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The $Cu^{63}(\gamma,n)Cu^{62}$ Cross Section*

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The cross section for the reaction $Cu^{63}(\gamma,n)Cu^{62}$ has been determined as a function of energy by the analysis of the x-ray activation curve. D_2O loaded emulsions and a pair spectrometer were used as monitors, and the results obtained are in good agreement with the results of recent measurements which depend upon the calculated response of r-meters.

I. INTRODUCTION

A NUMBER of workers have measured cross sections for gamma-ray reactions by analyzing x-ray activation curves. In most cases an r-meter or ionization chamber has been used as a monitor, and the monitor response as a function of photon energy has been determined by calculations.[1–4] In this way the absolute cross section as a function of photon energy has been determined for numerous reactions. Also, reactions have been used to monitor one another,[2–5] but the results (expecially the absolute measurements) remain dependent upon the calculated response of an r-meter or ionization chamber.

In order to obtain a result independent of ionization measurements we have monitored the activation curve for $Cu^{63}(\gamma,n)Cu^{62}$ with an 180° magnetic pair spectrometer operating at 10.3 Mev. As the absolute response of the spectrometer was not well known, three points on the activation curve were monitored with D_2O loaded emulsions. The theoretical cross section for photodisintegration of the deuteron[6] together with experimental determinations in good agreement with the theory[7] allow us to obtain an absolute cross section scale for the copper reaction with an uncertainty of ten percent.

II. EXPERIMENTAL

Reduction of the accidental background to a level sufficiently low for efficient operation of the pair spectrometer requires gamma-ray pulses of appreciably longer duration than are obtained when expansion is forced by pulses through the betatron expander coils. Using self-expansion, gamma-pulses of about 150-μsec duration are available from the Case betatron.[8] These pulses have a full width at half-max which corresponds to 0.8 Mev at 13 Mev and 0.3 Mev at 21 Mev. Unfortunately, the self-expanded beam was not available at energies above 21 Mev.

The desired energies were obtained by adjusting the betatron to superimpose a photomultiplier pulse from the gamma-ray output upon a marker pulse on an oscilloscope. The marker pulse was one which is ordinarily used as the trigger of a constant energy expansion system described elsewhere.[9] This system was calibrated at the thresholds of $Cu^{63}(\gamma,n)Cu^{62}$ and $C^{12}(\gamma,n)C^{11}$ and is accurate within ± 0.2 Mev. In spite of the appreciable energy band resulting from self-expansion the data showed that errors in reproducing energies were less than 0.1 Mev.

All measurements were made within $\frac{1}{2}°$ of the center of the gamma-ray beam. Copper disks were aligned with the monitor (D_2O loaded plate or spectrometer radiator) and subtended approximately the same solid angle at the betatron target. When the spectrometer was used as the monitor, it was cycled to count accidental

* Work supported by the AEC.
[1] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948).
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[5] R. Sagane, Phys. Rev. **84**, 586 (1951).
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[7] J. H. Carver and D. H. Wilkinson, Nature **167**, 154 (1951).
[8] E. C. Gregg, Jr., Rev. Sci. Instr. **22**, 176 (1951).
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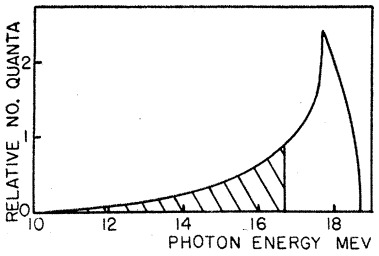

FIG. 1. Difference spectrum obtained by subtracting 17.7-Mev spectrum from 18.7-Mev spectrum after the two were normalized at 10.3 Mev. Results obtained from data taken at lower energies were used to calculate the contribution to the activation by the quanta corresponding to the shaded area of the figure. The remaining increase in activation was then attributed to the quanta corresponding to the remaining area under the difference spectrum.

background with a 0.05-μsec delay line in one channel during two minutes of each ten-minute run.

Exposures with the D_2O loaded emulsions acting as monitors varied from two to five minutes. A background was obtained from an H_2O loaded emulsion exposed with each D_2O loaded plate. Proton tracks resulting from gamma-rays of energy less than 6 Mev were eliminated from the data while gamma-rays of energy greater than 12 Mev were of little importance in determining gamma-ray intensities because of the poor statistics obtained from proton tracks corresponding to higher gamma-energies. Allowance was made for the escape of protons from the emulsions and for the absorption of some of the heavy water by the pure gelatin used as a base in the manufacture of the NTB plates. Although the plates used in this work were perpendicular to the gamma-ray beam, these corrections are similar to those used by the authors for plates exposed parallel to the beam.[10] The assumption that the gelatin in the emulsion and in the base absorb water in the ratio of their volumes led to agreement of the results from plates which had 4 percent of their gelatin in the base with the result from one plate which had 30 percent of its total gelatin in the base.

End-window counters calibrated with standard RaD+E and P^{32} sources were used to count the ten-minute positron activity of the copper. The usual corrections were made for the decay of the copper activity during and after the irradiations, and an extrapolation to zero thickness was used to correct the counting rate per Cu^{63} atom for self-scattering and self-absorption.

III. CALCULATIONS

The analysis of activation curves has been discussed at length in the literature,[3,5] so only a brief discription of our procedure will be given. For the spectra the total radiation formula of Schiff[11] was used rather than his zero angle formula. This was done because one effect of a target of appreciable thickness or of electrons going through the target more than once would be the scattering of electrons in the target through angles comparable with the intrinsic width of the bremsstrahlung. In fact, this scattering may be expected to reduce deviations from the thin target spectra as most electrons which have lost appreciable energy in the target will have been scattered through angles from which they cannot contribute to the radiation at the center of the beam. Fortunately, the zero angle and total radiation formulas of Schiff are so nearly identical that our choice of spectra had very little effect on our results.

Spectra were calculated for each datum point and normalized at 10.3 Mev, and each was subtracted from the spectrum following it in energy. The difference spectra obtained must account for the increase in yield between the corresponding points on the activation curve. After cross sections near the threshold had been determined they were used to predict the contribution to the activation by the lower energy gamma-rays present in the difference spectra at higher energies. In order to minimize oscillations in the cross section curve without smoothing the activation curve we avoided use of the predictions for energies above the highest gamma-ray energy present in the second preceding difference spectrum. Thus, with points on the activation curve spaced at approximately one-Mev intervals the points on the cross section curve represent averages over approximately two-Mev energy intervals. A typical difference spectrum is shown in Fig. 1.

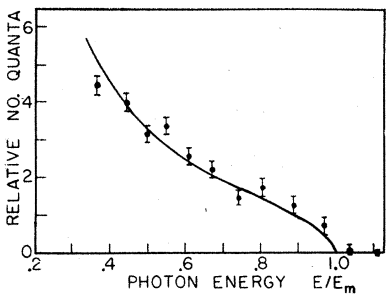

FIG. 2. Experimental and theoretical bremsstrahlung spectra normalized $E/E_m<0.6$.

IV. RESULTS

Experimental bremsstrahlung spectra were obtained from the D_2O loaded emulsions used in this work and in our study of the angular distribution of photoprotons from the deuteron.[10] The cross section for photodisintegration of the deuteron given by Bethe and Longmire[6] was used in the reduction of the data. The results from both experiments and for 14.0-, 16.7-, and 19.8-Mev bremsstrahlung have been combined and are presented in Fig. 2. The solid curve represents the Schiff total radiation spectrum for thin molybdenum targets. Actually, the Schiff spectra plotted in terms of E/E_m (where E is the quantum energy and E_m is the kinetic energy of the electrons producing the bremsstrahlung) differ for the three values of E_m. The curve

[10] V. E. Krohn, Jr., and E. F. Shrader, Phys. Rev. **86**, 391 (1952).
[11] L. I. Schiff, Phys. Rev. **83**, 252 (1951).

of Fig. 2 is a compromise which never differs from any of the three Schiff spectra by more than two percent. When the spectra were considered separately each was consistent with the combined result within the statistical error.

The activation curve for the reaction $Cu^{63}(\gamma,n)Cu^{62}$ is shown in Fig. 3, and the resulting cross section curve is presented in Fig. 4 along with the results of several recent investigations in which r-meters served as monitors. The shape of the smooth cross section curve was taken into account in the final calculation of the points of Fig. 4.

V. DISCUSSION

The experimental spectrum of Fig. 2 is in satisfactory agreement with the expression of Schiff, but with the

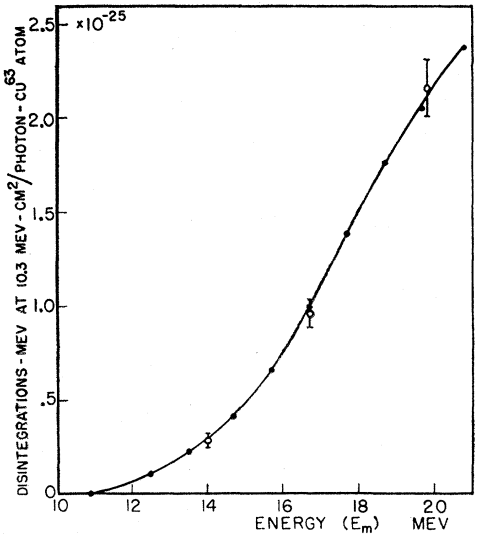

FIG. 3. The activation curve for the copper reaction. The solid points were obtained with the pair spectrometer serving as monitor and have been normalized to the open circles which were obtained from the results of runs monitored by D_2O loaded emulsions.

theory and experiment normalized for $E/E_m<0.6$ there is evidence of more quanta than the theory predicts at higher energies.

The result obtained for the $Cu^{63}(\gamma,n)Cu^{62}$ cross section is in good agreement with the other experimental results shown in Fig. 4. Our result is independent of

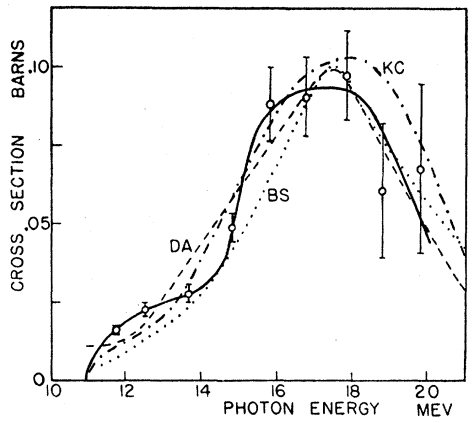

FIG. 4. Results obtained for the $Cu^{63}(\gamma,n)Cu^{62}$ cross section. Errors shown do not include the ten percent uncertainty in the absolute cross section scale. It should be noted that the combination of two adjacent points would reduce the error by a factor of 2 rather than the usual $\sqrt{2}$. The dotted curves are the results of: DA—Diven and Almy,[2] KC—Katz and Cameron,[3] and BS—Byerly and Stephens.[4]

the others to the extent that we have substituted the theoretical cross section for photodisintegration of the deuteron and the linear response of the pair spectrometer to 10.3-Mev photons for the calculated response of an r-meter. All the results of Fig. 4 have probably been affected in a similar way by errors in the theoretical spectrum. Johns *et al.*[12] have discussed the possible effect of such errors. In our case, the molybdenum ($Z=42$) target should reduce errors arising in the use of the Born approximation in bremsstrahlung theory. The cross section obtained in this work rises as the $\frac{1}{2}$ power of the energy above the threshold up to about 3 Mev above threshold, but one must remember that a detail of this sort will be affected by errors in the theoretical spectrum to a greater extent than the position of the resonance and the area under the cross section curve which Johns *et al.*[12] have shown to be relatively insensitive to the spectrum assumed.

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[12] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).