strahlung is about 35% of the charge bremsstrahlung at $k/E_0=0.9$ and about 1% at $k/E_0=0.1$. We note that the effect of finite nuclear size on the magnetic bremsstrahlung is more uniform, as a function of k/E_0, than for the charge bremsstrahlung. This is undoubtedly due to the extra factor of x multiplying R_{mag} in Eq. (1).

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Angular Distribution and Polarization of Neutrons from the $Be^9(p,n_0)B^9$ and $B^{11}(p,n_0)C^{11}$ Reactions*

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The angular distribution of neutrons from the $Be^9(p,n_0)$ B^9 reaction has been measured for the proton energies between 3.5 and 10.9 MeV and from the $B^{11}(p,n_0)$ C^{11} reaction at 7.1 and 8.2 MeV over the angular range of 0 to 150°. The polarization of the neutrons from the two reactions was measured for proton energies from 7 to 11 MeV and neutron emission angles between 0 and 80°. Both experiments employed the Livermore time-of-flight facility. Neither the angular distribution nor the angular dependence of the polarization of the $Be^9(p,n_0)$ B^9 neutrons changes appreciably with increasing proton energy, while for the $B^{11}(p,n_0)$ C^{11} reaction, both the angular distribution and polarization are quite energy-sensitive. These results are *not* in agreement with the twin-reaction hypothesis of Bloom *et al*.

INTRODUCTION

It has been pointed out by Bloom *et al.*[1] that a fruitful aspect of the direct-interaction mechanism is the investigation of the effective two-nucleon force in nuclei. It was also suggested[1,2] that a study of (p,n) reactions connecting the ground states of mirror nuclei would be a most useful method of performing this investigation. Furthermore, in this framework of direct interactions, reaction pairs such as $Be^9(p,n_0)B^9$ and $B^{11}(p,n_0)C^{11}$, $C^{13}(p,n_0)N^{13}$ and $N^{15}(p,n_0)O^{15}$, or $O^{17}(p,n_0)F^{17}$ and $Al^{27}(p,n_0)Si^{27}$ should be "twin" reactions.[2] That is, the interaction for each pair could be considered as taking place between the incoming (outgoing) particle and a nucleon or nucleon hole in the field of a doubly closed shell (or subshell) nuclear core. Assuming j-j coupling, the extracore nucleon or nucleon hole would be in a $p_{3/2}$ state for the Be^9-B^{11} pair, $p_{1/2}$ for the C^{13}-N^{15} pair, and $d_{5/2}$ for the O^{17}-Al^{27} pair.

Support for this twin-direct-reaction hypothesis was noted by Wong *et al.*[3] in their investigations of the ground-state neutrons from the $C^{13}+p$ and $N^{15}+p$ reaction pair employing time-of-flight detection techniques; in the proton energy range of 5 to 13 MeV, the many similarities of the (p,n_0) angular distributions and integrated cross sections are quite evident. The neutron polarization measurements by Walker *et al.*[4] also exhibited some similarities for the C^{13}-N^{15} pair for proton energies above 10 MeV. Further confirmation has been reported by Albert *et al.*[5] in comparing the relative angular distribution measurements of the Be^9-B^{11} pair obtained with a "long" counter for proton energies from threshold to 4.3 MeV.

Previous measurements of the angular distribution and polarization of the $Be^9(p,n)B^9$ neutrons have been performed by Kelsey *et al.*[6] from threshold to 4.1 MeV. The polarization measurements have since been extended by Kelsey[7] to 8.5 MeV. The study of the ground-state neutrons ($Q_0=-1.854$ MeV) from this reaction is complicated by the production of continuum neutrons predominantly from the four-body breakup process[8] $Be^9+p\rightarrow n+p+2\alpha(Q=-1.573$ MeV). In the experiments cited, the effect of these neutrons was reduced by suitable neutron energy discrimination. Using time-of-flight techniques, Marion and Levin[9] have determined the $Be^9(p,n_0)B^9$ excitation curves at 0 and

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[9] J. B. Marion and J. S. Levin, Phys. Rev. **115**, 144 (1959).

90° from 2.5 to 5.4 MeV and Cranberg[10] has measured the neutron polarization at an emission angle of 45° between 4.5 and 5.3 MeV. At the higher energies of interest in this work, the production of the continuum neutrons increases and time-of-flight methods are required to eliminate their contribution to the ground-state cross-section and polarization measurements.

The $B^{11}(p,n)C^{11}$ reaction has recently been investigated by Overley and Borchers[11] employing time-of-flight and proton-electron pulse-shape discrimination techniques. The relative angular distribution of the ground-state neutrons was measured for proton bombarding energies between 4 and 11 MeV.

In order to further test the twin-reaction hypothesis of Bloom *et al.*,[1,2] and to determine the usefulness of these reactions as a source of polarized neutrons, the angular distributions and neutron polarizations were measured for the $Be^9(p,n_0)B^9$ and $B^{11}(p,n_0)C^{11}$ reactions. The angular distributions for the Be^9 reaction were measured in the energy range from 3.5 to 10.9 MeV and for the B^{11} reaction at 7.1 and 8.2 MeV. The polarizations were determined from 7 to 11.4 MeV.

EXPERIMENTAL METHOD

Angular Distributions

The method and apparatus, including the time-of-flight electronics, employed to measure the angular distributions are described in a previous publication.[3] The beryllium target was prepared by evaporating the element on a 0.020-in. tantalum backing while the boron target (98% B^{11}) was made as a self-supporting colloidal suspension. Both targets were approximately 100-keV thick to 8-MeV protons and were mounted in a target changer designed to minimize neutron absorption (less than 5%) throughout the angular range between 0 and 150°.

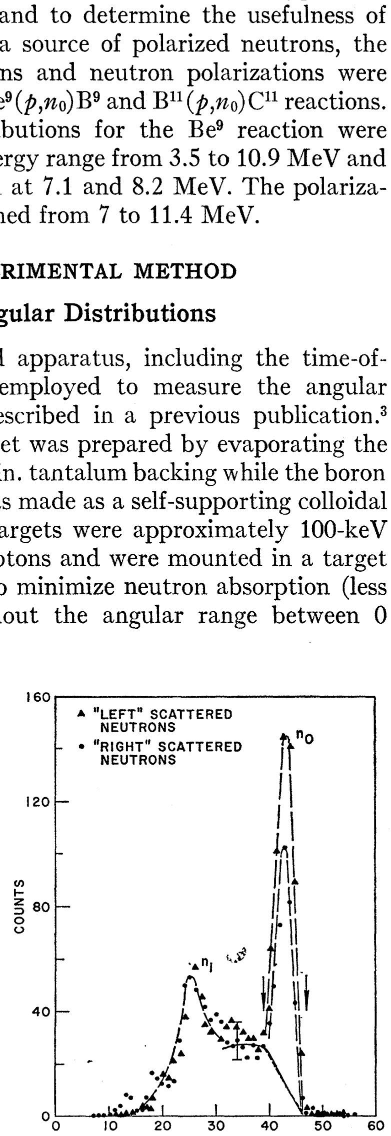


FIG. 1. Time-of-flight spectra of helium-scattered neutrons from Be^9+p for $E_p=8.1$ MeV, $\theta=30°$ (lab) with background subtracted. See text for notation.

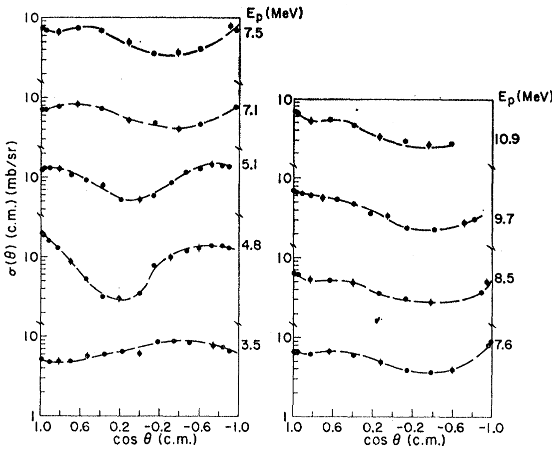


FIG. 2. Center-of-mass absolute differential cross sections for the $Be^9(p,n_0)B^9$ reaction versus laboratory bombarding energy.

Polarizations

The techniques employed in the determination of the neutron polarizations are also described in detail elsewhere.[4,12] Instead of performing the conventional left-right scattering measurements, the neutrons emerging from the target at the reaction angle θ with polarization[13] $P(\theta)$ were precessed by a solenoid magnet. The polarization of the neutrons was then determined from their measured asymmetry in scattering from a liquid-helium analyzer. The targets used for these measurements were fabricated in a manner similar to that described above. However, because of the higher intensity proton-beam currents required in these experiments, it was necessary to mount the boron suspension target on a suitable backing to permit the use of external cooling. The suspension was secured to the backing (0.040-in. gold) by an evaporated thin film ($\sim$100 $\mu g/cm^2$) of gold.[14]

Time-of-flight spectra of neutrons from Be^9+p at $E_p=8.1$ MeV and $\theta=30°$ for "left" and "right" scattering by helium are shown in Fig. 1. The scattering angle from helium was 60° (lab). The background spectra obtained with a blank analyzer in place have been subtracted. The peaks labeled n_0 identify the ground-state neutrons and n_1 those neutrons leaving B^9 in its first excited state (2.4-MeV level). The solid curve represents the expected four-body breakup spectrum in the region of the monoenergetic ground-state group. The low-energy portion of the measured continuum spectrum is sharply reduced because of the high bias employed in the polarization measurements. The net

[10] L. Cranberg, Helv. Phys. Acta Suppl. **6**, 324 (1961).

[11] We are indebted to Dr. J. C. Overley for sending us his results before publication. J. C. Overley and R. R. Borchers (to be published).

[12] B. D. Walker, Ph.D. thesis, Lawrence Radiation Laboratory (Livermore), UCRL-7676, 1964 (unpublished).

[13] The Basel convention [Proceedings of the International Symposium on Polarization Phenomena of Nucleons, Helv. Phys. Acta Suppl. **6**, (1961)] was used to determine the sense of the neutron polarization.

[14] We wish to express our gratitude to Marvin A. Williamson for the preparation of the targets.

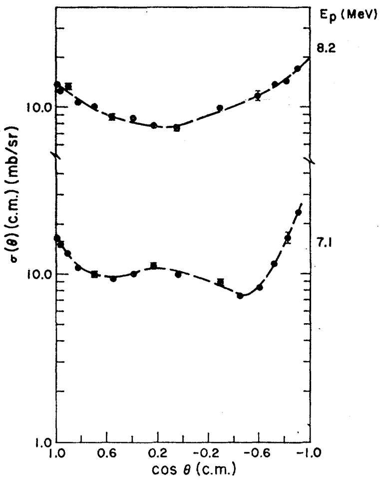


FIG. 3. Center-of-mass absolute differential cross sections for the $B^{11}(p,n_0)C^{11}$ reaction versus laboratory bombarding energy.

number of "left" and "right" helium-scattered neutrons was determined by summing over the peaks as indicated and subtracting the corresponding continuum background. To facilitate data analysis the continuum contribution was approximated by the dashed linear curve (Fig. 1).

RESULTS

Angular Distributions

The center-of-mass absolute differential cross sections $\sigma(\theta)$ for the $Be^9(p,n_0)B^9$ and $B^{11}(p,n_0)C^{11}$ reactions are displayed in Figs. 2 and 3. The two measurements for the $B^{11}(p,n_0)C^{11}$ reaction were used to provide an absolute normalization for the relative measurements of Overley.[11] The agreement in shape with the relative measurements is excellent in both cases. The Be^9 angular distribution at 3.5 MeV is in reasonable agreement with the "long" counter results of Albert *et al.*[5] and with the measurements of Kelsey *et al.*[6] The 0 and 90° differential cross sections at 3.5 and 5.1 MeV are also in good agreement with the Be^9 excitation functions determined by Marion and Levin.[9]

The errors shown reflect relative errors, and are an indication of the accuracy obtained in determining the shape of the angular distribution. Relative errors are compounded from counting statistics and from the reproducibility of the zero-degree cross section measured before and after an angular distribution measurement. Generally, relative errors were of the order of 5% or less, while absolute errors on the differential cross section were of the order of 10% or less. The absolute errors include the uncertainties involved in determining the continuum spectrum line shape below the ground state group for the Be^9 data. The proton energy spread, due to the beam energy loss in the targets and to the energy width of the beam, is about 1%.

Neutron Polarizations

The neutron polarizations $P(\theta)$ are shown plotted in the center-of-mass system in Figs. 4 and 5. Corrections for multiple scattering of the neutrons in the helium analyzer, calculated in the same manner as described in Ref. 4, have been applied. These corrections generally increased the measured asymmetries by 10%. The values used for the analyzing power of helium were computed[15] from Seagrave's[16] n-α phase shifts.

As a check on reproducibility, the neutron polarizations were measured in two angular sets of 20° steps. That is, the order taken for the reaction angle θ was 0, 20, 40, 60, and 80° followed by 70, 50, 30, 10, and another 0°. The zero-degree measurements were made since, at this angle, the polarization must vanish and a nonzero measurement would therefore indicate the presence of false asymmetries. Within statistics, a null value was consistently obtained. In addition to computing the polarization at each angle, the "left" and "right" measurements were averaged, corrected for the helium elastic-scattering cross sections and compared to the measured (p,n_0) angular distributions. Figure 6 represents a typical comparison for $B^{11}(p,n_0)C^{11}$, at $E_p=7.6$ MeV, normalized at $\theta=20°$. The good agreements with the known angular distribution, as well as the fact that the measurements from the two angular sets of θ indicated the same angular dependence for the

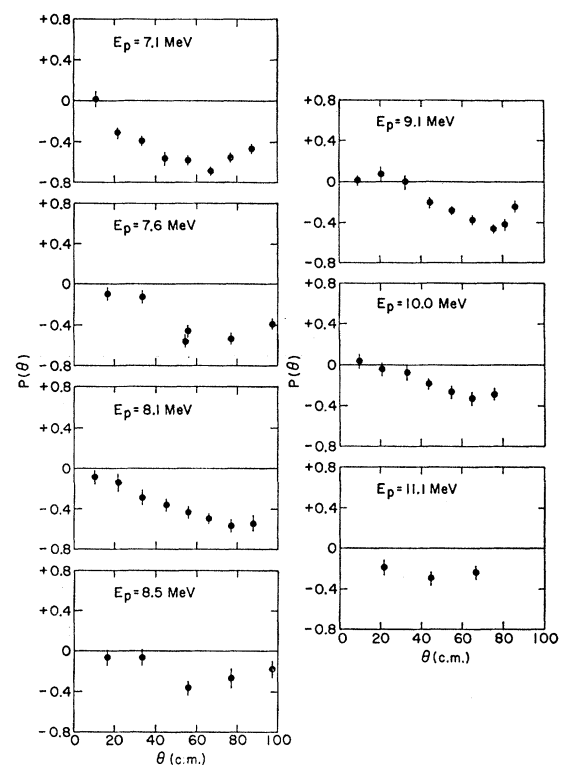


FIG. 4. Neutron polarizations for the $Be^9(p,n_0)B^9$ reaction versus laboratory bombarding energy.

[15] L. Stewart (private communication).

[16] J. D. Seagrave, Phys. Rev. **92**, 1222 (1953).

polarization, served as a check on the long-term stability of the electronic and associated equipment.

The errors shown on the magnitudes of $P(\theta)$ for the $Be^9(p,n_0)B^9$ reaction were compounded from both the statistical counting errors on the measured asymmetry and the uncertainties involved in estimating the contribution of the continuum neutrons to the ground-state peak (see Fig. 1). This line-shape error was assumed to be 25% of the continuum spectrum subtracted. Since the production of breakup neutrons in the region of the ground state group is forward peaked, the line-shape errors generally exceeded the statistical errors for $\theta<40°$. For the $B^{11}(p,n_0)C^{11}$ reaction the polarization errors were computed only from the statistical counting errors. The proton energy spread in these measurements was also about 1%.

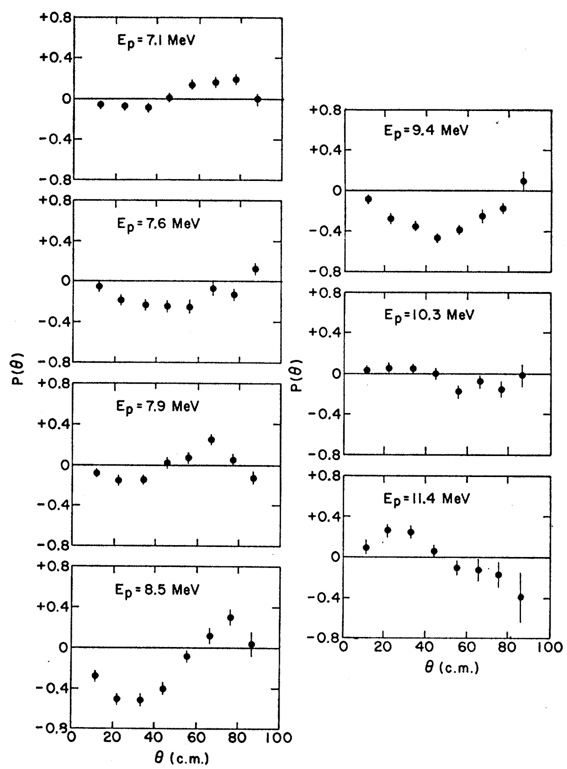
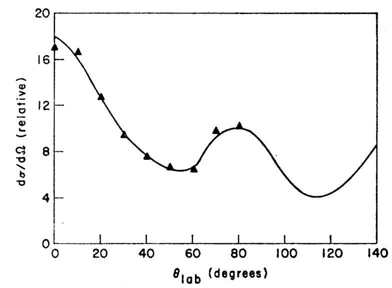


FIG. 5. Neutron polarizations for the $B^{11}(p,n_0)C^{11}$ reaction versus laboratory bombarding energy.

To compare these neutron polarization results with those reported by Kelsey,[7] the polarizations for the $Be^9(p,n)B^9$ reaction were also computed including the contribution of the continuum neutrons to the ground-state group. It was found that these values were generally higher in magnitude than those earlier reported by $\approx 20\%$. However, in all cases, agreement could be achieved by simply extending the lower limit from which the summation was made by a few (two to four) channels, i.e., including more continuum neutrons. This corresponds to enlarging the summation interval by 100 to 300 keV, and is in accordance with the observation of Kelsey[7] that the effective polarization measured for this reaction is quite sensitive to the discrimination or bias level employed.

FIG. 6. Comparison of the angular distribution measurements of Overley (Ref. 11) for the $B^{11}(p,n_0)C^{11}$ reaction (solid curve) with the averaged "left" and "right" scattering measurements for $E_p=7.6$ MeV and normalized at $\theta=20°$.



DISCUSSION

Figure 7 displays the features of both the integrated angular distributions $\sigma(E_p)$, and the polarization data $P(\theta,E_p)$ for the Be^9-B^{11} reaction pair. The closed circles represent the integrated angular distributions reported here, while the open circles are the relative measurements of Overley[11] normalized at 7.1 and 8.2 MeV. Contrary to the many similarities observed for the C^{13}-N^{15} pair,[3,4] it is clear that the Be^9-B^{11} pair does *not* yield the results one would expect from the twin reaction

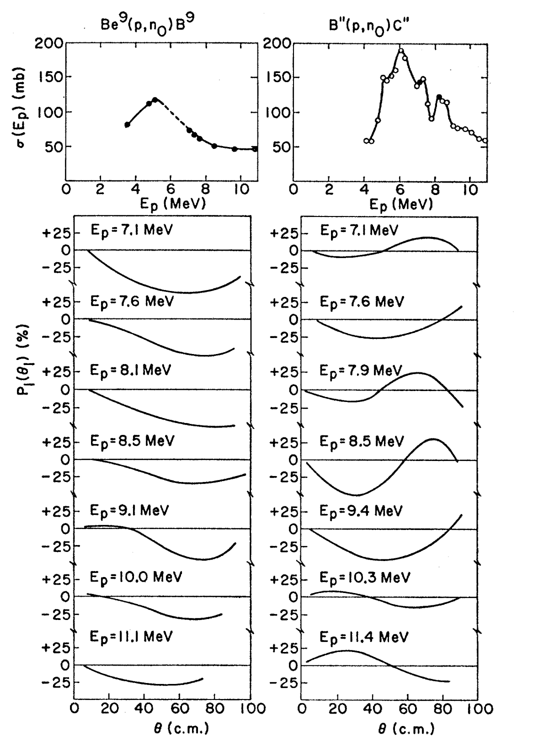


FIG. 7. Comparison of $\sigma(E_p)$ and $P(\theta,E_p)$ for the $Be^9(p,n_0)$ reaction with the $B^{11}(p,n_0)C^{11}$ reaction. See text for notation.

hypothesis of Bloom *et al.*[2] Over the proton energy range of these experiments, the $B^{11}(p,n_0)C^{11}$ reaction exhibits pronounced resonance structure of $\sigma(E_p)$ with corresponding fluctuating angular distributions (not shown) and polarizations. The $Be^9(p,n_0)B^9$ reaction, however, is characterized by a smaller cross section and, except for the region of 6 MeV (where measurements are lacking), appears to be free of any resonance structure. In addition, the angular distributions (see Fig. 2) and polarizations vary quite slowly with proton energy. It was pointed out in Ref. 5 that whereas some good experimental and theoretical grounds indicate that B^{11} may be regarded as having the structure characterized by a proton hole in a $p_{3/2}$ state, the model of the Be^9 nucleus, being a relatively inert Be^8 core with an extracore $p_{3/2}$ neutron, is perhaps hypothetical.

Finally, it should be mentioned that both reactions produce neutrons with appreciable polarizations in this energy region. However, the $B^{11}(p,n_0)C^{11}$ reaction would be comparatively more useful as a source of polarized neutrons, since besides being free of contaminating breakup neutrons, this reaction combines large polarizations with large differential cross sections. In particular, for $E_p=8.5$ MeV and $\theta=30°$, the $B^{11}(p,n_0)C^{11}$ reaction produces 5.5-MeV neutrons with a differential cross section of about 11 mb/sr and polarization of -0.5 ± 0.04.

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Total Cross Section for $^9Be(\alpha,n)$*

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The absolute total (4π) neutron yield from $^9Be(\alpha,n)$ has been measured for alpha energies from 1.7 to 10.5 MeV by extension of earlier measurements. In addition to previously reported states in ^{13}C, resonance peaks are observed corresponding to E_{ex} of 15.3 and 17.0 MeV. The widths for resonances at $E_\alpha=1.92$, 2.25, and 2.58 MeV are 0.2, 0.4, and 0.3 MeV, respectively. Near $E_\alpha=10$ MeV, reactions leading to states in ^{12}C apparently account for $<30\%$ of the observed cross section.

I. INTRODUCTION

THE last neutron in ^9Be is bound by less energy than in any other stable nucleus. This property and the nature of the remaining part of the nucleus (^8Be) has made studies of reactions involving ^9Be of special interest in nuclear-structure physics for many years. Neutrons from $^9Be(\alpha,n)$ have been studied in a variety of ways in an effort to understand the direct versus compound-nucleus contributions to the reaction yield. Several years ago[1] we reported total cross section results for the range $2.5<E_\alpha<8.5$ MeV. The total cross section, *per se*, does not shed much light upon the reaction mechanism, but it is a helpful aid when combined with other measurements. The large value and high Q of the cross section for (α,n) have caused some concern about the use of beryllium in structures of space vehicles which may encounter energetic solar helium nuclei. It was for these several reasons that we undertook the additional measurements reported in this paper.

II. EXPERIMENTAL

The equipment used was substantially the same as that described in an earlier report.[1] We used singly and doubly charged alpha-particle beams from the ORNL 5.5-MV Van de Graaff accelerator, evaporated Be metal targets on Pt backings, and the graphite sphere 4π neutron detector.[2] In extending the reaction to $E_\alpha=10.5$ MeV, the range of constant efficiency ($\pm5\%$) of the neutron detector is potentially considerably exceeded. However, the cross section leading to the ground and first three excited states of ^{12}C has been measured.[3,4] Using these results and our computed efficiency curve,[2] we calculated a correction of $+20$ mb (or 3%) at the highest energy point. The states of higher excitation yield neutron groups averaging within the constant efficiency region of the detector (i.e., 0–5.7 MeV for $\pm5\%$ constancy) for our alpha-particle energy range. An over-all uncertainty of $\pm6\%$ for the corrected cross section is suggested.

* Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

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[2] R. L. Macklin, Nucl. Phys. **1**, 335 (1957); and unpublished calculations.

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[4] V. V. Verbinski (private communication).