transitions depopulating the gamma vibrational levels, assuming pure $E2$ radiation. It appears that the ratio of R.T.P.'s for transitions depopulating the (2, 2+) levels agree with the theoretically predicted values (see Table XI). However if one takes into account the probable $M1$ admixture to the $(2, 2+) \rightarrow (0, 2+)$ transition, the experimental ratio, $B(E2;\, 22 \rightarrow 00)/B(E2;\, 22 \rightarrow 02)$ will increase and thus the agreement with theory might be only fortuitous. Similarly since the $(2, 4+) \rightarrow (0, 4+)$ transition is also probably $M1+E2$, the ratio $B(E2;\, 24 \rightarrow 02)/B(E2;\, 24 \rightarrow 04)$ will increase. In the case of transitions depopulating

TABLE XI. Theoretical ratio of R.T.P.'s.

K value	$\frac{B(E2;\,22\rightarrow00)}{B(E2;\,22\rightarrow02)}$	$\frac{B(E2;\,22\rightarrow04)}{B(E2;\,22\rightarrow02)}$	$\frac{B(E2;\,23\rightarrow02)}{B(E2;\,23\rightarrow04)}$	$\frac{B(E2;\,24\rightarrow02)}{B(E2;\,24\rightarrow04)}$
0	0.7	1.8		
1	2.8	2.3		
2	0.7	0.05	2.5	0.34

the (2, 3+) levels, since both $(2, 3+) \rightarrow (0, 2+)$ and $(2, 3+) \rightarrow (0, 4+)$ transitions are probably $M1+E2$ nothing much can be said until better experimental data are available.

Recently Davydov and Filipov[45] proposed a theory of the energy states and the electromagnetic transitions between them for nuclei which do not possess axial symmetry. A comparison of their predictions to experimental data is made in Table XII. The values of γ given in Table XII are those calculated from the ratio of the energy of the second (2+) state, $E'(2)$, to that of the first (2+) state, $E(2)$. The ratio $E'(2)/E(2)$ depends only on γ. According to their predictions $E'(2)+E(2)=E(3)$, where $E(3)$ is the energy of the (3+) state. In Table XII are given the experimental and theoretical ratio of R.T.P.'s for transitions from the second (2+) level. The theoretical values were calculated using the values of γ as determined by the ratio $E'(2)/E(2)$. It appears that almost in all cases the experimental values are higher than the theoretical values.

TABLE XII. Comparison of experimental data with predictions of Davydov and Filipov.

Nucleus	$\frac{E'(2)}{E(2)}$	deg γ	Experimental (kev) $E'(2)+E(2)$	$E(3)$	$\frac{b(E2;\,2'\rightarrow0)}{b(E2;\,2'\rightarrow2)}$ Expt.	Theory	Reference
Sm^{152}	8.9	13.1	1204	1226	0.6	0.44	31, 32
Gd^{154}	8.1	13.9	1121	1130	0.56	0.41	33
Gd^{156}	12.7	11.2	1223	1229	0.61	0.50	34, 35, 43
Dy^{160}	11.1	11.9	1051	1047	0.42	0.48	36, 37
Er^{166}	9.8	12.7	868	861	0.50	0.45	This work
W^{182}	12.2	11.4	1322	1332	0.62	0.50	40
W^{184}	8.1	13.8	1015	1006	0.58	0.41	39
Os^{186}	5.6	16.5	905		0.45	0.32	41, 42
Os^{188}	4.1	19.2	788		0.41	0.31	41, 42

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[45] A. S. Davydov and G. F. Filipov, Nuclear Phys. 8, 237 (1958).

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$Cu^{65}(\gamma,3n)$ Reaction and Its Bearing on the Use of the $Cu^{63}(\gamma,n)Cu^{62}$ Reaction for Bremsstrahlung Monitoring

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The $Cu^{65}(\gamma,3n)$ reaction has been measured from threshold to 110 Mev. The integrated cross section at 110 Mev is 0.037 ± 0.004 Mev barn. The consequent error in bremsstrahlung monitoring through ignoring this contribution varies from 0.9% at 40 Mev to 1.4% at 110 Mev.

IN developing a bremsstrahlung monitoring system based on the 9.7-minute Cu^{62} activity resulting from the $Cu^{63}(\gamma,n)$ reaction,[1] it was necessary to measure the $Cu^{65}(\gamma,3n)Cu^{62}$ cross section since this reaction will not only affect the absolute intensity calibration but may also introduce errors into the normalization of beams with different energies. This latter is of particular importance when using bremsstrahlung subtraction techniques[2] to obtain photon cross sections.

A target,[3] consisting of 196.6 mg of Cu^{65} (Cu^{63} contamination $0.6\pm0.08\%$) on a 0.001-in. platinum support, was irradiated at various beam energies and counted with the following schedule: (a) Irradiation 0–10 min. (b) First count 11–20.5 min. (c) Second

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[1] C. Whitehead *et al.*, Phys. Rev. 110, 941 (1958).
[2] L. Katz and A. G. W. Cameron, Can. J. Phys. 29, 518 (1951). A. S. Penfold and J. E. Leiss, University of Illinois (unpublished).
[3] Supplied by the Atomic Energy Research Establishment, Harwell, England.

TABLE I. The ratio of Cu^{62} activities produced in Cu^{65} and Cu^{63} by bremsstrahlung beams.

Bremsstrahlung energy Mev	Ratio of activity in copper and Cu^{65} Cu^{65}/Cu
110	0.0444±0.0007
70	0.0411±0.0007
60	0.0356±0.0017
50	0.0350±0.0010
38.2	0.0285±0.0017
35	0.0205±0.0014
33.8	0.0070±0.0028
28.8	0.0017±0.0021

TABLE II. Error introduced into absolute intensity calibration of bremsstrahlung beams by the $Cu^{63}(\gamma,n)Cu^{62}$ reaction when $Cu^{65}(\gamma,3n)$ is not allowed for.

Bremsstrahlung energy Mev	Error %
40	0.9±0.2
50	1.1±0.2
70	1.3±0.2
110	1.4±0.2

count 21–30.5 min. This enabled a rapid separation of the Cu^{62} activity to be made. Before each Cu^{65} irradiation rod targets of natural copper were irradiated under identical conditions, the dose in each case being monitored by a thin ionization chamber through which the beam passed. The activity produced in the rod targets had been related to the activity in thin copper foils as previously described.[1] The corrected results are shown in Fig. 1 and Table I, the errors given here being statistical. Corrections were made for the residual count in the scintillation detector and for other activities induced in the target and its backing. An uncertainty of ±3% is introduced in making these corrections. Further corrections have been made to allow for backscatter of the Cu^{62} positrons in the platinum backing, which causes an increase of (7±2)% in the Cu^{62} count; and the activity produced in the Cu^{63} contamination by the (γ,n) reaction.

The results are not sufficiently accurate near threshold to determine the shape of the cross section, but do show clearly that at least 90% of the integrated cross section lies between threshold and 70 Mev. The results are well fitted by[4]

$$\int_0^{110} \sigma(E)dE = 0.037\pm0.004 \text{ Mev barn},$$
$$\bar{E} = 33\pm2 \text{ Mev},$$

where $\bar{E}$ is given by

$$\frac{N(\bar{E},E_m)}{N(\bar{E},E_m')} = \frac{\int \sigma(E)N(E,E_m)dE}{\int \sigma(E)N(E,E_m')dE},$$

where $N(E,E_m)$ is the number of photons of energy E

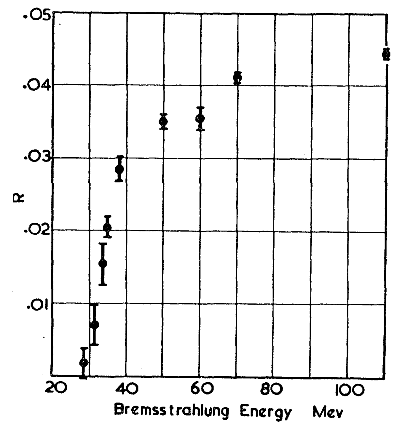

FIG. 1. $Cu^{65}(\gamma,3n)Cu^{62}$ yield curve: R is the ratio of Cu^{62} activity induced in equal weights of Cu^{65} and Cu^{63}.

per unit energy in a bremsstrahlung beam of maximum energy E_m.

The significance of this data is that if the Cu^{65} contribution is ignored, the intensity calibration of a bremsstrahlung beam will be low by the percentage shown in Table II.

[4] Using $Cu^{63}(\gamma,n)$ cross section of A. I. Berman and K. L. Brown, Phys. Rev. 96, 83 (1954).