Photodisintegration Cross Section of Beryllium near Threshold*

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The cross section for the reaction $Be^9(\gamma,n)$ has been measured near threshold using gamma rays from radioisotopes. With an Sb^{124} source ($E_\gamma = 1.692$ MeV) the cross section is found to be 1.31 ± 0.08 mb, in good agreement with a recent determination by Gibbons *et al.* With Bi^{206} ($E_\gamma = 1.720$ MeV) the cross section is found to be 0.93 ± 0.05 of the cross section at 1.692 MeV, while with Al^{28} ($E_\gamma = 1.78$ MeV) the cross section is found to be 0.67 ± 0.03 of the cross section at 1.692 MeV. These results can be fitted by the single-nucleon calculation of Francis *et al.* which employs Woods and Saxon potential wells. The value for the diffuseness parameter of the final state is reduced to a normal value by using the modified theory including coupling to the Be^8 core introduced by Blair.

I. INTRODUCTION

EARLY measurements[1,2] of the reaction $Be^9(\gamma,n)$ using radioactive gamma-ray sources showed that the cross section rises sharply to a peak just above threshold. To explain this and other features of the photodisintegration, Guth and Mullin[3] employed a single-particle model. Square-well potentials were used to generate the wave functions. Near threshold an electric dipole transition takes place between the ground p state and a final s state in the continuum. The peak was attributed to the existence of a slightly bound level in the final well which acts like a resonance level. One difficulty with the calculation is that the required final-state well depth seems unrealistically small.

Recently, Francis, Goldman, and Guth[4] have recalculated the single-particle model using the diffuse-edge Woods and Saxon potential well. The experimental data can be fitted with reasonable potential well parameters except that the diffuseness parameter of the final state is about 1.2 F. Alternately, with a more usual diffuseness of 0.6 F, the computed cross section is 1.8 times the experimental one. Because of this difficulty and also because of some new accelerator results of Jakobson,[5] Blair[6] has applied a new model assuming a strong coupling in the ground state between the orbital neutron and the ground and first-excited states of the Be^8 core. He finds that the single-nucleon cross sections of Francis *et al.*[4] should be multiplied by a reduction factor of 0.60, bringing them into better agreement with experiment. In testing the theoretical models, accurate experimental cross sections near threshold are needed.

Gamma rays from radioactive sources have been used many times in the past to perform (γ,n) experiments. At present there still appears to be some advantage in the use of sources over electron accelerators in determining cross sections because of the well-known difficulties with the bremsstrahlung spectrum. We have measured the total cross section for $Be^9(\gamma,n)$ at 1.692, 1.720, and 1.78 MeV using gamma rays from Sb^{124}, Bi^{206}, and Al^{28}, respectively. These measurements were partially motivated by the large discrepancy between earlier measurements with Sb-Be sources.[7] While this work was in progress, new results using Sb^{124} and Y^{88} were published by Gibbons, Macklin, Marion, and Schmitt[8] and used by Francis *et al.*[4] in their recent theoretical calculations. The latter also cited our unpublished results. In the present paper those results are reported with some revision on the basis of additional work.

II. EXPERIMENTAL MEASUREMENTS

A. Sb^{124}-Be Source

The antimony source consisted of a hollow sphere of 1.6-mm-thick aluminum having a 1.36-cm outside diameter and packed with granulated antimony to a density of about 2.7 g/cm³. Activation was by neutron capture in the Livermore Pool-Type Reactor followed by a decay period of several months to eliminate any short-lived activities. The gamma-ray source was then positioned by a Styrofoam support at the center of a spherical shell of beryllium with an outside diameter of 8.2 cm and a thickness of 0.645 cm. The shell was an assembly of nesting hemispheres precisely machined from high-purity beryllium. Figure 1 is a drawing of the photoneutron source. The particular source geometry used was chosen to: (1) give spherical symmetry; (2) minimize the correction necessary for the finite size of the antimony source; and (3) minimize the Compton scattering of gamma rays and the moderation of neutrons in the beryllium.

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1 B. Russell, D. Sachs, A. Wattenberg, and R. Fields, Phys. Rev. **73**, 545 (1948).

2 A. H. Snell (unpublished), cited by Guth and Mullin (reference 3).

3 E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949).

4 N. C. Francis, D. T. Goldman, and E. Guth, Phys. Rev. **120**, 2175 (1960).

5 M. J. Jakobson, Phys. Rev. **123**, 229 (1961).

6 J. S. Blair, Phys. Rev. **123**, 2151 (1961).

7 The discrepancy is nearly a factor of 2 for the values reported in references 1 and 2 above. Before comparing, it is necessary first to correct the result of Russell *et al.* for the branching ratio of Sb^{124}.

8 J. H. Gibbons, R. L. Macklin, J. B. Marion, and H. W. Schmitt, Phys. Rev. **114**, 1319 (1959).

B. Absolute Neutron Counting

The neutron yield was determined by comparing the Sb-Be photoneutron source to a Ra-Be standard source by means of a manganous sulfate bath. The source was suspended at the center of a tank, 112 cm in diameter and 74 cm deep, filled with water containing dissolved $MnSO_4$ 28.3% by weight. A Geiger tube was then used to measure the saturated manganese activity. For strong sources the bath results were reproducible to within 1%. Corrections were made for neutron escape from the bath and for capture of fast neutrons in the bath constituents other than Mn according to the procedure followed by Geiger and Whyte.[9]

The Ra-Be standard source (No. *E*-1277) was calibrated by the National Bureau of Standards approximately 5 years prior to the present measurements to a quoted accuracy of $\pm 3\%$. The Ra-Be source has been compared to a Po-Be source recently calibrated by the Bureau and agreement to 1.4% was found after the Ra-Be strength had been corrected for growth of Po^{210}. The principal uncertainty in the neutron count is believed to be due to the calibration of the standard source.

C. Absolute Gamma-Ray Counting

An NaI scintillation spectrometer was used to determine the strength of the 1.692-MeV gamma ray[10] from the Sb^{124} source. From the number of counts in the photopeak the source strength was calculated from unpublished efficiency curves furnished by Dr. H. West of this laboratory. In the present application, the use of the photopeak method has several advantages: (1) The measurement is independent of the branching ratio for the 1.692-MeV gamma ray. The decay scheme of Sb^{124} is complicated, resulting in uncertainty in the branching ratio. (2) An automatic correction is made for absorption and Compton scattering in the source. Approximately 6% of the gamma rays are scattered in the source. Only 1% of these remain above the photoneutron threshold. Thus only 0.06% of the neutrons are produced by degraded gamma rays. But considering the resolution of the crystal, we also estimate that less than 0.5% of the scattered gamma rays are detected within the photopeak. (3) The absence of gamma rays from impurities is verified.

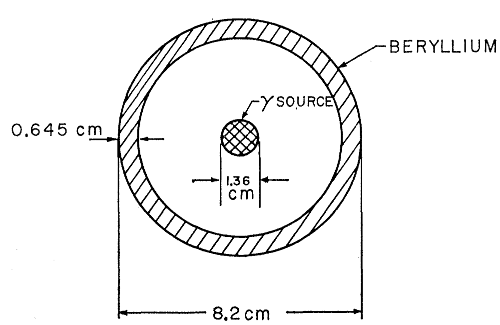

FIG. 1. Beryllium photoneutron source.

The bare Sb source was suspended 1.5 m above the ground at distances varying from 1 to 15 m from the NaI crystal. No intervening objects were present that could scatter gamma rays through small enough angles to be detected within the photopeak. At the large distances employed here, the crystal efficiency could be simply calculated from the solid angle and absorption coefficient of NaI, the effect due to penetration of the side of the crystal being only about 0.5% and easily estimated. The peak-to-total ratio for the 2-in.-thick $\times$1.75-in.-diam crystal at 1.692 MeV was 0.216 according to the curve obtained by West from measurements on radioisotopes with simple decay schemes. In his work, total activities were based on $4\pi\beta$ counting. West's gamma-ray counts were made at distances from 0 to 0.5 m. One may ask whether the peak-to-total ratio varies appreciably with distance. The results of Heath[11] show the variation to be small. We counted a weak Sb source at distances of 111 cm and 4.5 m, obtaining an agreement within 1.5%.

Care was taken to limit the counting rates. In addition to using large distances and a relatively small crystal, the 256-channel pulse-height analyzer was biased to count only the high-energy peaks and these in the lower channels. Under these conditions, the live-time indicator showed that there were no significant dead-time losses in the analyzer. Finally, the results obtained at the various distances agreed typically to within 1%. The principal uncertainty in the absolute gamma counting was in the value of the peak-to-total ratio, the estimated error due to the ratio being $\pm 5\%$.

D. $Be^9(\gamma,n)$ Cross Section at 1.692 MeV

Two Sb^{124} sources were prepared. The first had a strength of 25 mC at the time of the neutron yield measurement in the $MnSO_4$ bath and could be gamma-counted within a day of the neutron count. However, the low neutron bath counting rate resulted in a statistical uncertainty of 5.4%. The second Sb source was made stronger (590 mC) to improve the counting statistics. It was then necessary to allow the source to decay before attempting the gamma count. Gamma counts were made 221, 475, and 551 days after the neutron count. Decay corrections were made using the known 60.4 ± 0.2 day half-life,[12] a value confirmed by our own work. The results from the two Sb sources agreed well within the errors.

The presence of the 2.09-MeV gamma ray in the Sb^{124} spectrum introduced some complications into the cross-section determination. In analyzing the 1.692-MeV photopeak, the Compton tail from the 2.09-MeV gamma was subtracted, based on the shape of the 1.78-MeV gamma-ray spectrum from Al^{28}. In addition, a

[9] K. W. Geiger and G. N. Whyte, Can. J. Phys. **37**, 256 (1959).

[10] *Nuclear Data Sheets*, compiled by K. Way *et al.*, National Academy of Sciences (National Research Council, Washington, D. C., 1958).

[11] R. L. Heath, U. S. Atomic Energy Commission Report IDO-16408, 1957 (unpublished).

[12] R. L. Macklin, J. Nuclear Instr. **1**, 335 (1957).

TABLE I. Corrections and estimated uncertainties in the determination of the $Be^9(\gamma,n)$ cross section using Sb^{124} gamma rays (1.692 MeV).

Item	Correction (%)	Uncertainty (%)
1. Gamma-ray source strength		
(a) peak-to-total ratio	...	5.0
(b) subtraction of 2.09-MeV Compton tail	...	2.0
(c) half-life of Sb^{124}	...	0.8
2. Neutron source strength		
(a) absolute strength of NBS source	...	3.0
(b) neutron escape from $MnSO_4$ bath	−0.9	0.3
(c) capture of fast neutrons in bath	−2.8	0.5
(d) neutron counting statistics	...	0.8
3. Finite source size	−0.6	<0.1
4. Attenuation of gamma rays in Be shell	+2.5	<0.1
5. Neutrons produced by 2.09-MeV gamma rays	−4.4	1.0
Total correction	−6.2%	
Over-all uncertainty (square root of sum of squares)		6.4%
$\sigma(\gamma,n)=(1.31\pm0.08)\times10^{-27}$ cm^2		

correction[8] of −4.4% to the neutron yield was made to account for the photoneutrons produced by the 2.09-MeV gamma ray.

Other corrections were made for the finite Sb source size and for attenuation of gamma rays in the beryllium shell. The corrections and estimated uncertainties in the cross-section determination as well as the final result are listed in Table I.

E. Comparison Technique

It was desirable to find other radioisotopes with gamma rays suited to the measurement of the Be photoneutron cross section on the peak near threshold. Two such isotopes are Bi^{206} ($E_\gamma=1.720$ MeV) and Al^{28} ($E_\gamma=1.78$ MeV). Neither has previously been used for this purpose. However, the Bi^{206} source could not be prepared strong enough for an $MnSO_4$ bath measurement and the Al^{28} half-life (2.3 min) is too short to permit the use of an $MnSO_4$ bath. Therefore it was decided that the neutron and gamma-ray strengths of the sources should be determined relative to those of the Sb-Be source. Figure 2 shows the experimental arrangement devised for the source comparison measurements. Except for the gamma-ray sources, the photoneutron sources were identical with that used for the Sb absolute measurements. (See Fig. 1.) A long counter served to count neutrons and an NaI crystal detected gamma rays. Because there were about 10^4 photons per neutron and, moreover, the gamma counter is more efficient than the neutron counter, the source was located near the long counter and much farther from the NaI. A small source-long counter distance helps also to minimize the effect of room-scattered neutrons.

For each source the neutron and gamma-ray yields were determined simultaneously. This eliminates any correction for decay. The gamma source was then replaced by the Sb source and the yields again measured. From these data the cross sections relative to the Sb^{124} cross section at 1.692 MeV were determined. Correction was made for the change in the NaI crystal photofraction and intrinsic efficiency with gamma-ray energy. This does not introduce much error into the result. The principal uncertainty inherent in the comparison method employed here is the possible variation of the long-counter efficiency with neutron energy. The counter used was a copy of the "Harwell IV" counter, a modification of the Hanson-McKibben counter described by Allen.[13] Allen found the efficiency of this counter to be flat down to the Sb-Be neutron energy if account is taken of the effective source-counter distance. In tests with various neutron sources we found trends for the effective face of the counter similar to those reported by Allen, but the effective face was somewhat deeper in the counter. The energies of the photoneutrons from Sb-Be and Al-Be sources differ by less than 100 keV so that the depth of the effective face is nearly the same. However, the distance from the center of the source to the top of the counter was only 6.5 cm, so that the effect was not negligible. For the Al-Be source we applied a correction of 3% and assigned an uncertainty of ±3% in the neutron count due to this effect. No correction was applied to the Bi-Be measurements.

It should be noted that the relative cross sections reported here are more accurate than the corresponding absolute cross sections which of course depend also on the Sb-Be absolute measurement. The relative cross

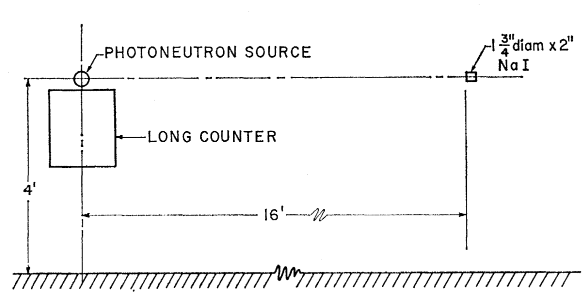

FIG. 2. Experimental arrangement for comparison technique.

[13] W. D. Allen, Harwell Report Atomic Energy Research Establishment NP/R 1667 (unpublished).

sections can be useful, as for example, in fixing the well depth of the final state in the theory of Francis *et al.*[4]

F. Measurements using a Bi^{206}-Be Source

Bi^{206} seemed suitable for the present experiment since the only gamma ray above the Be photoneutron threshold which has been reported is at 1.720 MeV.[14] A source was prepared by bombarding a lead foil in the 60-in. cyclotron at Berkeley to produce the reaction $Pb^{206}(d,2n)Bi^{206}$. The 1.8-g high-purity lead foil was 220 mg/cm^2 thick and coated with 3 mg/cm^2 of Al on both sides to minimize damage by heating. To avoid producing Bi^{205} by the $Pb^{206}(d,3n)Bi^{205}$ reaction, the deuteron beam energy was reduced by an aluminum absorber to 14 MeV entering the lead. Alburger and Pryce[14] have observed that the threshold for the $Pb^{206}(d,3n)Bi^{205}$ reaction is at about 16 MeV. The bombardment lasted 14 h at 15-μA beam current, producing approximately 3 mC of Bi^{206}. The foil was then crumpled into a 1-cm-diam ball for insertion into the Be shells.

The photoneutron source was counted following the method discussed above in Sec. E. A count was made 12 h after bombardment and then daily for 6 days. One count was made 12 days and another 17 days after bombardment. Some short-lived activity containing high-energy gamma rays was present in the first count. After that the decay of both the gamma-ray and neutron activity was compatible with the 6.3-day half-life[10] of Bi^{206}. From the decay curves there was no clear evidence for the presence of any 15-day Bi^{205}, although, considering the errors, it could have been present with an abundance up to 6% of the counting rate on the fourth day after bombardment. The 1.720-MeV gamma-ray peak of Bi^{206} was not resolved from the weaker 1.596-MeV peak, necessitating a curve-peeling procedure in the spectrum analysis. In addition, a peak was observed at 1.9 MeV with an abundance 8.5% as great as the 1.720-MeV peak in the last two counts. The half-life of the 1.9-MeV gamma ray was from 3 to 6 days. Further work would be necessary before the 1.9-MeV gamma ray could be assigned to Bi^{206}. However, since it was present in our source spectrum, we made a correction for the photoneutrons it produced, assuming a cross section of 0.60 mb.[14a]

The result of the Bi^{206} experiment was that the ratio of $\sigma(\gamma,n)$ at 1.720 MeV to that at 1.692 MeV is 0.93 $\pm$0.05. The error was estimated from the spread in the results from several counts, including the uncertainty due to the presence of the 1.9-MeV gamma ray. Due to the weakness of the source and the complications arising from the gamma-ray spectrum, the measurement did not realize the full accuracy of which the comparison technique should be capable.

[14] D. E. Alburger and M. H. L. Pryce, Phys. Rev. **95**, 1482 (1954).

[14a] *Note added in proof.* Three new gamma transitions in Bi^{206} at 1.846, 1.880, and 1.904 MeV have recently been reported by R. Wiener, P. Harihar, and C. S. Wu, Bull. Am. Phys. Soc. **7**, 353 (1962).

G. Measurements using an Al^{28}-Be Source

Al^{28} is an ideal isotope for the present work, having only a 1.78-MeV gamma ray following beta decay. A solid sphere of high-purity aluminum the same size as the antimony source was activated to saturation in the Livermore Pool-Type Reactor. Since the half-life of the Al^{28} is only 2.3 min, it was necessary to work rapidly. This was accomplished by removing the source from the reactor by a pneumatic-tube delivery system. It was possible to begin counting in a remote laboratory within 2 min.

Neutrons and gamma rays were counted simultaneously using the method described above in Sec. E. To reduce the gamma-ray counting rate relative to the neutron counting rate, a collimator was placed in front of the NaI crystal. The collimator, a lead block with a 1.91-cm-diam hole, could be accurately aligned before the experiment by means of a sighting tube. Successive counts of several minutes each were made as the source decayed. The first one or two counting periods were discarded due to excessive gamma-ray counting rates. In two activations, a total of four counting periods were obtained with from 2000 to 5000 neutron counts each. A correction was made for analyzer dead time which ranged from 0 to 5%. For each counting period the ratio of neutron to gamma counts was computed. The runs were weighted by the neutron counting statistics and averaged. The root-mean-square deviation of the results of four runs from the average was 2.5%. The Sb-Be source was counted in the same geometry with good statistics, the rms deviation for three runs being 0.4%.

A 3% correction was applied for change in efficiency of the neutron counter as discussed above in Sec. E. No correction was made for the effects of bremsstrahlung from the beta particles stopping in the sources, since we estimate these effects to be negligible.

The ratio of $\sigma(\gamma,n)$ at 1.78 MeV to $\sigma(\gamma,n)$ at 1.692 MeV is found to be 0.67$\pm$0.03.

The energy of the Al^{28} gamma ray has been reported to be 1.782$\pm$0.010 MeV[15] and 1.769$\pm$0.010 MeV.[16] From the approximate slope of the excitation function at 1.78 MeV, a change of 10 keV in gamma-ray energy corresponds to a change of about 0.03 mb in cross section.

III. RESULTS AND DISCUSSION

The results are summarized in Table II.

The cross section measured with the Sb-Be source is in good agreement with the value 1.262$\pm$0.069 mb obtained by Gibbons *et al.*[8] The cross sections obtained with the Bi^{206} and Al^{28} sources are reported here for the first time. Recent measurements of the cross section on the peak near threshold using bremsstrahlung from electron accelerators are in agreement with the source

[15] H. T. Motz and D. E. Alburger, Phys. Rev. **86**, 165 (1952).

[16] R. K. Sheline, N. R. Johnson, P. R. Bell, R. C. Davis, and F. K. McGowan, Phys. Rev. **94**, 1642 (1954).

TABLE II. Measured cross sections for $Be^9(\gamma,n)$.

Gamma-ray source	E_γ (MeV)	$\sigma(\gamma,n)/\sigma_{1.692}(\gamma,n)$	$\sigma(\gamma,n)$ (mb)
Sb^{124}	1.692	$\cdots$	1.31 ± 0.08
Bi^{206}	1.720	0.93 ± 0.05	1.22 ± 0.11
Al^{28}	1.78	0.67 ± 0.03	0.88 ± 0.06

data reported here. Miller *et al.*[17] found a maximum cross section of 1.2 ± 0.1 mb at 1.69 MeV. Jakobson[5] obtained 1.15 ± 0.15 mb at 1.70 MeV. Due to the rapid fall of the cross section just above 1.7 MeV, our point at 1.78 MeV and the point of Gibbons *et al.* at 1.85 MeV are more accurate than the accelerator measurements.

Although the theory by Guth and Mullin[3] is probably outmoded by the theory of Francis, Goldman, and Guth[4] employing a diffuse well, it may be of some interest to determine to what extent the older theory agrees or disagrees with the experimental results. We have made some calculations using the current values of the parameters involved. The radii of the potential wells were chosen to be 3.92 F ($1F\equiv10^{-13}$ cm), the radius appropriate to a uniform model according to electron scattering measurements.[18] The well depth of the initial state necessary to give the observed binding energy of 1.667 MeV was found to be 18.4 MeV. The depth of the well for the final state was adjusted to give the ratio of the cross sections at $E_\gamma=1.692$ and $E_\gamma=1.78$ MeV found in the present experiment. The final well depth turned out to be 4.2 MeV. The magnitude of the cross sections calculated with the above parameters turns out to be too large. In order to obtain agreement with experiment, the theoretical values would have to be multiplied by a reduction factor of 0.4. Thus even with the reduction factor of 0.6 derived from Blair's theory[6] the calculation would not agree with experiment. The Guth and Mullin theory *can* be made to agree with experiment by reducing the radii of the potential wells to approximately 2.9 F and using Blair's reduction factor of 0.6.

Francis *et al.*[4] have calculated the cross sections on the single-particle model using the Woods and Saxon potential.[19] They have argued that the square-well approximation is not good since the results of their calculations are sensitive to the diffuseness parameter. In Fig. 3 the cross sections from the present experiment as well as the results of Gibbons *et al.*[8] are plotted. The curve is from the theory of Francis *et al.*[4,20] for a final-state diffuseness parameter of 0.6 F multiplied by a reduction factor of 0.56 to secure reasonable agreement with the experimental points. Without a reduction factor the diffuseness parameter required to obtain a fit to the data is greater than 1.2 F.

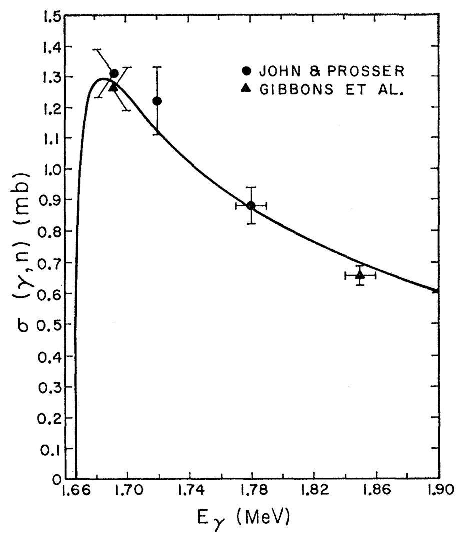

FIG. 3. Total cross section for the reaction $Be^9(\gamma,n)$ near threshold. The curve is the theoretical S-wave photoneutron cross section derived by Francis *et al.* for a final-state diffuseness parameter of 0.6 F. The theoretical values have been multiplied by a reduction factor of 0.56. As discussed in the text, Blair has calculated a reduction factor of 0.60 by introducing coupling to the Be^8 core.

Blair[6] pointed out that the cross sections calculated with a final-state diffuseness parameter of 0.6 F could be made to agree with experiment if coupling of the "valence" neutron to the Be^8 core were introduced. The ground state of Be^9 then contains an admixture of the first-excited core state (2+) as well as the 0+ core state. Only the latter contributes to the cross section just above threshold. In the extreme strong coupling model Blair finds that the single-nucleon cross sections should be multiplied by a reduction factor of $\frac{1}{2}$, while with a model involving band mixing he obtains 0.60 for the reduction factor. Figure 3 shows that the experimental data are in good agreement with the theory as modified by Blair.[21] However, the agreement is probably only significant in a semiquantitative sense due to the uncertainties associated with the models employed.

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[17] W. C. Miller, M. F. Shea, and R. L. Walter (private communication).

[18] R. Hofstadter, Revs. Modern Phys. **28**, 214 (1956).

[19] R. D. Woods and D. S. Saxon, Phys. Rev. **95**, 577 (1954).

[20] The curve was plotted from a table kindly supplied by Dr. Goldman and is similar to Fig. 1 of reference 4. The cross sections listed in Table I of reference 4 are in error according to Dr. Goldman.

[21] *Note added in proof.* For another derivation of the reduction factor with similar results, see F. C. Barker, Nuclear Phys. **28**, 96 (1961).