Simpler distributions as represented by Eqs. (3) or (4), adjusted to give the experimental anisotropy in projected angle, have nearly the same anisotropy in spatial angle although the resulting form of the distribution in projected angle is somewhat different. The anisotropy for the total fission products from fission induced by 22-Mev protons[5] is estimated from measurements made on five specific fragments.

The anisotropy behaves as expected at the lower energies going through a maximum in the vicinity of 45 Mev and thereafter decreasing. However it does not appear to approach any limiting value at higher energies but decreases as a smooth function of energy to quite large negative values.

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Cross Section for the $Al^{27}(\gamma,2p)Na^{25}$ Reaction to 65 Mev*

L. B. AULL AND W. D. WHITEHEAD
University of Virginia, Charlottesville, Virginia
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The $Al^{27}(\gamma,2p)Na^{25}$ cross section has been determined from 25 to 65 Mev with respect to the $Cu^{63}(\gamma,n)Cu^{62}$ cross section. The cross section has a maximum value of 0.29 mb at 32 Mev and the integrated cross section from 25 to 64 Mev is 2.8 Mev mb.

INTRODUCTION

THE (γ,n) and (γ,p) cross sections have been determined for a number of elements, and the parameters describing the giant resonances as functions of A have been well systematized.[1] Several $(\gamma,2n)$ cross sections have been investigated[2,3] and the cross sections for some multiple processes have been measured,[4,5] but no $(\gamma,2p)$ reactions have been investigated in detail.[6] We have determined the cross section for the $Al^{27}(\gamma,2p)Na^{25}$ reaction, which has a threshold at 21.4 Mev, from 25 Mev to 65 Mev using the bremsstrahlung from the University of Virginia synchrotron, by measuring the induced Na^{25} activity in pure aluminum disks.[7] The yield function, determined with respect to the $Cu^{63}(\gamma,n)Cu^{62}$ cross section, was unfolded by means of the Leiss-Penfold matrices[8] to give the cross section as a function of energy.

EXPERIMENTAL PROCEDURE

To determine the aluminum yield curve, an aluminum disk and a copper disk were clamped together, the pair was irradiated for three minutes at each energy, and then the induced activity in each sample was determined. The samples were irradiated at 1-Mev intervals in the maximum photon energy range 25 to 36 Mev and at 2-Mev intervals in the range 36 to 65 Mev. The aluminum disks were 0.845 g/cm² thick and $1\frac{1}{2}$ inches in diameter, and the copper monitor disks were the same diameter and 0.133 g/cm² thick; the sample holder was 41 cm from the internal tungsten target and was centered with the aid of x-ray plate exposures. The beam was monitored with an ionization chamber also, and for each irradiation the sample was placed in the beam by remote control when the intensity was steady. If the intensity as determined with the ionization chamber fluctuated during a run, the run was discarded.

The synchrotron, which was built by the General Electric Company,[9] has a maximum energy of 65 Mev, and the gamma-ray intensity at this energy from a 0.020-inch internal tungsten target measured with a Victoreen R-meter in a $\frac{1}{8}$-inch lead thimble is 300 r/min at 1 meter from the target. The energy of the electrons was determined by means of an integrating fluxmeter,[10] and the energy scale of the machine was established with reference to breaks in the $C^{12}(\gamma,n)C^{11}$ yield function at 19.10 and 19.55 Mev.[11] The estimated uncertainty in the maximum photon energy values obtained from the integrator is ±0.25 Mev.

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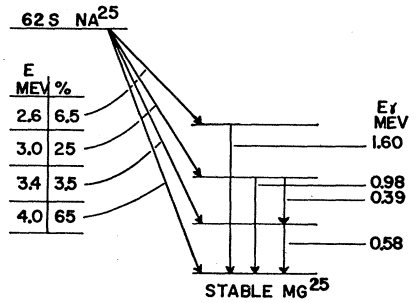

FIG. 1. The decay scheme for Na^{25} as determined by Maader and Staehelin.[12]

The induced activities in the aluminum and copper samples were measured with a 2π plastifluor scintillation crystal 0.25 inch thick mounted on an RCA–6342 photomultiplier which fed a Hamner N301 linear amplifier and discriminator, and then extrapolated to the end of the irradiation. In a three-minute irradiation the only measurable activities induced in the aluminum samples were the 6-sec Al^{26} from the $Al^{27}(\gamma,n)Al^{26}$ reaction and the 60-sec Na^{25} from the $Al^{27}(\gamma,2p)Na^{25}$, and no 6-sec component was detected in the decay curve if a 70-sec delay was introduced before starting the counter. Since the decay scheme for Na^{25} has previously been determined[12] (Fig. 1) and the component beta-ray spectra all have maximum energies greater than 2.5 Mev, the counter was biased to count all beta rays above 50 kev and this resulted in very little loss in efficiency. The only appreciable activity induced in the copper sample was the 10-min Cu^{62}, and no long-lived components were detected in the decay curve. Since the Cu^{62} decays by positron emission and 2% K capture,[3] the discriminator was set to count all positrons above 1.5 Mev to avoid pileup from the 0.51-Mev annihilation radiation.

The counting rates at the end of the irradiation, time $t=0$, were determined after the counting rates at time $t=T$ were corrected for losses due to discriminator setting, back scattering, and absorption in the sample. The Na^{25} data were not corrected for losses due to discriminator setting because, as mentioned before, all beta rays above 50 kev were counted. The counting rates from the copper samples were corrected for discriminator setting by using the experimentally determined shape[13] of the Cu^{62} positron spectrum to extrapolate to zero bias. About 30% of the Cu^{62} positrons have energies greater than that corresponding to the discriminator setting used. The self-absorption correction for the Na^{25} was similar to that used by Katz and Baker.[14] The self-absorption correction was also experimentally determined by irradiating aluminum samples of various thicknesses at a fixed beam energy, and the two correction factors agreed in value. The experimentally determined value for the half-life of Cu^{62} was 9.8 min and for Na^{25} was 62.0 sec; these values were used to extrapolate the counting rates to the end of the irradiation ($t=0$). The total induced activity was determined from the extrapolated corrected counting rates by use of the experimentally determined value for the geometrical efficiency of the counter. A calibrated Na^{22} source was used to measure the effective solid angle subtended by the counter, to measure the efficiency of the crystal for gamma rays, and to establish the energy scale for the discriminator. The efficiency of the counter for 0.5 Mev was less than 1%, and since 65% of the beta rays from Na^{25} go directly to the ground state of Mg^{25} and the decay γ rays from the other levels of Mg^{25} all have an energy greater than 0.4 Mev, no corrections were made for gamma rays in the Na^{25} counting. The contribution of the $Cu^{63}(n,2n)Cu^{62}$ reaction[15] to the Cu^{62} activity was determined by an experiment in which a copper sample was placed just outside the beam. This contribution was found to be negligible. No corrections were made for the $Cu^{65}(\gamma,3n)Cu^{62}$ reaction[5] which has a threshold, computed from the masses, at 27.6 Mev.

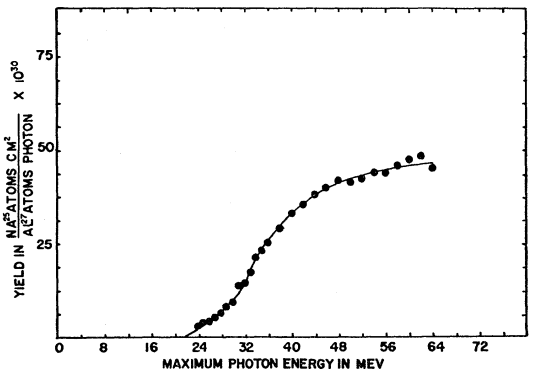

FIG. 2. The yield function for the $Al^{27}(\gamma,2p)Na^{25}$ normalized to the $Cu^{63}(\gamma,n)Cu^{62}$ cross section of Berman and Brown.[3] The statistical uncertainty in the points is about 2%.

The beam intensity for each run was computed from the Cu^{62} yield curve using the relation

$$n=\frac{Y(E_m)}{N\int_{E_t}^{E_m}P(E,E_m)\sigma(E)dE},$$

where n=number of photons striking the sample for maximum energy E_m, $Y(E_m)$=yield of Cu^{62} atoms calculated from the induced activity at the maximum photon energy E_m, N=number of Cu^{63} nuclei per cm^2 in the sample, $P(E,E_m)$=Schiff spectrum integrated over angles at E_m,[16] E_t=threshold energy for the $Cu^{63}(\gamma,n)Cu^{62}$ reaction, and $\sigma(E)$ is the cross section for that reaction at energy E. The sample subtends a

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half-angle of 2.6°, and the experimentally determined half-width of the beam at 64 Mev is ~2° so that the Schiff spectrum integrated over the solid angle is a good approximation.[17] There are still some discrepancies in the published values for the $Cu^{63}(\gamma,n)Cu^{62}$ cross section[3,18,19]; we have used the value of Berman and Brown[3] and have assumed that the cross section is zero above 30 Mev.

RESULTS AND DISCUSSION

The $Al^{27}(\gamma,2p)$ yield function, normalized to beam intensity n, is shown in Fig. 2, in which each point is the average of three determinations and the statistical errors due to counting are about 2%. In order to compute the cross section, a smooth curve was drawn through these points. The cross section derived from this curve by use of the Leiss-Penfold matrices[5] is plotted in Fig. 3. The points were computed by using the values from the smooth yield curve at energies midway between the data points. The statistical errors

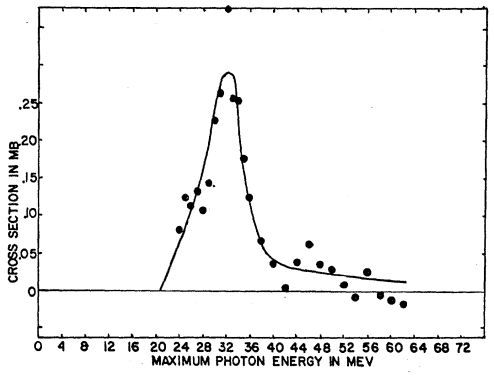

FIG. 3. Cross section for the $Al^{27}(\gamma,2p)Na^{25}$ reaction derived from the smooth yield curve of Fig. 2. The estimated statistical uncertainty in the points is about 30%.

on the cross section curve are difficult to estimate but are the order of 30%. The smooth cross section curve is the estimated best fit, and the integrated cross section using this curve is 2.8 Mev mb in agreement with the published value.[20] In Fig. 4 the cross sections for the

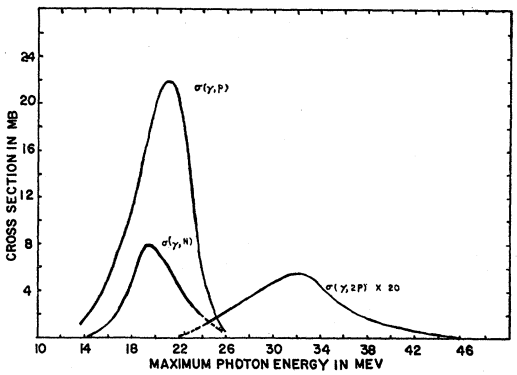

FIG. 4. Cross sections for the $Al^{27}(\gamma,p)Na^{26}$ reaction from Halpern and Mann,[21] for the $Al^{27}(\gamma,n)Al^{26}$ reaction from Katz and Cameron[22] and for $Al^{27}(\gamma,2p)Na^{25}$ from this work.

$Al^{27}(\gamma,p)$,[21] $Al^{27}(\gamma,n)$,[22] and $Al^{27}(\gamma,2p)$ reactions are plotted. The maximum value of the $(\gamma,2p)$ cross section is 0.29 mb at 32 Mev, and within the uncertainty of the data the cross section is finite up to 65 Mev. From the experimentally determined elastic γ-ray scattering cross section and the absorption cross section determined from the (γ,n) and (γ,p) processes, Fuller and Hayward[23] have concluded, using the dispersion relations, that the aluminum nucleus must absorb γ rays at higher energies than those of the giant resonances for these processes. The integrated cross sections for $Al^{27}(\gamma,n)$, $Al^{27}(\gamma,n2p)$, and $Al^{27}(\gamma,2p)$ have been determined to 70 Mev by Edwards and MacMillan and, as in this experiment, the multiple processes do not make a significant contribution to the total absorption cross section. The (γ,p) process has the largest integrated cross section, although it has only been measured to 24 Mev, and it may be that this process makes the largest contribution to the absorption cross section even at the higher energy.

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