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α decay of the $T = 1, 2^+$ state in ^{10}B and isospin symmetry breaking in the $A = 10$ triplet

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The rate of the $T = 1, 2^+$ to $T = 1, 0^+$ transition in ^{10}B ($T = 1, T_z = 0$) is compared to the analog transitions in ^{10}Be ($T = 1, T_z = -1$) and ^{10}C ($T = 1, T_z = +1$) to provide constraints on *ab initio* calculations using realistic nuclear forces. The relevant state in ^{10}B, at $E_x = 5.164$ MeV, is particle unbound. Therefore, a determination of the $B(E2)$ electromagnetic transition rate requires a precise and accurate determination of the width of the state, as well as the α-particle and γ-ray branching ratios. Previous measurements of the α-particle branching ratio are just barely in agreement. We report on a new study of the α-particle branch by studying the ^{10}B$(p,p')^{10}$B* reaction in inverse kinematics with the HELIOS spectrometer. The α-particle branching ratio that we observe, 0.144 ± 0.027, is in good agreement with the evaluated value and improves the associated uncertainty. The resulting experimental $B(E2)$ value is 7.0 ± 2.2 e^2fm^4 and is more consistent with a flat trend across the $A = 10$ triplet than previously reported. This is inconsistent with Green's function Monte Carlo predictions using realistic three-nucleon Hamiltonians, which overpredict the $B(E2)$ value in ^{10}C and ^{10}B.

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The extension of *ab initio* calculations to systems involving more than just a few nucleons is a challenging attempt to understand nuclear structure from a "first principles" standpoint. The scope of the effort is highlighted by the number of techniques that are being implemented [1–6]. The calculations have been used to successfully reproduce various aspects of nuclei, such as binding energies, RMS radii, and electromagnetic transition rates. Recent studies [7–9] have provided data on $B(E2, 2_1^+ \rightarrow 0_1^+)$ electromagnetic transition rates in ^{10}C and ^{10}Be to test predictions of charge-symmetry breaking from variational Monte Carlo (VMC) and Green's function Monte Carlo (GFMC) calculations. The experimental results for the $B(E2)$ in both ^{10}Be and ^{10}C were found to be quite similar, and the corresponding value for ^{10}Be was in reasonable agreement with the GFMC calculation. The calculations, however, consistently predict a significant increase in the $B(E2)$ for ^{10}C compared to ^{10}Be that is inconsistent with the experimental results. To determine whether the discrepancy between the GFMC prediction seen in ^{10}C persists in ^{10}B, a precise measurement of the analogous γ-ray transition rate in ^{10}B is required.

The corresponding transition in ^{10}B is between the $T = 1$, 2^+ (5.164 MeV) and 0^+ (1.704 MeV) states. The total width of the 2^+ state, $\omega\gamma = 387 \pm 27$ meV, is known to 7% [10]. The γ decay of the 2^+ level is dominated by $M1$ transitions to 1^+ states at 0.718 and 2.154 MeV, as shown in Fig. 1. Also, the 2^+ state is above the α-decay threshold, but since the α decay is isospin forbidden and has a hindered rate, α decay and γ decay will compete. Therefore, to determine the relevant $B(E2)$ in ^{10}B, both α-decay and γ-decay branching ratios must be known. To reach a total uncertainty of 10%, the current evaluations of the α and the relevant γ branching ratio are insufficient [11]. McCutchan *et al.* [9] improved the determination of the pure $E2$ partial γ-decay branch, previously evaluated with an upper limit of <0.5%, reporting a branching ratio of 0.16(4)%. The current evaluation of the α branch is based on two results that only marginally agree; their weighted average carries an uncertainty of 25%.

Table I summarizes the previous measurements of the α-particle branching ratio for the 5.164 MeV state in ^{10}B. The 5.164 MeV state was firmly established as the $T = 1$ isobaric analog to the first excited states of ^{10}Be and ^{10}C in a study of ^{6}Li$(\alpha,\gamma)^{10}$B by Sprenkel, Olness, and Segel [12]. Since then, three measurements of Γ_α/Γ for this state have been made. Riley *et al.* [13], using the ^{9}Be$(d,n)^{10}$B reaction, observed no α decay for the 2^+, $T = 1$ state. Alburger *et al.* [14] used the ^{11}B$(^3$He$,\alpha)^{10}$B reaction, and observed α-α and α-γ coincidences, with a result of 0.13 ± 0.04 for Γ_α/Γ. Finally, Segel *et al.* [15] obtained a less precise value of 0.27 ± 0.15 from a pure γ-ray experiment with the α branch inferred from the total integrated γ-ray yield. Here, we present a new determination of the α-particle branch of the 5.164 MeV state from a study of the ^{10}B$(p,p')^{10}$B* reaction in inverse kinematics using the HELIOS (HELIcal Orbit Spectrometer) device at Argonne National Laboratory [16,17].

In inverse kinematics, the reaction products are emitted at forward angles and their trajectories constrained by the solenoidal field of HELIOS. Population of the 5.164 MeV state is identified by the detection of the inelastically scattered protons. Different decay paths are identified by detecting either ^{10}B recoils for γ-ray emission or ^{6}Li, α particles, or both in the case of α decay. The α-decay branch is extracted by comparing the number of ^{10}B decay products detected in coincidence with the inelastically scattered protons to the total number of

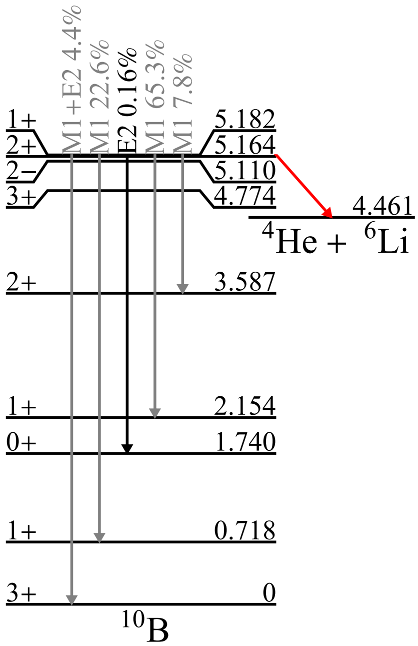

FIG. 1. Decay paths of the 5.164 MeV state. The pure $E2$ γ-ray transition to the $T=1$, $J^{\pi}=0^{+}$ state is shown in black, whereas $M1$ and $E2$ transitions to $T=0$ states are shown in gray. The transitions and energy levels are from Refs. [9,11].

protons detected:

$$\frac{\Gamma_\gamma}{\Gamma} = \frac{Y_\gamma \eta_\gamma}{Y_p} \tag{1}$$

and

$$\frac{\Gamma_\alpha}{\Gamma} = 1 - \frac{\Gamma_\gamma}{\Gamma}, \tag{2}$$

where Y_γ is the proton-^{10}B coincidence yield, Y_p is the proton-singles yield, and η_γ is the ^{10}B recoil-detection efficiency.

The particle branch is also obtained through the direct comparison of the ^{10}B coincidence yield to the α-decay coincidence yield:

$$\frac{\Gamma_\alpha}{\Gamma} = \frac{Y_\alpha \eta_\alpha}{Y_\alpha \eta_\alpha + Y_\gamma \eta_\gamma}, \tag{3}$$

where Y_α is the proton-^{6}Li/^{4}He gated coincidence yield, and η_α and η_γ are the corresponding recoil-detection efficiencies.

TABLE I. Results of previous measurements of the α-particle branching ratio of the 5.164 MeV state in ^{10}B.

Reference	Reaction	Branching Ratio
Riley *et al.* [13]	(d,n)	<0.20
Segel *et al.* [15]	(p,p')	0.27 ± 0.15
Alburger *et al.* [14]	$(^3\mathrm{He},\alpha)$	0.13 ± 0.04
Evaluated [11]		0.16 ± 0.04

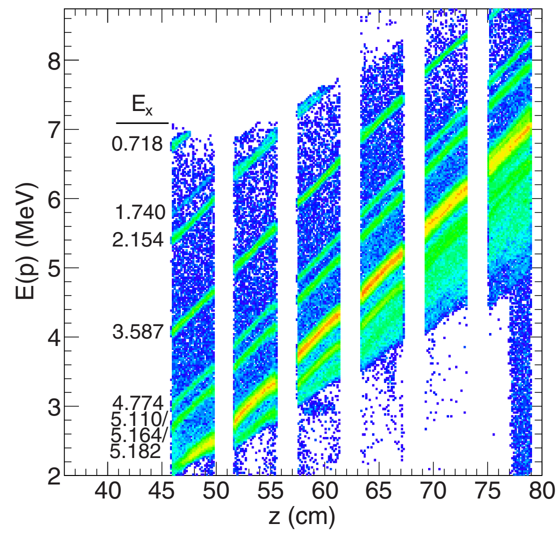

FIG. 2. Measured proton energy and distance from the target position for the ^{10}B(p,p') reaction at 10 MeV/nucleon. The different lines correspond to different excited states in ^{10}B, labeled by their energy in MeV.

A 10 MeV/nucleon ^{10}B beam, with an intensity of 0.1 p nA, was delivered to HELIOS by the ATLAS facility at Argonne National Laboratory. This beam bombarded targets consisting of 120 μg/cm^2 polypropylene (C_3H_6) foils, as well as a natural carbon target to evaluate the backgrounds from the carbon in the C_3H_6 foils. In inverse kinematics, the protons from the (p,p') reaction are emitted at forward angles in the laboratory frame. The protons then follow helical orbits through the solenoid to an array of position sensitive silicon detectors, covering a range of 45–70° in the center-of-mass frame for the 5.164 MeV state. States that are unbound with respect to α emission ($Q_\alpha = -4.46$ MeV) can decay and the resulting decay products will also be emitted at forward angles. To detect the decay products of interest, a telescope configuration of annular silicon detectors placed 22.5 cm downstream of the target covered small polar angles between 2.3 and 8 degrees. The experimental setup is similar to that described in Refs. [18,19].

The correlation between proton kinetic energy and position along the solenoid axis determines the excitation energy of the recoiling ^{10}B. Figure 2 shows an example of this correlation from proton-singles events. Each diagonal line corresponds to a different state in ^{10}B. The state of interest, at 5.164 MeV, appears as part of a triplet with states at 5.11 MeV ($T=0$, $J^{\pi}=2^{-}$) and 5.182 MeV ($T=0$, $J^{\pi}=1^{+}$). All of these levels lie above the α-decay threshold; however, while α decay is isospin suppressed for the 5.164 MeV state, the 5.110 and 5.182 MeV states decay nearly 100% of the time by α emission. The contributions from each state can thus be cleanly identified by selecting the appropriate recoils in the annular silicon detectors. The ΔE-E particle identification spectrum used to select ^{10}B, ^{6}Li, or ^{4}He appears in Fig. 3. Figure 4 shows the excitation energy spectrum from a single detector at a distance of 65 cm downstream from the target.

To determine the α-particle branching ratio for the 5.164 MeV state from Eq. (2), we require the proton-singles

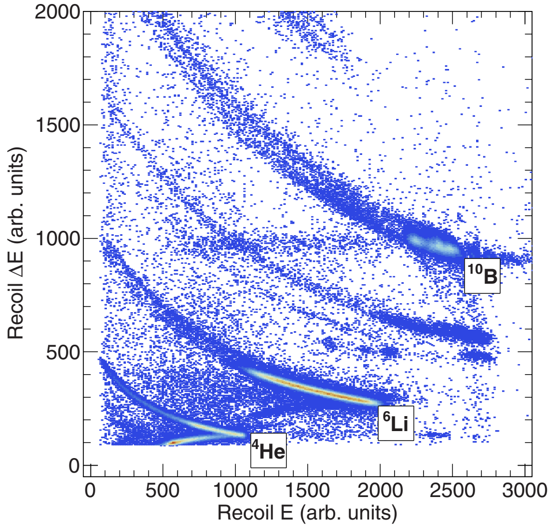

FIG. 3. ΔE-E particle-identification spectrum obtained from the forward-angle silicon detector telescopes.

yield, proton-^{10}B coincidence yield, and the proton-^{10}B recoil detection efficiency. The isolation of the yield for the 5.164 MeV state in the proton-singles spectrum is complicated by the nearby $T = 0$ states. The 5.110 MeV state is narrow ($\Gamma = 0.5$ eV) and the contribution can be determined by fitting the observed spectrum. The 5.18 MeV state is broad ($\Gamma \approx 100$ keV) and contributions from it must be subtracted. A Monte Carlo simulation of the reaction and experimental setup indicates that the ^{10}B recoil-detection efficiency for the 5.164 MeV state, η_γ, at center-of-mass angles between 50 and 70 degrees, should be equal to that of the particle bound 3.587 MeV state. The recoil detection efficiency for the 5.164 MeV state can then be obtained from the ratio of the coincidence yield to singles yields of the 3.587 MeV state, assuming that γ-recoil angular-correlation effects are negligible. This assumption can be checked by measuring the corresponding ratio at different center-of-mass angles for different bound states.

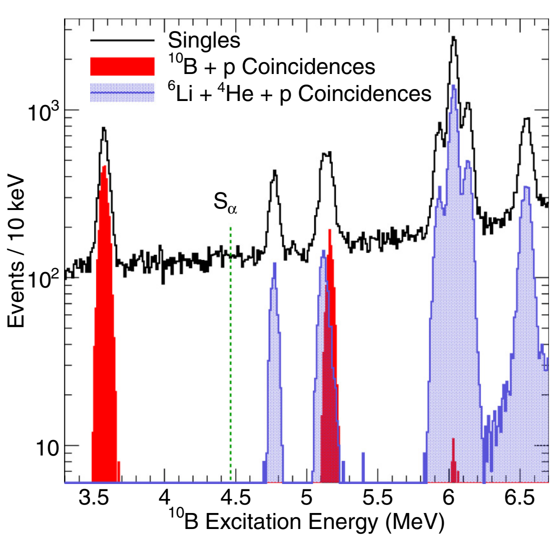

FIG. 4. ^{10}B excitation-energy spectrum for proton singles (open histogram), proton-^{10}B coincidence (solid filled histogram), and proton-^{6}Li-^{4}He coincidence (hatched histogram) events.

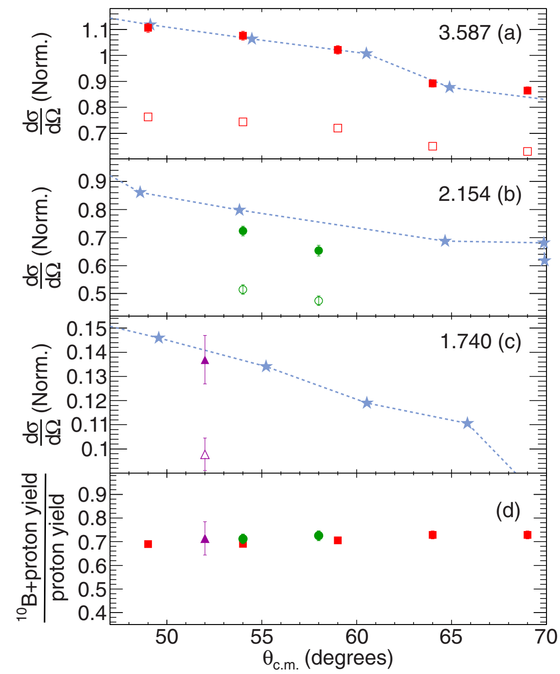

FIG. 5. Angular distributions of the (a) 3.587 MeV (red squares), (b) 2.154 MeV (green circles), and (c) 1.74 MeV (purple triangles) states for proton singles (filled) and proton-^{10}B coincidences (open). For the 1.740 MeV state, the acceptance of HELIOS allowed for protons to be detected only in a limited range of z, as shown in Fig. 2. (a)–(c) The stars and dashed lines represent the angular-distribution data from Ref. [15]. The present data are normalized to those of Ref. [15] for the 3.587 MeV state. (d) $Y(p\text{-}^{10}\text{B})/Y(p\text{-singles})$ for each state.

Analysis of the 3.587 MeV state yields a ratio of 0.70 ± 0.02 for the coincidence yield to singles yield. We obtain consistent ratios of 0.71 ± 0.06 and 0.72 ± 0.02 for the states at 1.740 and 2.154 MeV, respectively. Figure 5 shows angular distributions for the 3.587, 2.154, and 1.74 MeV states, for both the singles yields and for the coincidence yields. The experimental data are normalized to those of Ref. [15] for the 3.587 MeV state for comparison. The consistency indicates that we have a reliable understanding of the recoil-detection efficiency and it is determined by the geometry of the annular silicon detectors and the two-body kinematics. The ^{10}B recoil detection efficiency of the 5.164 MeV state is adopted from the observed coincidence yield to singles yield of the 3.587 MeV state. The boron-gated spectrum showing the 5.164 MeV state is shown in Fig. 6(c). The γ-decay yield of the 5.164 MeV state is determined by the efficiency corrected ^{10}B coincidence yield, with a statistical uncertainty of 1.4% in the ^{10}B gated yield and 2% in the efficiency correction.

As previously mentioned, isolation of the 5.164 MeV state in the proton-singles spectrum is complicated by a broad $T = 0$ state at 5.182 MeV. In Ref. [14], the 5.182 MeV state was not observed; however, an additional 4% uncertainty was adopted to account for any possible contribution from this state. In addition, no evidence for this state was observed by

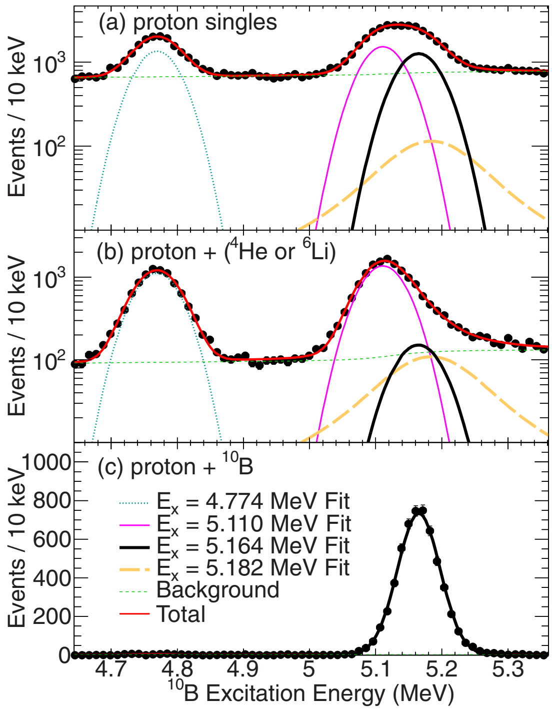

FIG. 6. Fit results for excited states above the α decay threshold for (a) proton singles, (b) proton-^{6}Li/^{4}He coincidence events, and (c) proton-^{10}B coincidences.

Riley *et al.*, who reiterate a conclusion previously stated by Gorodetzky *et al.* [20] that the 5.182 MeV state may belong to a doubly excited configuration that is suppressed in single nucleon transfer reactions.

To determine if this α-decaying broad state is populated in (p,p'), we begin by analyzing the α-decay coincidence events shown in Fig. 6(b). The narrow 5.110 and 5.164 MeV states are reproduced in the fit using Gaussian distributions with the shape of both states obtained from the fit of the isolated ^{10}B gated 5.164 MeV state, with a resolution of 70 keV FWHM. The broader 5.182 MeV state is characterized by the convolution of a Gaussian distribution, with a width of 70 keV FWHM to reproduce the detector resolution, and a Lorentzian distribution, with a width allowed to vary between 75 and 200 keV. Including the 5.182 MeV state, the fit yields a reduced χ^2 of 1.1 for energies between 5.0 and 5.3 MeV. If the 5.182 MeV state is omitted, the fit is significantly poorer, with a reduced χ^2 of 4.1. Figure 6(a) shows the result of fitting the proton singles spectrum using parameters obtained from the γ- and α-decay coincidence spectra. The width of the 5.182 MeV state from the fit, 130 ± 30 keV, is consistent with previously reported values [11,21]. The yield of the 5.182 MeV state accounts for 10% of the total yield of the triplet in the singles spectrum and 20% of the total yield in the α-gated spectrum, suggesting that the 5.182 MeV state cannot be neglected in this reaction.

The second method to calculate the α-particle branching ratio, given by Eq. (3), carries additional uncertainty from the need to estimate the $p + {}^6$Li/^{4}He coincidence efficiency. However, we expect that by summing the coincidence yields for the detection of either ^{6}Li or ^{4}He, the detection efficiency will be larger and less sensitive to angular-correlation effects when compared to the detection of a specific decay particle or the simultaneous detection of both decay particles. This is confirmed by the Monte Carlo simulation which shows that the efficiency is independent of the choice of angular distribution of the decaying particles at the 2% level.

More information about the efficiency for detecting $p + {}^4$He/^{6}Li events is obtained from the neighboring α-unbound excitations. The ratios of the summed ^{6}Li/^{4}He coincidence yields to the singles yields for the 4.77, 5.11, and 5.9 MeV states are 0.84 ± 0.02, 0.89 ± 0.02, and 0.95 ± 0.03, respectively. The ratio for each resonance is independent of the center-of-mass angle of the emitted proton, indicating that the coincidence-detection efficiency is not strongly affected by angular-correlation effects, which will be different for states of different spin. The linear dependence of efficiency on the excitation energy is expected, as the decay particles from higher-lying α resonances are emitted in a wider cone around the recoil direction, making it more likely that one of the decay fragments is detected. Based on the Monte Carlo simulation, we assume a 2% uncertainty due to angular-correlation effects and take the proton-^{6}Li/^{4}He detection efficiency of the 5.164 MeV state to be the same as that of the 5.110 MeV state.

We obtain consistent results for the α-decay branching ratio of 0.153 ± 0.029 and 0.135 ± 0.027, from Eqs. (2) and (3), respectively. Our final value of 0.144 ± 0.027 is an average of the two methods. This result is in excellent agreement with the result of Alburger *et al.* [14] and is consistent with the previously evaluated value. This result also settles any ambiguity in the branching ratio when compared to Segel *et al.* [15], which was only marginally in agreement with Alburger *et al.*. Taking the weighted average of the Alburger *et al.* result and our result of 0.144 ± 0.027, we suggest a new value for the α-particle branching ratio of 0.140 ± 0.022 (see Fig. 7). This new value is smaller than the previously adopted value by 10% and the uncertainty has been reduced from 25% to 15%.

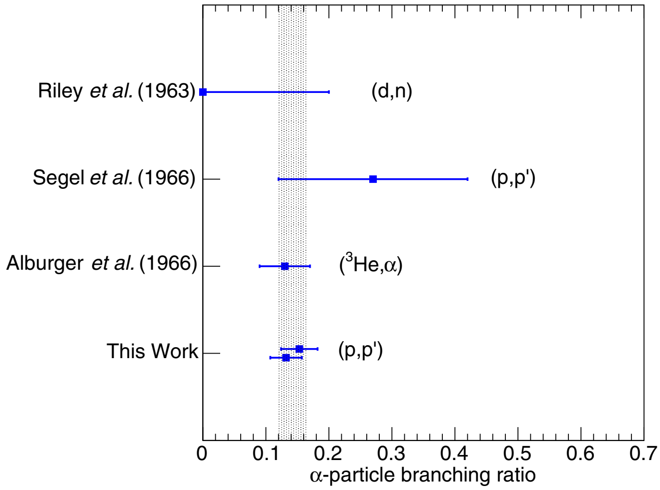

FIG. 7. Past and current results for the α-particle branching ratio. The results for both methods used to determine the branching ratio in this work are shown. The gray band illustrates the new value for the branching ratio suggested in this work.

Adopting the literature value for the reduced width of the state and the new value for the α-particle branching ratio from this work, we obtain partial-decay widths of

$$\Gamma_{\gamma}^{5.164} = 1.66 \pm 0.32 \text{ eV}$$

and

$$\Gamma_{\alpha}^{5.164} = 0.27 \pm 0.03 \text{ eV}.$$

Finally, adopting the value for the partial γ-decay branch of the $T = 1$, $J^{\pi} = 2^+ \rightarrow 0^+$ transition from Ref. [9], we determine a $B(E2)$ value of $7.0 \pm 2.2\ e^2\text{fm}^4$. The corresponding values from Refs. [7,8] for ^{10}Be and ^{10}C are 9.2 ± 0.3 and $8.8 \pm 0.3\ e^2\text{fm}^4$, respectively. In those studies, the VMC and GFMC calculations of the $B(E2)$ value were consistent for ^{10}Be but did not reproduce the constant trend observed when compared to ^{10}C. For ^{10}B, the *ab initio* GFMC calculations that include three-nucleon forces predict a $B(E2)$ value of $11.4 \pm 0.6\ e^2\text{fm}^4$. Thus the current experimental $B(E2)$ value remains low when compared to theoretical estimates. A comparison of the experimental $B(E2)$ values for the $A = 10$ triplet is shown in Fig. 8. Note that our experimental $B(E2)$ value is 10% larger than the one previously reported by Ref. [9] due to our smaller α-particle branch as compared to the previously evaluated branch. As a result, the $B(E2)$ value that we report is more consistent with a flat trend across the $A = 10$ triplet. However, the mean value is still lower than the average of the corresponding transitions in ^{10}Be and ^{10}C, indicating that a significant contribution arising from charge symmetry breaking could be present.

With this result, the leading uncertainty in the $B(E2)$ value is now the uncertainty of the branching ratio of the pure $E2$ partial γ-decay branch. A future experiment to make a more precise measurement of this quantity is planned using Gammasphere at Argonne National Laboratory. Finally, additional measurements of the α-decay branching ratio utilizing different reactions would also help to isolate the properties of the 5.182 MeV state, that remains a significant source of uncertainty in our measurement.

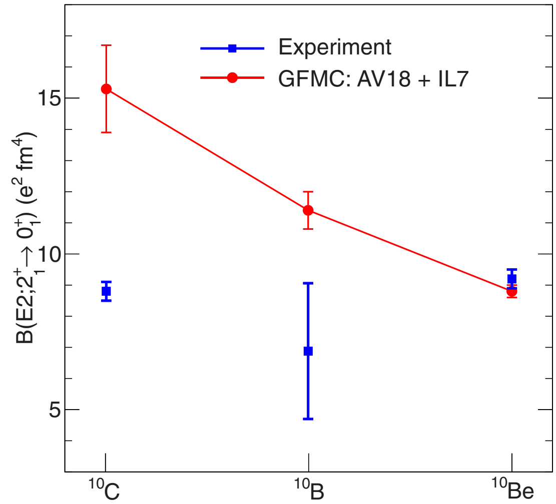

FIG. 8. Experimental (squares) and theoretical (circles) $B(E2)$ values for ^{10}C, ^{10}B, and ^{10}Be. The $B(E2)$ values, except for the experimental $B(E2)$ value for ^{10}B, are from Ref. [8]. The line between the theoretical values is to guide the eye. The uncertainty in the experimental ^{10}B $B(E2)$ includes contributions from the partial γ-decay branch and total width of the state, which were not measured in this work.

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