6 of Table I. In order to perform this calculation, it was necessary to determine the average path length of a γ-ray through the target material. The average path length was first estimated graphically and later checked by a numerical integration by A. V. Martin of the Theoretical Division of the Argonne Laboratory. The average path length was 0.74 cm.**

4. UNCERTAINTIES

The largest uncertainties in these measurements are those concerned with the determination of the strength of the photon sources employed. The relative "pile neutron" flux measurements are good to about 2 percent, but the absolute values of the flux may be in error by 15 percent. The activation cross sections are considered to be reliable to 20 percent. The next largest error is probably that of the number of neutrons emitted by the $Ra(\alpha,n)Be$ source with which the other sources were compared. Seidl and Harris[12] estimate a 7 percent probable error for this value. The known variation of the efficiency of the long counter is probably reliable to 5 percent. The errors in the comparison of the sources are estimated to be less than 5 percent.

These known uncertainties, if they are subject to the theory of errors, would give an uncertainty of about 27 percent in the absolute values. The relative values are not subject to the uncertainties in the absolute flux measurement and in the $Ra(\alpha,n)Be$ source calibration. The relative values are therefore considered to be more reliable. Ratios of the photo-disintegration cross sections for beryllium and deuterium for the same γ-ray source will suffer only from errors in the intercomparison of the sources and the uncertainty in the efficiency of the "long counter." Therefore, ratios of σ_{Be}/σ_D given in Section 6 are good to about 7 percent.

5. THE PHOTO-DISINTEGRATION CROSS SECTION OF DEUTERIUM

In the case of Na^{24}, since one photon of 2.76 Mev is emitted per disintegration,[10,11] each curie of radio-isotope emits 3.7×10^{10} of the desired γ-rays per second, and the data of column 6 can be used directly to calculate $\sigma_D(\gamma,n)$. The value so obtained is 16.4×10^{-28} cm² for 2.76-Mev γ-rays.

Rarita and Schwinger[4] have calculated that $\sigma_D=15.3\times10^{-28}$ cm² for 2.62-Mev γ-rays, and

** This average path length for the γ-rays includes those γ-rays that escape from the end of the source without ever passing through any target material.

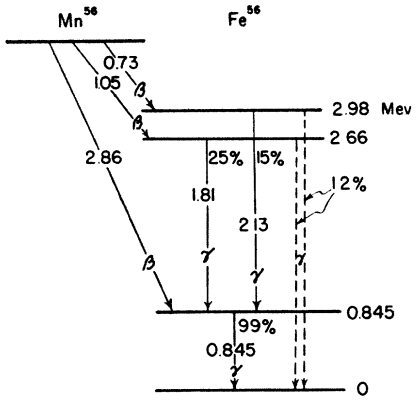

FIG. 2. The disintegration scheme of Mn^{56}. The solid lines and associated data are from Elliott and Deutsch (reference 20). The broken lines indicate the transition (or transitions) which give rise to the 2.7-Mev γ-ray.

Halban[5] observed 10×10^{-28} cm^2 for 2.62-Mev γ-rays.

S. Moskowski has used the curves and formulae of Rarita and Schwinger to calculate $\sigma_D(\gamma,n)$ at several other energies. Moskowski's value at 2.76 Mev is $\sigma_D=18.7\times10^{-28}$ cm^2. The value obtained in this experiment of 16.4×10^{-28} cm^2 seems to be in slightly better agreement with the theory than the previously obtained values. Unfortunately the large uncertainty of 27 percent raises the possibility of this agreement being merely fortuitous.

6. THE PHOTO-DISINTEGRATION CROSS SECTION OF Be

$\sigma_{Be}(\gamma,n)$ can be calculated in the same manner as $\sigma_D(\gamma,n)$, using the data of column 6, and the value so obtained is $\sigma_{Be}=7\times10^{-28}$ cm^2 at 2.76 Mev. From the discussion of the uncertainties, the ratio of $\sigma_{Be}(\gamma,n)/\sigma_D(\gamma,n)$ is a more reliable quantity than the individual cross sections. This ratio is 0.43 for 2.76-Mev γ-rays from the Na^{24} data, and is 0.30 at 2.50 Mev from the La^{140} data.

From Moskowski's calculations σ_D at 2.50 Mev is estimated to be $0.67\times\sigma_D$ at 2.76 Mev. Using this factor and the ratios for σ_{Be}/σ_D at 2.50 and at 2.76 Mev we obtained σ_{Be} at 2.50 Mev $=0.47\times\sigma_{Be}$ at 2.76 Mev. The slope of the curve of σ_{Be} *versus* photon energy is seen to be steeper in this energy region than the curve for σ_D.

It will be noticed in column six that the Sb+Be source has a larger yield than any other source using Be. This was unexpected as the γ-rays from Sb^{124} are only 0.04 Mev above the threshold for the (γ,n) reaction in Be. There was some question as to whether Sb^{124} might not emit in each disintegration two γ-rays whose energies are so close that they have not been resolved.[15] However, the most recent studies on γ—γ coincidences[16] indicate that there is only one photon emitted that is sufficiently energetic to disintegrate beryllium, and this photon is emitted in approximately half of the disintegrations. If one uses the data of column six and just assumes that less than one 1.67-Mev photon is emitted per disintegration, one gets a lower limit for σ_{Be} of 9.7×10^{-28} cm^2 at 1.67 Mev.

σ_{Be} is thus greater at 1.67 Mev than at 2.76 Mev, and its value at 2.50 Mev is lower than both of these values. Therefore the curve of σ_{Be} *versus* energy must pass through at least one maximum and one minimum between 1.63 Mev and 2.76 Mev.

These results are not in agreement with the theoretical conclusions of Mamasachlisow.[8] Snell and co-workers,[17] at Oak Ridge independently and concurrently with the work reported here, measured yields of photo-neutrons from sodium, antimony, and lanthanum sources. They employed differently shaped sources and entirely different techniques. The above conclusions concerning the energy variation of $\sigma_{Be}(\gamma,n)$ are consistant with Snell's results.

7. THE 2.7-MEV γ-RAYS FROM Mn^{56}

The decay scheme for Mn^{56} has been studied by Elliott and Deutsch[18] and K. Siegbahn[19]; their result are essentially in agreement, and the decay scheme as given by Elliott and Deutsch is shown in Fig. 2. The solid lines indicate the transitions which were observed. The 2.66-Mev and 2.98-Mev levels were both observed to decay by the emission of two quanta in cascade. The 2.7 ± 0.2-Mev photons found in previous photo-neutron work[1] fit into this decay scheme as

[15] W. E. Meyerhoff and G. Scharff-Goldhaber, Phys. Rev. **72**, 164A (1947).
[16] W. E. Meyerhoff and G. Scharff-Goldhaber, Phys. Rev. **72**, 273 (1947).
[17] Snell *et al.*, to be published in the Plutonium Project Record.
[18] L. G. Elliott and M. Deutsch, Phys. Rev. **64**, 321 (1943).
[19] K. Siegbahn, Arkiv F. Mat. Astro. o Fys. **33A**, No. 10 (1946).

direct transitions to the ground state of Fe^{56} of the 2.66-Mev and/or the 2.98-Mev levels. (The uncertainty of ± 0.2 Mev does not permit a decision as to whether solely the 2.66-Mev level or the 2.98-Mev level or some combination of the two is involved.) These direct transitions are indicated by the dotted line in Fig. 2. By taking the ratio of the data in column 6 for $Na+D_2O$ and $Mn+D_2O$ one gets (neglecting a small energy correction) an estimate of the frequency of occurrence of the direct transitions to the ground state. The number of such transitions is 0.011 per disintegration. Compared to the probabilities for the transition to the 0.845 level, the low probability of 0.011 would indicate that the transition to the ground state is of a higher electric or magnetic multipolarity than the transitions to the 0.84-Mev level.

It is the experience of the authors that the photo-neutron techniques can be extended to measurements of γ-rays that are emitted with a probability as low as 0.0001 per disintegration.

ACKNOWLEDGMENT

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On the Mobility of Electrons in Pure Non-Polar Insulators

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It is pointed out that Peierls' condition for the validity of time-dependent perturbation theory in the determination of the mobility μ of electrons in crystals can be transformed to the form

$$\mu > 30 \text{ cm}^2/\text{volt-sec. (at room temperature)}$$

in the case in which the electrons are distributed classically. Since the recent investigations of the mobility of electrons in diamond, silicon, and germanium indicate that the mobility in these materials is at least several times greater than the foregoing limit, it would appear that perturbation methods may be used to discuss the mobility in these materials and possibly in other non-polar insulating materials, such as sulfur.

An expression is derived for the collision frequency for conduction electrons having velocity v as a result of collisions with the acoustical modes of oscillation. It is pointed out that these modes will be the only ones of interest in diamond at room temperature because the characteristic temperature is in the vicinity of 1800°K. The collision time τ is found to satisfy the equation

$$1/\tau = (4/9\pi)(C^2 k_0 T/\hbar^3 c^2 n_0)(m^{*2}/M)k, \qquad \text{(A)}$$

where C is a constant, having the dimensions of energy. that measures the interaction between the lattice and the electron, k_0 is Boltzmann's constant, T is the absolute temperature, c is the acoustical velocity, n_0 is the density of atoms, m^* is the effective electron mass, M is the mass of the atoms in the crystal, and k is the wave number vector of the electron. Since the mean free path is proportional to k, it follows that the mean free path is independent of velocity in the approximation in which (A) is valid. The conditions for validity of the equation, all of which are normally well satisfied in diamond at room temperature, are: (1) The temperature be sufficiently low that the principal inelastic collisions involve only one lattice vibrational quantum; (2) only the acoustical modes of vibration be excited; (3) the temperature of the electrons be sufficiently high that their mean energy be large compared with m^*c^2, in which c is the acoustical velocity; (4) the electrostatic field be sufficiently low that only linear terms are important. The second of these conditions is usually not satisfied in materials such as silicon, germanium, or sulfur near room temperature, although it will be satisfied at lower temperatures. The temperature m^*c^2/k_0 is near 10°K for diamond, but is much less than this for most other materials, so that (A) should be applicable for determining the mobility of conduction electrons in a large number of pure non-polar insulators at low temperatures not too close to 1°K.

In the case of diamond, the mobility at room temperature is found to have the value

$$\mu = (1.46/C^2)10^5 \text{ cm}^2/\text{volt-sec.}$$

if m^* is taken as the free electron mass. This leads to a mobility of about 156 cm²/volt-sec. if C is assumed to have a value of 30.6 ev obtained from the relation $C(\text{ev}) = 1.7 \cdot 10^{-2}\Theta$ that seems to be obeyed for the electrons in the simpler metals. In a range of temperature in which