magnetic field and which, moreover, has a history which suggests the existence of a considerable and variable inhomogeneity. By the criteria of the data it appears that, by good fortune, the data were taken in a section of the magnet which was homogeneous at the time of the observations. Extensive efforts to obtain lines as narrow as those whose observation is here reported by subjecting the magnet to various magnetizing and demagnetizing procedures have been unsuccessful; ultimately it appeared that the efforts were misdirected, in the sense that even a successful effort would be a rare accident and would not have any inherent criterion of the quality of the field external to the data obtained by use of the field. Apparatus is now being constructed in which the field will have much better inherent properties.[3]

Hughes and Grabner report the occurrence of certain double-quantum transitions in the radio-frequency spectrum of RbF observed by the electric resonance method. These occur between two levels between which a single-quantum transition is also allowed in the presence of a static electric field. They correspond to the absorption or emission of two quanta, which may be equienergetic, whose total energy is equal to that of the single quantum ordinarily absorbed or emitted. The double-quantum transitions occur when the amplitude of the field and the static electric field are of comparable magnitude. The phenomenon is different from that here reported where the double- and triple-quantum transitions occur between states between which a single-quantum transition cannot ordinarily occur. The present effects depend on states intermediate to the terminal states of the multiple-quantum transition; the position of the intermediate states relative to equally spaced intervals between the terminal states strongly affects the probability of the multiple-quantum transition for any rf amplitude. On both experimental and theoretical grounds, the transitions here reported can occur even when the radio-frequency magnetic field has an amplitude small compared to the static field.

A discussion of the theory of multiple-quantum transitions and its application to the present data will be given by Mr. R. Salwen in a forthcoming paper. The theory predicts line widths which are in satisfactory agreement with those here reported. However, no satisfactory explanation of shifts of the order of those presently observed has been obtained.

I am indebted to Mr. Joseph Hendrie and to Mr. A. G. Prodell for their aid in taking the data of these experiments.

[3] V. Hughes and L. Grabner, Phys. Rev. **79**, 314 (1950); **79**, 829 (1950); **82**, 561 (1951).

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A Determination of the Energy of Antimony-Beryllium Photoneutrons

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The effective energy of Sb—Be photoneutrons has been measured by comparison of the transmission cross sections of five elements for the photoneutrons with previously measured cross-section values over a range of energies. The result placed the energy close to 25 kev.

INTRODUCTION

INTENSE gamma radiation from Sb^{124} falling upon Be^{9} provides a copious source of nearly monoenergetic neutrons,[1] and has been used extensively for activation cross-section determinations.[2,3] Degradation by various scattering processes in any source large enough to be useful poses the main difficulty in assigning the proper energy to the Sb—Be photoneutrons.[4] Several measurements by various methods and with different source sizes have been made,[1,5,6] with values being quoted from 25 to 35 kilovolts. The present work concerns the possibility of narrowing the limits of error in the stated energy by a comparison of transmission cross sections for Sb—Be photoneutrons with transmission cross sections measured with the Argonne electrostatic generator in the 20 to 40 kilovolt region.

The specific purpose of this research was to assign a more definite value to the energy of the neutrons from that photoneutron source used by Hummel, Hamermesh, and Kimball[2,3] in their activation cross-section work. A similar source was also used by others[1,4,7] in various experiments involving cross sections, energy, and abundance of Sb—Be photoneutrons. The energy value determined in this experiment will thus provide cross checks on these earlier data.

[1] A. Wattenberg, Phys. Rev. **71**, 497 (1947).
[2] V. Hummel and B. Hamermesh, Phys. Rev. **82**, 67 (1951).
[3] C. Kimball and B. Hamermesh, Phys. Rev. **89**, 1306 (1953).
[4] Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).
[5] G. S. Klaiber and G. Scharff-Goldhaber, Phys. Rev. **67**, 733 (1942).
[6] D. Hughes and C. Eggler, Phys. Rev. **72**, 902 (1947).
[7] Russell, Sachs, Wattenberg, and Fields, Phys. Rev. **73**, 545 (1948).

The method used was a determination of total cross section by transmission measurements of several pure metal samples. The energy was then determined as the intersection of the cross section *versus* neutron energy curve[8] with a constant cross-section line at the experimental cross-section value. Five elements were chosen for their rapid variation of cross section in the 20 to 40 kilovolt region.

It is to be emphasized that the use of this method does not constitute a fundamental measurement, and that the result is dependent upon both the errors in the Van de Graaff curve determinations and experimental errors in the present work. The assumption is made that reproducibility of the energy value from the five independent metallic samples would constitute sufficient evidence for an accurate energy determination.

DISCUSSION

In general, a transmission measurement determines the sum of the cross sections for all processes that attenuate a given beam. In the energy range of the Sb—Be photoneutron source, the absorption cross section for most elements is small in comparison with the total scattering cross section. For the purposes of this experiment, the transmission and scattering cross sections are assumed equal within the range of error of the method used.

In the ideal case a transmission experiment would consist of two measurements: an intensity determination with the detector having unrestricted view of the source, and an intensity measurement with the transmission sample completely hiding the source from the detector. For a beam of neutrons, the situation is usually complicated by the presence of a background arising from incomplete collimation. The effects of small angle and multiple scattering must also be considered.

The background may usually be quantitatively determined, but statistical difficulties are encountered if it represents a major fraction of the total count. It is for this reason that source sizes are chosen as large as possible consistent with good collimation. Theoretical determinations of the small angle scattering have been made.[1] The small angle scattered count results from those neutrons that are deflected by angles so small that they still reach the detector.

Multiple scattering is not correctable by any simple process. For this experiment, the transmission samples were designed to pass more than 60 percent of the beam, thus minimizing the probability of more than one collision per particle.

The use of an omnidirectional source allows two general methods of collimation. The beam may be defined by a system of slits or the uncollimated radial beam may be used with sample eclipsing the detector. Hibdon, Langsdorf, and Holland[8] used a collimated beam in their work with the Van de Graaff accelerator, while Wattenberg[1] chose the "infinite beam" method for his photoneutron sources.

The defining slits for moderately fast neutrons are necessarily massive. A combination of paraffin and cadmium is an effective neutron shield for this energy range. The paraffin slows the neutrons down by successive collisions to a point where cadmium presents a high absorption cross section to them. Such a paraffin-cadmium combination was used in this experiment.

APPARATUS

The threshold for the photoemission of neutrons from beryllium is 1.666 Mev.[9] Meyerhoff and Scharff-Goldhaber proposed 1.7 Mev as the energy of the hard gamma ray from Sb^{124}.[10] NBS-499 reports 1.75 Mev for the same gamma ray.[11] A calculation of the neutron energy from considerations of momentum and energy conservation is not practical since such a calculation would give the neutron energy from a theoretical dimensionless source and could not account for the self-degradation of any real source.

The physical makeup of the source used in this experiment is shown in Fig. 1. The aluminum cylinder containing nearly 100 grams of fused antimony was irradiated in the central thimble of the heavy water pile at Argonne for seven months. The 60-day activity was

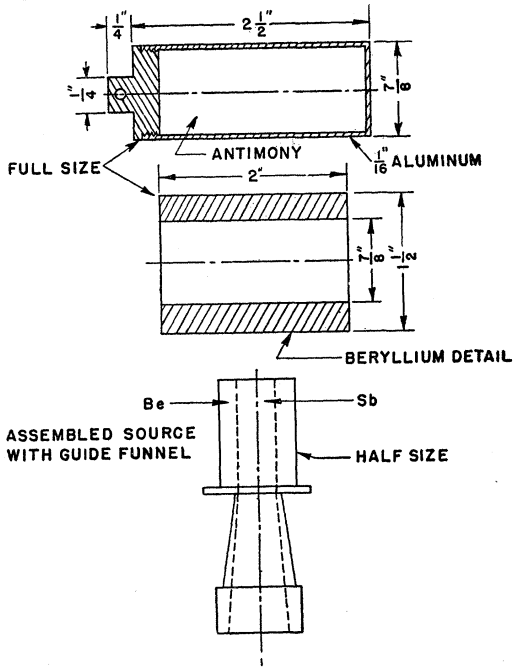

FIG. 1. Sb—Be photoneutron source.

[8] Hibdon, Langsdorf, and Holland, Phys. Rev. **85**, 595 (1952).

[9] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).

[10] W. E. Meyerhoff and G. Scharff-Goldhaber, Phys. Rev. **72**, 273 (1947).

[11] *Table of Nuclear Data*, National Bureau of Standards Circular 499 (U. S. Government Printing Office, Washington, D. C., 1950).

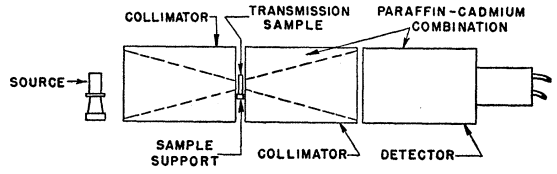

FIG. 2. Platform assembly for transmission measurements.

then about 90 percent saturated. The source was allowed to cool for two weeks after removal from the pile to eliminate possible interference from short-lived activities. The gamma activity at the start of measurements was 40 curies.

The intensity and high energy of the gamma-ray source necessitated remote handling. Upon removal from the pile, the source was strung with a length of wire leader and stored in a 1000-pound lead pot. All subsequent handling was accomplished by means of strings and pulleys from a distance of 50 feet. In practice, the antimony cylinder was pulled into the beryllium annulus through the aluminum funnel by means of a string passing axially through the assembled source.

The pulse ionization chamber used in these experiments was the so-called "long counter." Attached directly to the ionization chamber was a preamplifier designed to increase pulse size for transmission along the 50-foot cable to the final amplifier and scaler. The long cable was necessitated by the intensity of the gamma-ray source. The entire assembly (counter, paraffin thermalizer, and preamplifier) was assembled within a cylindrical aluminum case. A 0.120-in. layer of cadmium sheet shielded the detector from any thermal neutrons that might have been present. The pulse-height selector on the final amplifier was set to discriminate against gamma pulses. No counts from gamma rays resulted even when the 40-curie source was only 12 inches from the detector.

The paraffin-cadmium combination mentioned earlier was arranged as shown in Fig. 2. Two cylindrical paraffin collimators of the same outside diameter as the detector were placed between detector and source. All units were aligned axially by the framework that supported them. The collimators had conical apertures and were placed on the support frame with apexes adjacent. A small paraffin platform was molded on one collimator to support the transmission sample so that it completely covered the opening. The samples were placed by hand after the antimony source was lowered into the lead pot.

METHOD

The collimated beam method was chosen for this experiment for the reason that pure samples of the desired metals were not available in sizes large enough to blanket the detector to prevent it from seeing the source. It was considered desirable to use the same samples as had been used by Hibdon, Langsdorf, and Holland[8] in their transmission measurements. These samples were of various shapes and dimensions, but none was smaller than one inch square in the plane perpendicular to the neutron beam. Collimation by the paraffin cylinders, even in conjunction with the 0.120-in. cadmium shielding the counter, was not perfect. Those neutrons detected after being scattered and degraded by the collimator contributed to a latent counting rate analogous to background. Neutrons scattered by the walls of the room also contributed a fraction of this latent count, though this room scattering was reduced by supporting the transmission apparatus on a light framework 12 feet high in the center of a large quonset building.

The transmission cross sections of the various samples were measured relative to an already well established cross section. The "standard" used was carbon, the cross section of which is known to 1 percent and is independent of energy from 20 to 60 kev.[12] The transmission cross section of carbon is 4.55 barns in this energy region. By designing the carbon plugs to reproduce accurately the geometry of each sample both in transmission and transverse dimensions, it was possible approximately to duplicate the erroneous counts resulting from small angle and multiple scattering. The unknown counting rates arising from these processes in (1) the metallic sample and (2) the carbon duplicator, then canceled in the calculation of sample transmission.

Let N_0 = count observed with no scatterer in place (open beam), N_b = collimator and room scattered count, N_{tb} = true beam (N_0-N_b), N_c = count observed with carbon plug in beam (closed beam), N_s = count observed with metallic sample in beam, T_c = transmission of carbon plug (calculated using 4.55 b cross section), and T_s = transmission of sample. If the carbon plugs are machined so that T_c closely approximates T_s, then to determine the true beam:

$$\begin{aligned} N_0&=N_b+N_{tb},\\ N_c&=N_b+T_c(N_{tb}),\\ N_0-N_c&=N_{tb}(1-T_c),\\ N_{\text{true beam}}&=(N_0-N_c)/(1-T_c). \end{aligned} \tag{1}$$

Similarly, for sample transmission:

$$N_0-N_s=N_{tb}(1-T_s),$$

so that

$$1-T_s=\frac{N_0-N_s}{N_{tb}}=\frac{(N_0-N_s)\times(1-T_c)}{N_0-N_c}. \tag{2}$$

A set of readings consisted of (1) open beam, (2) carbon plug transmission, (3) sample transmission, and (4) open beam. Any run was discarded if the open beam reading varied more than 2 percent from (1) to (4). Each counting period was long enough to achieve 1 percent statistics. Instrumental background was less

[12] *A Compilation of Neutron Cross Sections*, U. S. Atomic Energy Commission Report AECU-2040 (Office of Technical Services, Department of Commerce, Washington, D. C., 1952).

than 1 percent of the lowest counting rate used. The cross section was then calculated from T_s.

One effect which has not been included in the calculations is the so-called hardening of the beam. If cross section decreases with increasing energy in a given region, the more energetic neutrons of the beam will tend to be transmitted more readily than the slower ones. The sample cross section would then appear to decrease with increasing sample thickness. By using samples of transmission greater than 60 percent this effect was reduced sufficiently so as not to affect our Sb—Be energy value.

The thickness of all samples and carbon plugs were machined to within 0.001-in. tolerance. The metals used and the number of samples of each were as follows: Ti (2), V(4), Mn (2), Co (1), and Ni (4).

RESULTS

The cross-section results and their corresponding energy values are given below, element by element. The original cross section *vs* energy curves, from reference 8, were used in order to determine the Sb—Be photoneutron energy.

Titanium

The thickest of the two samples of titanium available exceeded the arbitrary lower limit of transmission. It had a transmission of only 0.335. The cross section determined for this sample was 30.6 barns, 18 percent lower than the 37.2-barn value for the thinner sample. Considering the beam hardening involved, this difference is not excessive. The 37.2-barn cross section was used for the energy determination. (See Fig. 5, reference 8.) The result was 27.0 kev.[13] The other side of a resnance peak in the σ *vs* E_n curve made a value of 22 kev possible, though not probable, since the energy spread in the neutrons would normally blanket as narrow a dip between two resonances as appears in the curve for this metal.

Vanadium

The cross sections obtained from vanadium samples were in excellent agreement. They fell between 23 and 25 barns, which resulted in a 23- to 24-kev value for the neutron energy. (See Fig. 6, reference 8.) The cross-section values were close to a resonance peak. The constant cross-section line also intersected the curve at 19 kev. This value is much below that found for other samples.

Manganese

Increasing sample thickness brought decreasing cross section for manganese, indicating negative slope of the σ *vs* E_n curve at the point of intersection. Energy values on both sides of a resonance were possible. These values were 21 and 25 kev on the low- and high-energy side of the resonance. (See Fig. 8, reference 8.) The 25-kev value is favored in view of the negative slope.

Cobalt

Only cobalt powder was available in pure form. A sample consisting of a section of thin-walled aluminum tubing with end plates 0.001 in. thick was constructed. The density of the packed cobalt powder was determined as the average of six weight and volume determinations. The cross section was 16.7 barns, placing the energy at 28.5 kev or 32 kev. (See Fig. 7, reference 8.)

Nickel

No trend resulting from increasing thickness was indicated for the four samples of nickel metal. The cross sections varied from 19.9 to 22.7 barns, placing the energy at 22.5 kev (see Fig. 4, reference 8). The excellent reproducibility and well-resolved curve for nickel gave much weight to this energy value.[14]

CONCLUSION

The results indicate a probable energy spread of 20 percent or more in the neutrons from this Sb—Be photoneutron source. The average energy value is 24.6 kev. The complexity of possible errors is great enough to make a statement of the energy to closer than 4 kev unwise at this time, though the cross-section values determined in this experiment are accurate to 10 percent. It is proposed that a further study of the energy of this source be made after re-examination, with better resolution, of the variations of cross section *vs* energy. This project is now underway using the improved Argonne Van de Graaff accelerator.

ACKNOWLEDGMENTS

We wish to thank Dr. C. T. Hibdon and the members of the Van de Graaff group for the use of their original cross section *vs* energy curves.

[13] Results of a recent repetition of the cross section *vs* energy curve for titanium suggest an energy value for the Sb—Be photoneutron of 25.5 kev.

[14] Recent results for nickel revise the energy estimate downward to 20.5 kev.