because of the additional uncertainty introduced by possible errors in the decay energies.

Kurath[13] has shown that if the ground states of Ar^{40}, K^{40}, and Ca^{40} are assigned pure jj configurations, the ratio of the squared reduced matrix elements M_+^2/M_-^2 should equal $\frac{1}{8}$. The difference between the theoretical value and the experimental result is within the range of possible experimental error.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Dieter Kurath for calculating the theoretical ratio of the matrix elements for β^+ and β^- decay and to Dr. F. Porter and Dr. M. S. Freedman for assistance in formulating the calculation of the beta-spectrum shape-correction factors.

APPENDIX

The number of external pairs produced in the liquid scintillator per K^{40} disintegration depends upon the number of 1.46-Mev gammas per β^-, the fraction of these gammas stopped in the liquid scintillator, and the ratio of pair production to total cross sections for the gammas in the liquid scintillator. The number of 1.46-Mev gammas per β^-, 0.123, was taken from the NRC data tables.[9] Case *et al.*[14] present a table of the probability of an interaction within a uniform spherical source as a function of a/l, where a is the radius of the sphere and l is the mean free path of the radiation in the material. They show that the interaction probability P is quite insensitive to the exact geometrical shape: P(hemisphere) is 0.945 times P(sphere) and P(tetrahedron) is 0.944 times P(sphere) for equal volumes. For our liquid scintillator which approximated a cylinder of height equal to its radius, we assumed that P(cylinder) was 0.945 times P(sphere) of the same volume. All cross sections were interpolated from the tables of Davisson and Evans,[15] applied to scintillator solutions having the compositions listed in Table I, and include pair production in the potassium and sodium. A rough estimate was also made of the probability that a pair would be produced in the glass walls of the liquid scintillator cell and that at least one member of the pair would reach the liquid scintillator. This estimate is entered in Table III. Exact calculations of internal pair-production cross sections have been made by Jaeger and Hulme[16] for $Z=0$ and $Z=84$ for $E2$ radiation. The values at 1.46 Mev for $Z=0$ and $Z=84$ were read from their graph and introduced into Brimberg's[17] interpolation formula which yielded an average value of 7.2×10^{-5} pairs per gamma at $Z=18$.

TABLE III. Pair production in liquid scintillator.

a (6 ml volume)		1.126 cm
l (for toluene, 1.46-Mev γ)		20.28 cm
P (cylinder)		0.0382
$\sigma_{pair}/\sigma_{total}$	$5.95\times10^{-5}/4.93\times10^{-2}=$	1.207×10^{-3}
External pair production in liquid scintillator		4.61×10^{-5} per gamma
External pair production in walls		0.16×10^{-5} per gamma
Internal pair production		7.2×10^{-5} per gamma
Total pair production		12.0×10^{-5} per gamma

[13] D. Kurath, Argonne National Laboratory Physics Division Summary Report for November and December, 1961 (unpublished).

[14] K. M. Case, F. de Hoffman, and G. Placzek, *Introduction to the Theory of Neutron Diffusion* (U. S. Government Printing Office, Washington, D. C., 1953), Vol. 1.

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Photoproton Reaction in Be^9†

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The reaction $Be^9(\gamma,p)Li^8$ was measured from threshold (16.89 Mev) up to 57 Mev using the bremsstrahlung beam from the Iowa State University electron synchrotron. The data were taken in energy steps of ~0.050 Mev for the first several Mev and in energy steps of ~1.0 Mev for the remainder of the yield curve. A number of small resonances near threshold was observed. The giant resonance cross section reaches a peak value of 2.64±0.30 mb at an energy of 23 Mev, and it possesses a large high-energy tail. The integrated cross section to 56.8 Mev is 41.4±4.6 Mev-mb.

INTRODUCTION

In 1953 Haslam *et al.*[1] published the results of their measurement of the $Be^9(\gamma,p)Li^8$ cross section from the threshold for this reaction (16.89 Mev) up to 26 Mev. They observed the usual giant resonance and reported a peak cross section of 2.7 mb at 22.2 Mev, an integrated cross section of 13 Mev-mb up to 26 Mev, and a yield of 2.3×10^4 counts/mole roentgen at a bremsstrahlung energy of 26 Mev. Several years later Cohen *et al.*[2] measured the photoproton yield from Be^9

† Contribution No. 1066. Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.

[1] R. N. H. Haslam, L. Katz, E. H. Crosby, R. G. Summers-Gill, and A. G. W. Cameron, Can. J. Phys. **31**, 210 (1953).

[2] L. Cohen, A. K. Mann, B. J. Patton, K. Reibel, W. E. Stephens, and E. J. Winhold, Phys. Rev. **104**, 108 (1956).

with 23.5 Mev bremsstrahlung using nuclear emulsions. They reported a yield of 5.8×10^4 protons/mole roentgen and concluded that about half of their yield was due to the $Be^9(\gamma,pn)Li^7$ reaction.

In light nuclei, in addition to the well-known giant resonance, there is evidence for the absorption of photons into discrete nuclear states. This evidence consists of sudden changes of slope or breaks in the yield curve[3] and of discrete proton groups as measured in emulsions.[1,4] Geller has also performed an analysis of the yield curves for the $N^{14}(\gamma,n)N^{13}$ and $O^{16}(\gamma,n)O^{15}$ reactions near the thresholds and has obtained several resonances.[5] The data of Haslam *et al.*[1] were not taken in fine enough energy intervals to have detected any breaks in their yield curve, and the data of Cohen *et al.*[2] show no proton groups from Be^9 with energies greater than 2 Mev. Below this proton energy their data are somewhat uncertain due to energy losses in the target.

Since there are several known levels in Be^9 just above the (γ,p) threshold[6] which might show up in a photonuclear reaction, it was decided to examine the $Be^9(\gamma,p)Li^8$ reaction near threshold using an energy resolution of approximately 0.050 Mev. The remainder of the data (out to 57 Mev) was taken in steps of approximately 1.0 Mev.

EXPERIMENTAL PROCEDURES

The $Be^9(\gamma,p)Li^8$ reaction was studied by detecting the 0.8-sec, 13-Mev beta-particle decay of the Li^8 which resulted from the bombardment of a metallic beryllium target by the bremsstrahlung beam from one of the Iowa State University 65-Mev synchrotrons. The energy calibration for the synchrotron was determined by the $Be^9(\gamma,p)$ threshold and the injection voltage of the electrons into the synchrotron. This energy calibration was checked by measuring the 17.24 ± 0.03 Mev break in the $O^{16}(\gamma,n)$ yield curve[7] to be 17.19 ± 0.05 Mev. The energy stability of the synchrotron was ascertained to be ±0.03 Mev.

The Li^8 beta particles were detected with two scintillation counters arranged as a coincidence telescope. The discrimination level was set to reject beta particles from the He^6 decay. Both detectors were gated off during the synchrotron acceleration period and beam burst. The detectors were gated on one msec after the beam burst, allowed to count for 11.0 msec, and were then gated off until the next beam burst.

Radiation dosage was monitored during the runs with

[3] See for example: R. N. H. Haslam, L. Katz, R. J. Horsley, A. G. W. Cameron, and R. Montalbetti, Phys. Rev. **87**, 196(A) (1952); S. M. Penfold and B. M. Spicer, *ibid.* **100**, 1377 (1955); D. Sadeh, *ibid.* **123**, 855 (1961).

[4] S. A. E. Johansson and B. Forkman, Arkiv Fysik **12**, 359 (1957).

[5] K. N. Geller, Phys. Rev. **120**, 2147 (1960).

[6] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959); W. C. Barber, F. Berthold, G. Fricke, and F. E. Gudden, Phys. Rev. **120**, 2081 (1960).

[7] A. S. Penfold and E. L. Garwin, Phys. Rev. **115**, 420 (1959); K. N. Geller, J. Halpern, and E. G. Muirhead, *ibid.* **119**, 716 (1960); L. Katz and H. J. King, Can. J. Phys. **37**, 1357 (1959).

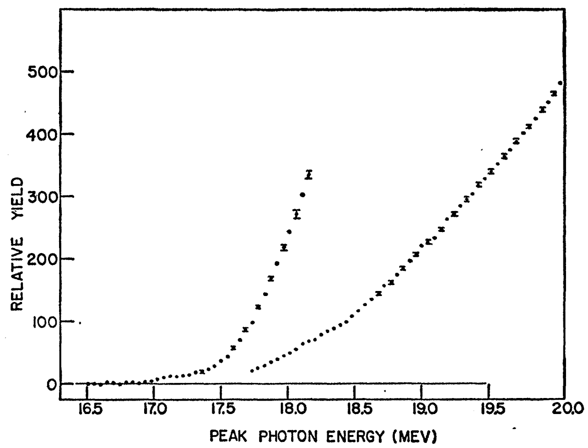

FIG. 1. Yield curve for the $Be^9(\gamma,p)Li^8$ reaction for the energy interval 16.5 Mev to 20 Mev taken in steps of 0.046 Mev.

a sealed transmission chamber and a vibrating reed electrometer. After each run, the target was removed and the transmission chamber was calibrated against an ionization chamber of the National Bureau of Standards design.[8]

The target used for measuring the yield curves was a block of beryllium metal $3.63\times3.25\times1.44$ in. with the 3.63-in. edge of the target placed parallel to the beam. At 60 Mev the total number of photons in the bremsstrahlung beam is reduced by 10% after passing through 3 in. of beryllium metal. However, since the ratio of the number of photons at 17 and 60 Mev is changed by less than 3%, it was decided to use the thick target for measuring the yield curve in order to increase the counting rate.

For the measurement of the absolute counting rate a beryllium target 0.044-in. thick was bombarded at an energy of 28 Mev. Radiation dosage measurements during this part of the experiment were made directly with the National Bureau of Standards chamber. The background was determined by replacing the beryllium target with a nickel target of the same size and shape and repeating the measurement.

Other information needed to determine the absolute yield included the efficiency of the coincidence telescope, the solid angle subtended by the detectors, the percentage of counts rejected by the discriminators, and the duty cycle.

Methods used to determine the absolute counting rate were checked by measuring the activity from a calibrated beta source. The measured source strength agreed within experimental accuracy with the value determined by a 4π/counter.

EXPERIMENTAL RESULTS

The yield curve for the region 16 to 20 Mev taken in energy intervals of 0.046 Mev is shown in Fig. 1. The integrated cross section to 20 Mev was calculated

[8] J. S. Pruitt and S. R. Domen, National Bureau of Standards Report No. 6218, 1958 (unpublished).

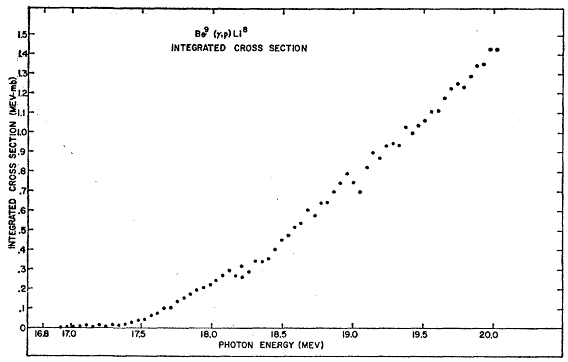

FIG. 2. Integrated cross section for the $Be^9(\gamma,p)Li^8$ reaction for the energy interval 16.5 Mev to 20 Mev in steps of 0.046 Mev. No smoothing has been applied.

directly from the experimental points with no smoothing and is shown in Fig. 2. The Iowa State University Cyclone digital computer was used for all cross-section calculations. Since the statistics are not sufficiently good, some smoothing must be applied in order to obtain the cross section itself. It was decided to smooth the integrated cross section by making a least-squares fit of a quartic equation to seven points, taking the value at the midpoint, and then advancing the group of points by one unit and repeating the process. The cross section obtained from this smoothed integrated cross section is shown in Fig. 3.

The yield curve for the region 16 to 57 Mev taken in energy intervals of 0.94 Mev is shown in Fig. 4. The unsmoothed integrated cross section is shown in Fig. 5. The unsmoothed and smoothed cross sections are shown in Figs. 6 and 7, respectively. The smoothing applied was the same as described above.

DISCUSSION

There are several excited states in Be^9 which lie above the (γ,p) threshold[6]; these are shown in Fig. 3 with the horizontal bars indicating known widths. It is seen that

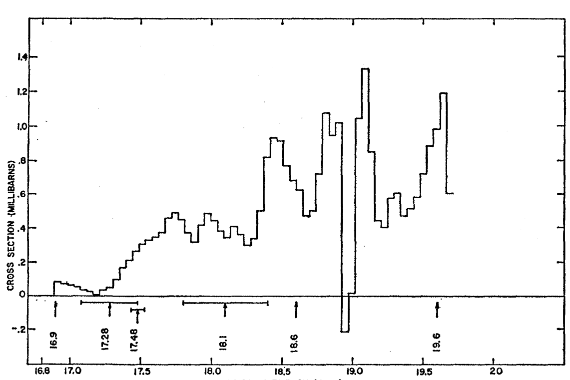

FIG. 3. Smoothed cross section for the $Be^9(\gamma,p)Li^8$ reaction for the energy interval 16 Mev to 20 Mev. The smoothing applied is discussed in the text. The known levels in Be^9 are shown by the arrows with the horizontal bars indicating their widths.

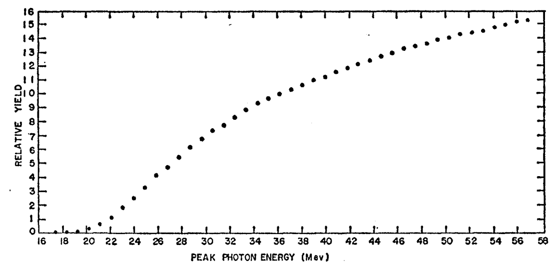

FIG. 4. Yield curve for the $Be^9(\gamma,p)Li^8$ reaction for the energy interval 16 Mev to 57 Mev taken in steps of 0.94 Mev.

there is a correspondence between the known levels (except for the one at 17.28 Mev) and resonances obtained from the $Be^9(\gamma,p)$ reaction. There is an indication from the (γ,p) cross section that Be^9 has an excited state at 17.8 Mev that is not included in the current level schemes.[6]

The giant resonance as shown in Fig. 7 reaches a maximum at about 23 Mev which agrees fairly well with the work of Haslam *et al.*[1] The peak value of the cross section obtained in this work is 2.64 ± 0.30 mb which is in good agreement with their value. However, the shape after the peak is quite different. While their cross section drops quite rapidly after 22 Mev, the present work shows a long high-energy tail with the value at 50 Mev being approximately $\frac{1}{6}$ of the value at 23 Mev. The integrated cross section to 57 Mev is 41.4 ± 4.6 Mev-mb.

The theoretical value for the total integrated cross section up to the photomeson threshold is 187 Mev-mb.[9] In order to compare the theoretical prediction with experiment, one must add together the experimental results for the (γ,n), (γ,p), $(\gamma,2n)$, (γ,pn), etc. reactions. While a number of measurements of the photoneutron cross section has been made below 25 Mev, only the work of Jones and Terwilliger[10] has been reported for higher energies.

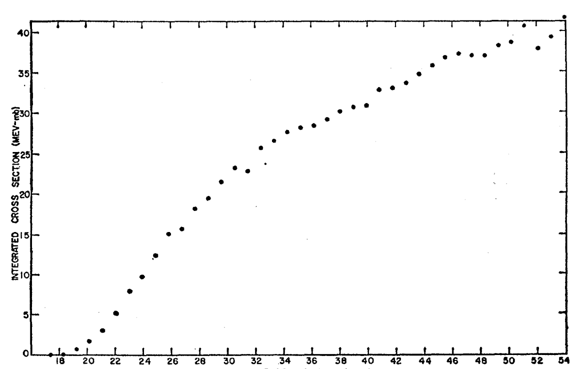

FIG. 5. Integrated cross section for the $Be^9(\gamma,p)Li^8$ reaction. No smoothing has been applied.

[9] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950); M. Gell-Mann, M. L. Goldberger, and W. E. Thirring, *ibid.* **95**, 1612 (1954).

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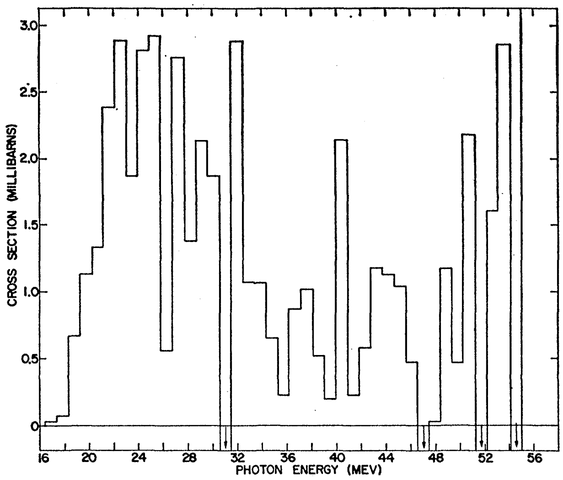

FIG. 6. Unsmoothed cross section for the $Be^9(\gamma,p)Li^8$ reaction.

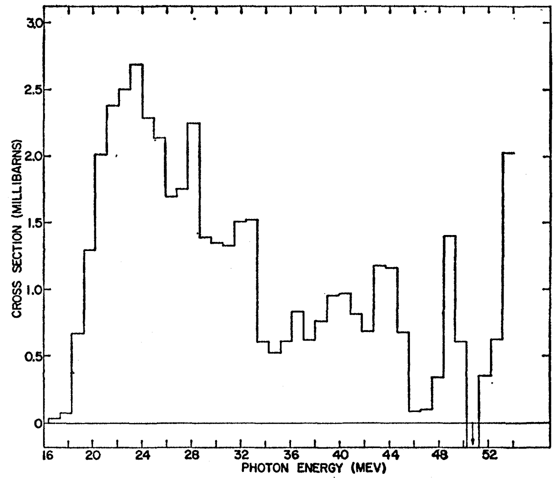

FIG. 7. Smoothed cross section for the $Be^9(\gamma,p)Li^8$ reaction. The smoothing applied is discussed in the text.

Taking the results of Fig. 4 from their paper, the integrated photoneutron cross section to 57 Mev is ~143 Mev-mb. This could be an over-estimate since the yield has not been corrected for the neutron multiplicity. Values for the peak cross section and integrated cross section to 25 Mev for the photoneutron reaction as reported by Nathans and Halpern[11] are about three-fourths the values given by Jones and Terwilliger.[10] Combining the results of our work for the (γ,p) reaction and the results of Jones and Terwilliger for the $(\gamma,n)+(\gamma,np)+\cdots$ reactions, the integrated cross section to 57 Mev is ~184 Mev-mb, or taking three-fourths of the result of Jones and Terwilliger this becomes ~148 Mev-mb. Even though the neutron multiplicity has not been taken into account, this may not be too serious for energies up to 50 Mev. For example, the integrated cross section (to 45 Mev) for the $Be^9(\gamma,2n)Be^7$ reaction has been reported by Foster[12] to be only 5 ± 2 Mev-mb, and the only other multiple neutron reactions with thresholds appreciably below 50 Mev are the $Be^9(\gamma,2np)Li^6$ and $Be^9(\gamma,3n2p)He^4$ reactions.

From the paper of Jones and Terwilliger[10] one can set a lower limit on the integrated photoneutron cross section. If one assumes a neutron multiplicity of five (which is the largest it can be) for reactions with photons whose energies are greater than 57 Mev, the integrated photoneutron cross section to 150 Mev is ~180 Mev-mb. Or using the lower value obtained by Nathans and Halpern,[11] this becomes ~135 Mev-mb. If the integrated cross section to 57 Mev for the (γ,p) reaction is added to this latter value, one obtains as a lower limit for the total integrated photonuclear cross section to 150 Mev, a value in the neighborhood of 180 Mev-mb. Thus it appears that the integrated cross section to the meson threshold will be at least as large as the theoretical value of 187 Mev-mb.

[11] R. Nathans and J. Halpern, Phys. Rev. **92**, 940 (1953).
[12] M. S. Foster, Ph.D. thesis, Iowa State University, 1960 (unpublished).