Corrections to the $^{11}B(p,\gamma_0)^{12}C$ cross section and its implications

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We have performed two independent measurements of the $^{11}B(p,\gamma_0)^{12}C$ reaction over the energy range of $E_p = 5-14$ MeV. The two measurements are in good agreement with each other and indicate that the previously accepted results are in error. The new values for the γ_0 cross section reported here resolve several outstanding conflicts. Their implications are discussed.

[NUCLEAR REACTIONS $^{11}B(p,\gamma)^{12}C$, $5 \le E_p \le 14$ MeV; measured E_γ, absolute cross sections for $d\sigma/d\Omega$ (90°, E_{γ_0}), $d\sigma/d\Omega$ (90°, E_{γ_1}).]

INTRODUCTION

There have been four reported absolute measurements[1–4] of the $^{11}B(p,\gamma_0)$ cross section in the region near and above the giant dipole resonance of ^{12}C, and these differ by up to a factor of 2. The first measurement by Allas *et al.*[1] covered the region from 4 to 14 MeV in proton energy. In the subsequent work of Brassard *et al.*[2] the cross sections at several energies in this range were remeasured and the data were extended to $E_p = 21$ MeV. However, these authors[2] claimed that the cross sections reported by Allas *et al.*[1] were too high and should be multiplied by a factor of 0.61. In a third paper,[3] the Stanford group remeasured the γ_0 cross section near the peak of the giant resonance ($E_p = 7.2$ and 8.0 MeV) and claimed that the Allas *et al.*[1] data should indeed be scaled down, but only by a factor of 0.9. Finally, Suffert[4] presented a combined version of the Allas *et al.*[1] and Brassard *et al.*[2] cross sections, renormalized by a combination of the Stanford measurements[3] and independent measurements at Strasbourg. The normalizing factor used in Ref. 4 was about 0.8 at $E_p = 6.0$ MeV and increased to 1.0 at $E_p = 11.0$ MeV, still leaving a large discrepancy with Brassard *et al.* at the higher energies.

In this paper we report the results of two new measurements of the absolute cross section for the $^{11}B(p,\gamma_0)^{12}C$ reaction. These measurements were performed independently in two different laboratories using high-resolution large NaI spectrometers. The results of these measurements are in good agreement and indicate that, despite previously raised objections,[3,4] the renormalizing factor that must be applied to the Allas *et al.*[1] data is indeed 0.6 at $E_p = 14$ MeV, as had been suggested in Ref. 2. However, this factor is energy dependent and increases to 0.8 near the peak of the giant resonance. (The measurement of Ref. 3 at $E_p = 7.2$ MeV overlaps our value at this energy, within error estimates.) These results affect several previously published experiments which had been normalized to the earlier $^{11}B(p,\gamma_0)$ data. Some of the implications are discussed below.

EXPERIMENT

The measurements performed at TUNL employed a 25.4×25.4 cm NaI detector having a plastic anticoincidence shield. This detector system, described in detail in Ref. 5, is shown schematically in Fig. 1. Spectra were taken at 90° for proton energies between 7.25 and 14.0 MeV; a typical one is shown in Fig. 2. The efficiency of this detector system was determined by employing the $^{12}C(p,\gamma_0)^{13}N$ reaction in the vicinity of $E_p = 14.24$ MeV. A yield curve at 125° (a zero of P_2) using a thick target (1.5 mg/cm^2) determines the efficiency since the number of γ's per proton $(6.83 \pm 0.22) \times 10^{-9}$ is well known for the 15.07 MeV resonance in ^{13}N.[6] The spectra obtained in this calibration run were fitted using a standard line shape[5] and integrated over the main region of the peaks. More precisely, the line shape fitting program extracted a centroid and a width for the peak of interest and then summed the experimental data from the high energy edge of the peak to a point two widths below the centroid. The same procedure was then used in extracting peak areas

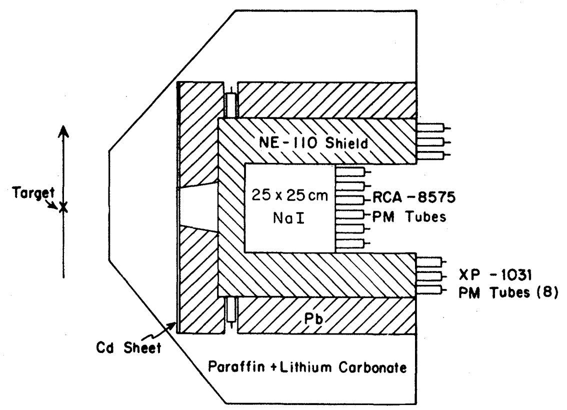

FIG. 1. Schematic of the TUNL γ-ray detection geometry. The shielding in front of the detector consisted of 20.3 cm of paraffin-plus-lithium carbonate (50% mixture by weight), followed by an active plastic scintillator 7.6 cm in thickness.

from the ^{11}B(p,γ_0)^{12}C spectra. The solid curve in Fig. 2 shows the result of a fit to the γ_0 peak using the TUNL standard line shape. With the shielding and rejection setup used in the experiment, the above procedure yielded an efficiency of (21.2$\pm$1.2)% for 15.1 MeV γ rays. (The solid angle has been taken out of this number.) In order to obtain the efficiency in the energy range of the present experiment, it was necessary to know the energy dependence of the attenuation due to the shielding material in front of the detector, and the energy dependence of the accept-reject ratio. These factors were measured by using the ^{3}H(p,γ)^{4}He and the ^{13}C(p,γ)^{14}N reactions as sources of γ rays in the

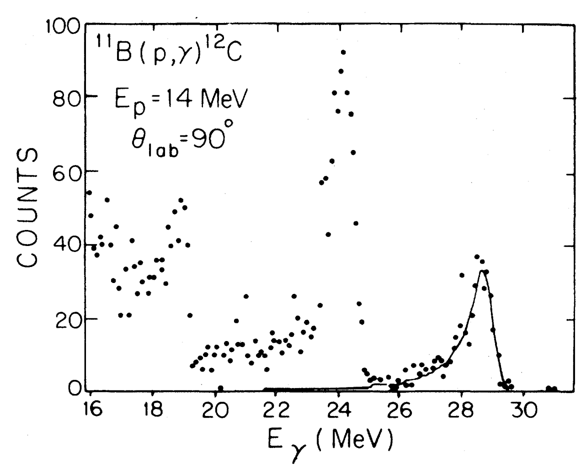

FIG. 2. The ^{11}B(p,γ)^{12}C spectrum obtained with the TUNL-NaI assembly at E_p=14.00 MeV and θ_γ^{lab}=90°. The solid line represents the intrinsic line shape for the ground state (γ_0) transition (see text).

energy range of interest. Spectra were taken with shielding in and out, and both accepted and rejected peak areas were determined. (Spectra taken with a similar system using monochromatic photons at 15 and 31 MeV show that the fraction of the full response in this region of the spectrum is the same at 15 and 31 MeV.[7] This has, in fact, been verified throughout the region of E_γ from 20.5 to 28.8 MeV in the BNL measurements described below.) This procedure was used to obtain an efficiency factor as a function of E_γ which varied from (20.8$\pm$1.5)% to (18.5$\pm$1.5)% over the energy region of E_γ=20$-$30 MeV.[5] The resulting efficiencies were verified by comparing the deduced cross sections with other (p,γ), (γ,p), and (γ,d) data. For example, the ^{3}H(p,γ) data obtained with these efficiencies are in excellent agreement ($\sim$5%) with those of Meyerhof *et al.*[8] for E_γ ranging from 26 to 33 MeV. (We have also compared these efficiencies against those obtained using the technique of integrating the line shape down to zero energy and accounting explicitly for the measured attenuation of the shielding material. This comparison has, for example, given agreement to within 5% at E_γ=26.5 MeV.[8])

The targets used in the TUNL measurements were prepared by evaporating 98.05% enriched ^{11}B to provide self-supporting foils. The target thickness was measured in several ways. First, the energy loss of the 5.5 MeV alphas from an ^{241}Am source was used to compute a foil thickness. Second, the elastic scattering of 2 MeV protons at θ_p=6° was measured and a target thickness obtained assuming Rutherford scattering. The results of these measurements (which agreed to within 6%) give a foil thickness of 480$\pm$30 μg/cm. As an additional check, the elastic scattering of protons from ^{11}B at E_p=10 MeV was measured. The results obtained assuming the above target thickness agreed with the previously reported cross section for this reaction[9] to within 10%. Considering all factors, the overall uncertainty in the TUNL absolute cross sections is estimated to be 10%.

The main source of controversy[1-4] between the Allas *et al.* and Brassard *et al.* measurements has revolved around the corrections for γ-ray absorption in the various thicknesses of paraffin that were used in front of the detectors to reduce the high NaI counting rates due to neutrons. The measurements performed at BNL employed a 23.8$\times$25.4 cm NaI detector (BNL-MARK II). The gain of this detector is controlled by transistor-stabilized photomultipliers and monitored by an externally stabilized light-emitting diode (LED) which injects light into each of the NaI phototubes through a system of fiber optics.[10] The detector is capable of functioning reliably at high counting rates and because of this it was possible to remove all material between the ^{11}B foil and the NaI crystal, saving only the 0.05 cm Ta wall of the vacuum chamber and the 0.16 cm Al radiation window of the NaI hermetic can. As shown schematically in Fig. 3, a conical lead aperture projected the solid angle cone subtended at the target onto an area significantly less than the back face of the NaI crystal. (To obtain the total γ-ray yield in each measurement, the plastic anticoincidence shield was *not* used.) The target beam dump was biased to $+300$ V to prevent the loss of secondary electrons.

A typical ^{11}B(p,γ) spectrum obtained with this geometry is shown in Fig. 4(a). The indicated resolution is about a factor of 2 better than in the previous measurements reported in Refs. 1 and 2. The dashed curve in Fig. 4(a), the intrinsic line shape fitted to the γ_0 line, is the sum of a Gaussian (describing the region of the peak) and two exponentials parametrizing the tail (see the Appendix). The line shape of γ_0 is well defined for at least 3.5 MeV below its centroid. This enables the counts due to the small γ_1 peak to be accurately defined to at least 7.9 MeV below the γ_0 centroid. The remaining uncertainty in the γ_0 line shape below this point is due to the presence of an exponentially falling background arising mainly from the pileup of low energy gamma rays. Figure 4(a) shows fits for two extreme choices of this exponential background (solid and dotted curves). The variation in the total γ_0 yield (peak + tail) from these two fits is 1.2%. This line shape [dashed curve of Fig. 4(a)], again combined with a small exponential background, produced an excellent fit from 8 MeV up to the 20.5-MeV-γ_0 peak obtained from the ^{3}H$(p,\gamma_0)^4$He reaction at $E_p=1.00$ MeV [dashed curve in Fig. 4(b)]. The dotted-dashed curve in Fig. 4(b) shows a line shape obtained by artificially reducing the exponential background below the level of the data

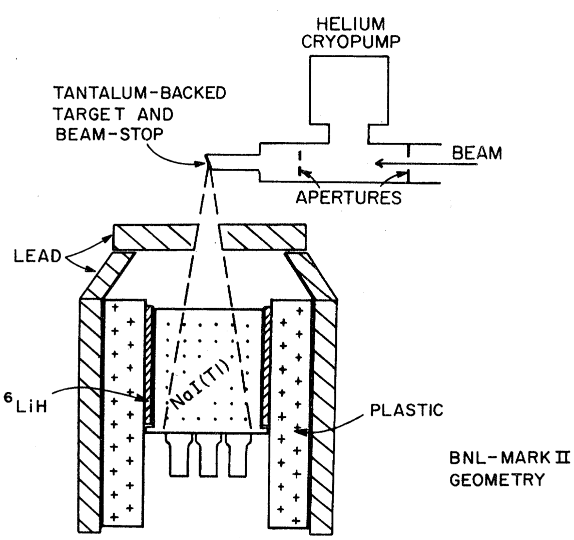

FIG. 3. Schematic of the BNL γ-ray detection geometry.

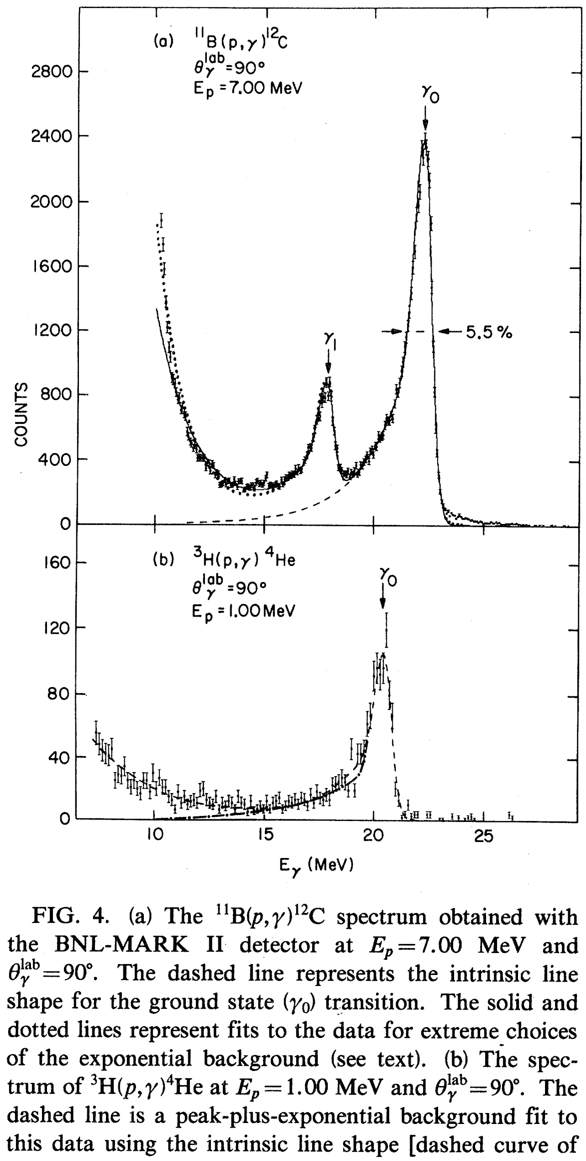

FIG. 4. (a) The ^{11}B$(p,\gamma)^{12}$C spectrum obtained with the BNL-MARK II detector at $E_p=7.00$ MeV and $\theta_\gamma^{\text{lab}}=90°$. The dashed line represents the intrinsic line shape for the ground state (γ_0) transition. The solid and dotted lines represent fits to the data for extreme choices of the exponential background (see text). (b) The spectrum of ^{3}H$(p,\gamma)^4$He at $E_p=1.00$ MeV and $\theta_\gamma^{\text{lab}}=90°$. The dashed line is a peak-plus-exponential background fit to this data using the intrinsic line shape [dashed curve of (a)]. The dotted-dashed curve represents a line-shape fit in which the contribution of the γ_0 tail was increased by artificially holding fixed the exponential background at a level below the data (see text).

and increasing the contribution of the tail. This exercise increased the total number of counts from $^{3}H(p,\gamma_0)$ by 7%, but could *not* produce a fit to the $^{11}B(p,\gamma)$ spectrum of Fig. 4(a). This is consistent with the analysis of potential errors in tail integration presented by Suffert.[4]

All of the BNL-$^{11}B(p,\gamma)$ spectra were fitted to the sum of an exponentially decaying background and two peaks (γ_1 and γ_0). The width of the Gaussian part of each peak was scaled with $[7.0/E\ (\mathrm{MeV})]^{-1/2}$, while all other parameters of the intrinsic line shape shown in Fig. 4(a) were held fixed. The total number of γ rays observed in each measurement was obtained by integrating the γ-ray peaks down to zero energy. We estimate the uncertainty in this procedure to be less than 8%. The ^{11}B target used in these measurements (98.6% isotopically enriched) was evaporated onto a Ta backing and its thickness measured with a crystal-deposition monitor. This thickness was checked by measuring the $^{11}B(p,\gamma_0)$ yield from this target and from a self-supporting ^{11}B foil under identical conditions. The thickness of the latter was deduced from the energy loss of 5.5 MeV alphas from an ^{241}Am source. The deduced values for the thickness of the target used in the BNL measurements reported here agree to within 2% ($716\pm30\ \mu g/cm^2$). Considering all factors, we estimate an overall uncertainty in the BNL absolute cross sections of less than 10%.

NEW RESULTS

The results of the two new measurements are shown in Fig. 5(a) along with the two data sets previously published in Refs. 1 and 2. In the case of Ref. 2 (Brassard *et al.*), their prescription of taking 0.61 times the data of Ref. 1 in the energy range of 7–14 MeV was used to generate the dotted-dashed curve. The present results are in good agreement with the data of Ref. 2 at 14 MeV, but indicate that the factor 0.61 does not hold at lower energies. In fact, the present results indicate an almost linear energy dependence for the correction factor [Fig. 5(b)] to be applied to the data of Allas *et al.*,[1] varying from 0.87 at 5.0 MeV to 0.6 at 14 MeV. The solid curve in Fig. 5(a) (proposed result) was generated by applying this energy dependent correction factor to the yield curve of Ref. 1.[11] The "renormalized" cross section presented by Suffert[4] is in good agreement with our data near $E_p=6.0$ MeV but differs drastically at higher energies. The absolute cross-section scale of the $^{11}B(p,\gamma_0)$ data of Snover *et al.* (Ref. 12) was normalized to Ref. 1 at $E_p=7.0$ MeV

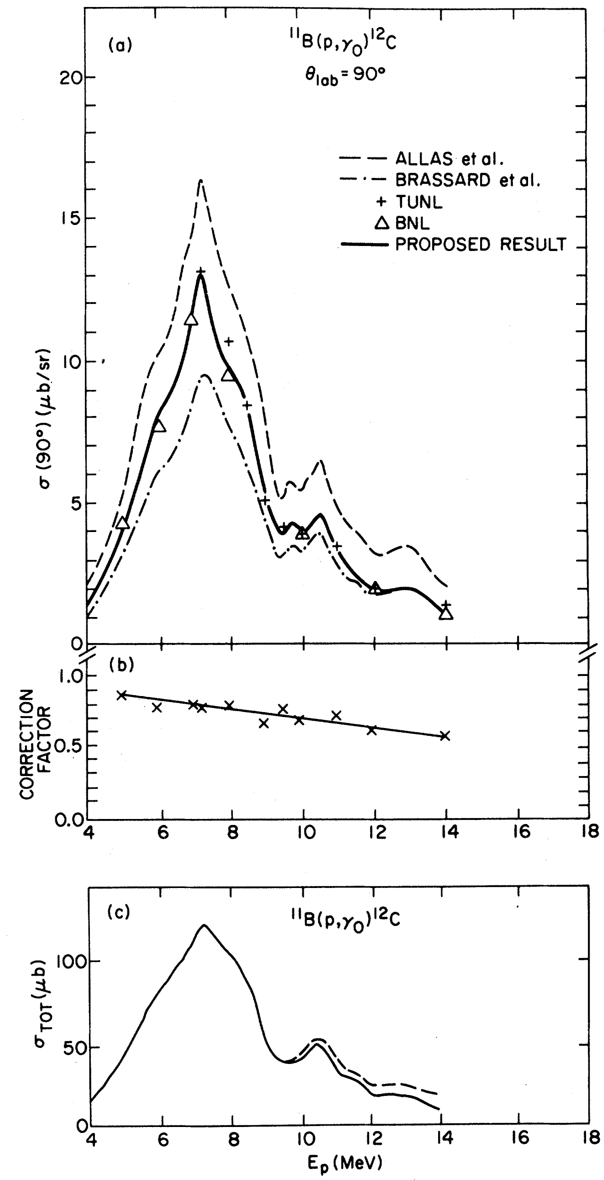

FIG. 5. (a) The $^{11}B(p,\gamma_0)^{12}C$ differential cross section at $\theta_\gamma^{lab}=90°$. The proposed result (solid curve) is obtained by applying the correction factor shown in (b) to the data of Ref. 1 (see Ref. 11). The total cross section, shown in (c) as the solid line, was constructed from the proposed result in (a) and the a_2 and a_4 angular distribution coefficients of Ref. 1. The dashed curve in (c) is the total cross section from Ref. 1.

and $\theta_\gamma^{lab}=90°$. If these data are scaled down by our correction factor of 0.8 for $E_p=7.0$ MeV, they then agree with the proposed result of Fig. 5(a) near the peak of the giant resonance, but lie between our results and those of Allas *et al.*[1] at higher energies.

The experimental differences among the earlier

$^{11}B(p,\gamma_0)$ measurements[1–4,12] (potentially arising from γ-ray attenuation in neutron absorbers, and from differences in intrinsic line shapes and peak stripping procedures) are not likely to vary as a function of angle at a fixed bombarding energy. Indeed, the angular distribution coefficients extracted by Allas *et al.*[1] are in good agreement with the later data of Snover *et al.*[12] at $E_p = 12.4$ MeV. The proposed yield curve [Fig. 5(a)] has been combined with the a_2 and a_4 coefficients of Ref. 1 to produce the total γ_0 cross section shown as the solid curve in Fig. 5(c). The dashed curve is the total cross section reported in Ref. 1. [As already noted,[11] the differences between the solid and dashed curves in Figs. 5(a) and (c) are not consistent.]

Our $^{11}B(p,\gamma_1)^{12}C$ cross sections are shown in Fig. 6 and deviate significantly from the yield curve reported by Allas *et al.*[1] (solid line) above $E_p = 10$ MeV. Some of the discrepancy between the TUNL and the BNL γ_1 data can be attributed to the rapid energy dependence of the cross section in this channel. However, there does appear to be a residual discrepancy of about 15%. We attribute this to the difference in the procedures used in spectrum stripping and background subtraction. These differences are more problematic for the $^{11}B(p,\gamma_1)$ cross section since the area under the γ_1 peak includes a contribution from the tail of the γ_0 line, and since the γ_1 peak is closer to the exponentially falling background arising from the pileup of low energy gamma rays.

IMPLICATIONS

The corrected cross sections for the $^{11}B(p,\gamma_0)^{12}C$ reaction shown in Fig. 5(a) have several ramifications. A result which should be reexamined in light of these new data is the ratio of the $^{12}C(\gamma,p_0)$ to the $^{12}C(\gamma,n_0)$ cross sections as a function of energy. In the review paper of Hanna,[4] this ratio was formed using data in Ref. 1. This produced a ratio for the 90° (γ,p) and (γ,n) cross sections near 2.0 at $E_x = 23$ MeV and around 1.7 for E_x in the 25–35 MeV range. This limiting value appeared to be in serious disagreement with theoretical estimates.[13] However, using the $^{12}C(\gamma,n_0)^{11}C$ cross sections of Wu *et al.*,[14] and our new $^{11}B(p,\gamma_0)^{12}C$ data (after detailed balancing), we obtain a ratio as shown in Fig. 7 (solid line). This ratio now approaches 1.0 near $E_x = 30$ MeV, in agreement with the calculation of Birkholz[13] (open circles in Fig. 7). (This is reminiscent of the most recent results in ^4He which indicate a ratio of around 1.8 near $E_x = 25$ MeV and a fall to 1.0 near 34 MeV.[15]) As another example, the revised cross sections shown in Fig. 5(a) affect the amount of $E2$ strength deduced from the $^{11}B(\vec{p},\gamma_0)^{12}C$ reaction using polarized protons.[16] In the work reported in Ref. 16 the percentage of the cross section due to $E2$ radiation was extracted from polarized and unpolarized angular distribution data. The absolute $E2$ cross sections were obtained

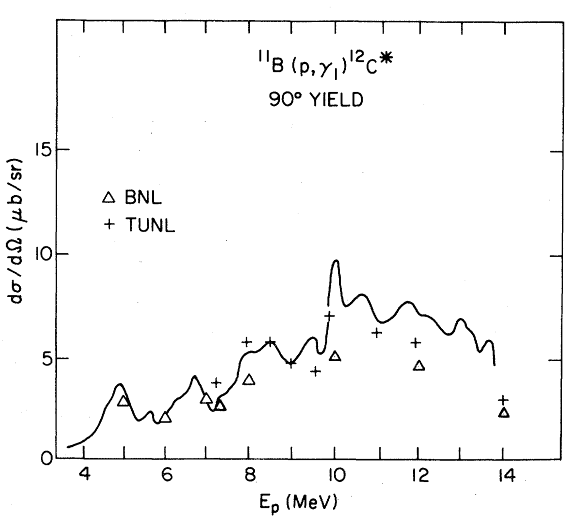

FIG. 6. The $^{11}B(p,\gamma_1)^{12}C$ differential cross section at $\theta_\gamma^{lab} = 90°$. The solid curve is taken directly from Ref. 1.

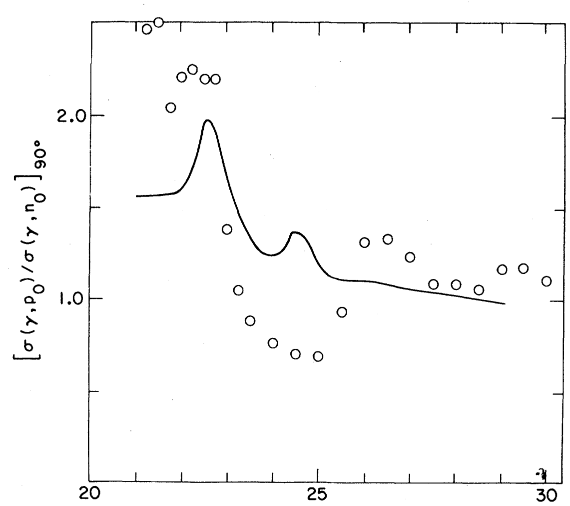

FIG. 7. The ratio of the 90° differential cross section for $^{12}C(\gamma,p_0)^{11}B$, deduced from the proposed result shown in Fig. 5(a), and the cross section for $^{12}C(\gamma,n_0)^{11}C$ taken from Ref. 14. The calculations of Ref. 13 are shown as open circles.

by assuming the *total* cross sections of Ref. 1 [dashed line in Fig. 5(c)]. A total of about 50% of the $E2$ energy-weighted sum rule, $S(E2)$, was deduced from these measurements. This appears to be in conflict with the $^{12}C(\alpha,\alpha'x)$ measurements reported in Ref. 17 which placed an upper limit of 15% on the total $S(E2)$ exhausted in all decay channels, and less than 4% exhausted in the p_0 channel alone. With the corrections of this work, the results of Ref. 16 must be scaled down by the ratio of the solid and dashed lines in Fig. 5(c). The corrected $E2$ cross sections are shown in Fig. 8, and imply that the percentage of the $E2$ sum rule exhausted in this channel is about 40% if the data points are used, and around 12% if the lower error limits are used. While this lower limit value is somewhat closer to the $(\alpha,\alpha'p_0)$ data of Ref. 17, the one-standard-deviation values for the cross sections still imply a disagreement. Of course, the origin of this discrepancy may be in the fact that the capture experiment can sample both isoscalar and isovector $E2$ strength while the α scattering measurements are sensitive to only isoscalar components.

The data of Ref. 1 have been used as a calibration standard for absolute γ-ray detection efficiencies, and the errors associated with this work affect a number of other previously published works (e.g., Refs. 18–24—which are not necessarily exhaustive). For example, the $^{12}C(\gamma,p)^{11}B$ measurements of Carchon *et al.*[23] claim to agree, after detailed balance, with *all* of the Allas *et al.* data, scaled down by the factor of 0.9 suggested in Ref. 3. However, these measurements assumed that all transitions left the ^{11}B nucleus in its ground state. This was justified by the results of Medicus *et al.*,[24] who claimed that 90% of the proton decay is in the p_0 channel. However, Medicus *et al.*[24] measured $\sigma(\gamma,p_{i\neq 0})$ and $\sigma(\gamma,n_0)$ and deduced $\sigma(\gamma,p_0)$ from the $\sigma(\gamma,p_0)/\sigma(\gamma,n_0)$ ratio presented by Wu *et al.*[14] Wu *et al.*[14] constructed this ratio from their data and those of *Allas et al.*[1] The claim of Carchon *et al.*[23] is thus based on a circular argument. For future experiments we recommend that, wherever possible, values near the peak of the excitation function shown in Fig. 5(a) be used for normalization. The result of this work is $d\sigma/d\Omega(90°) = 13.1 \pm 1.3$ μb/sr at $E_p = 7.25$ MeV.

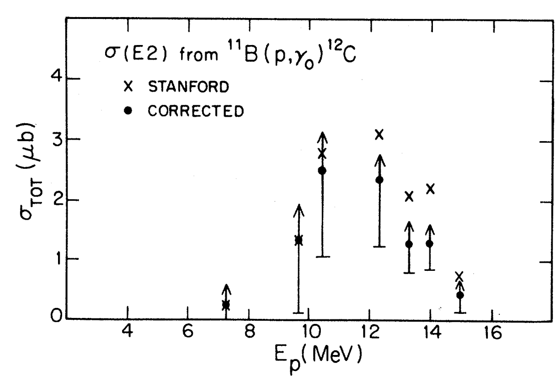

FIG. 8. The $E2$ cross section obtained from $^{11}B(\vec{p},\gamma_0)^{12}C$ measurements (Ref. 16) using the present results to correct the absolute scale.

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APPENDIX

In the BNL measurements, the line shape, as a function of channel number x, for a peak with centroid I, is parametrized as the sum of two components, a Gaussian $P(x)$ and a tail $T(x)$, defined as

$$P(x) = \frac{A}{B\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left[\frac{x-I}{\sigma B}\right]^2\right],$$

$$T(x) = C\frac{A}{B}\exp\left[D\left[\frac{x-I}{B}\right]\right] \times \left\{1-\exp\left[-\frac{1}{2}\left[\frac{x-I}{\sigma G B}\right]^2\right]\right\}, \quad \text{for } x < I ;$$

$$T(x) = 0, \quad \text{for } x \geq I .$$

Here, A is the area of the Gaussian part of the peak and 2σ is its associated width. C and D are parameters that define the exponential tail, and G defines how this tail smoothly merges with the Gaussian. During a line-shape fit A, I, σ, C, D and G are allowed to vary. B is unity when extracting the line shape from a single peak, and is $(I/I_0)^{1/2}$ when stripping the area out of a peak with the line-shape parameters determined from a peak at I_0. The latter scaling factor reflects the fact that the resolution decreases as roughly $(E_\gamma)^{-1/2}$.

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