

Evidence of the ${}^9\text{B}(1/2^+)$ state in the ${}^{12}\text{C}(p, \alpha){}^9\text{B}$ reaction

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The low-lying excitation region in ${}^9\text{B}$ has been studied through the ${}^{12}\text{C}(p, \alpha){}^9\text{B}$ reaction with a proton beam energy of 33 MeV at the Birmingham MC40 Cyclotron. Coincident recoil α -particle and ${}^9\text{B}$ breakup products were detected by a silicon double-sided strip detector array and reconstructed to identify signatures of the elusive ${}^9\text{B}(1/2^+)$ state. Data were collected for two distinct α -particle recoil angles, 31° and 106° , with a total beam exposure of ≈ 0.52 mC. *R*-matrix analysis indicates the presence of a state at $E_x = 1.83 \pm 0.05$ MeV with a width of $\Gamma = 850 \pm_{88}^{110}$ keV with a confidence level of 99.1% and no signature of any lower-lying state. This result is shown to be consistent with four previous measurements over the last 25 years, signifying strong evidence that the first excited state in ${}^9\text{B}$ lies at a weighted average excitation of $E_x = 1.84 \pm 0.04$ MeV with $\Gamma = 740 \pm_{66}^{77}$ keV.

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I. INTRODUCTION

The unparalleled role light mirror nuclei play in shaping our understanding of non- α conjugate cluster structures and the charge independence of the nuclear force makes study of such systems pivotal. With the ability for direct evaluation of *ab initio* models in these nuclei, research begins to unveil key information to questions that have remained unanswered for decades.

The ${}^9\text{Be}$ - ${}^9\text{B}$ mirror pair provides the simplest and first known instance of molecular structure in nuclei [1–4]; a structure which forms a foundation of many heavier systems. Additionally, the $1p$ - $1n$ mirror nature of the pair gives simplistic access to properties of the nuclear force. Research into these nuclei therefore indirectly probes much of the surrounding nuclear landscape. While the ${}^9\text{Be}$ nucleus has been the focus of much scrutiny because of its stable excess neutron structure, ${}^9\text{B}$ remains poorly understood, a facet which has given rise to the six-decade-long dilemma around the location of the first excited $1/2^+$ analog state.

From historical understandings of mirror symmetry, it is agreed a state should exist in ${}^9\text{B}$ around an energy of 1.6 MeV as observed in ${}^9\text{Be}$, with allowances for Coulomb energy differences. Earliest observations of the first excited state in ${}^9\text{B}$ were reported in 1962 by Symons and Treacy [5] through the ${}^{12}\text{C}(p, \alpha){}^9\text{B}$ reaction at 1.41 MeV, a measurement which instigated many other searches. Two paradigms emerged from these searches in 1988 when experiments

performed by Arena *et al.* [6] and Burlein *et al.* [7] independently measured inconsistent excitation energies. While not inherently troubling, later results from Tiede *et al.* [8] seemed to indicate the presence of symmetry breaking in which two $1/2^+$ states exist, one at 0.8 MeV and the other at 1.8 MeV. Subsequent experiments [9–16] were unable to resolve this mystery, leading to further confusion. Uncertainty was not alleviated by the fact that both candidates could also be obtained theoretically through normal and inverted Thomas-Ehrman shifts respectively [17,18]. Structural implications of both results, the former describing a more diffuse configuration and the latter a more compact one, mean that precise theoretical modeling of the system is currently not achievable.

Experiments performed since Tiede *et al.* suggest a strong bias in candidate preference from the chosen population mechanism. Reports of a lower excitation state emerged from more complex reactions, such as ${}^6\text{Li}({}^6\text{Li}, d){}^{10}\text{B}^*$, and a higher excitation state through simpler reactions, such as ${}^9\text{Be}({}^3\text{He}, t){}^9\text{B}$. Reexamination of these previous results [19] illustrated complex pathways are less likely to populate the $1/2^+$ state and that these experiments did not fully consider the ground-state ghost-peak contribution to the region of interest. Combined, this appears to result in a misidentification of a $1/2^+$ where one is not expected. Fortune and Sherr [20] more recently suggested a possible route via resonant scattering of the 11.86 MeV $1/2^+$ state in ${}^{13}\text{N}$ through the ${}^{12}\text{C}(p, \alpha)$ pathway; however, no reinvestigation of the original population channel has been performed since 1965. The current work provides further evidence resolving the long-standing confusion surrounding the location of the first excited state in ${}^9\text{B}$ by using the ${}^{12}\text{C}(p, \alpha)$ reaction channel.

II. METHODOLOGY

To study the low-lying excitation region within ${}^9\text{B}$, the ${}^{12}\text{C}(p, \alpha)$ reaction was utilized. This was accomplished with a

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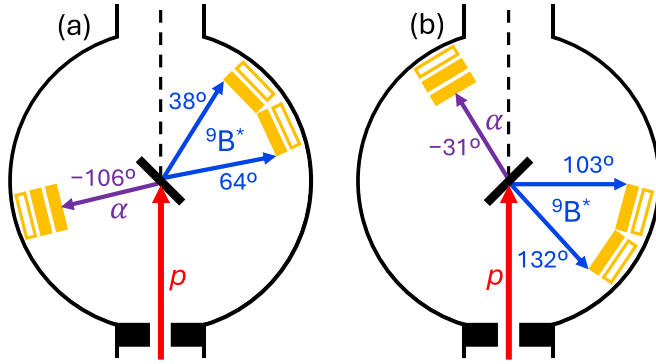


FIG. 1. DSSD array configurations for (a) 106° and (b) 31° recoil α detection. DSSDs are denoted by filled yellow boxes, with veto detectors denoted as unfilled yellow boxes. Each DSSD possesses 16 vertical strips on its front face and 16 horizontal strips on its back face and is positioned such that its center lies in the x - y plane. The target was set at $\pm 45^\circ$ relative to the beam direction in the x - y plane for each configuration as shown, in order to limit target thickness energy-loss effects for the outgoing α particle.

proton beam at an energy of 33 MeV, supplied by the Birmingham MC40 Cyclotron [21,22], collimated onto a $100 \mu\text{g}/\text{cm}^2$ ^{12}C target. Recoil α particles were detected in coincidence alongside ^9B breakup products within a combination of four double-sided silicon strip detectors (DSSDs). Resonant scattering through the 11.86 MeV $1/2^+$ state in ^{13}N was not feasible in the current work given the low incident beam energy required for population and the subsequent low energy of the final-state particles. Such low total energy in the final state means the breakup α particles have insufficient energy to escape a reasonable thickness target. Here, the 33 MeV beam was supplied for a total of 105 h with an average current of ≈ 1.37 nA, during which data were collected at two distinct angular arrangements of the DSSD array. The first of these was where the recoil α particle was detected within a telescope detector constructed from a 65- μm -thick front and 500- μm -thick back $50 \times 50 \text{ mm}^2$ 16-strip Micron W1 DSSD, centered at -106° relative to the beam direction in the x - y plane. In the other, the recoil α was detected by the same telescope centered at -31° to the beam direction. Two $500 \mu\text{m} \times 50 \times 50 \text{ mm}^2$ 16-strip “breakup” DSSDs were positioned relative to the recoil detector such that they would capture α particles and protons corresponding to the decay breakup of the populated ^9B nucleus. Schematic diagrams of these angular setups are detailed in Fig. 1.

To achieve high angular resolution, detectors were positioned as far as possible from the target within the allowed confines of the scattering chamber. For the 106° configuration this meant the front “ dE ” detector of the recoil telescope was at a distance of 215 mm from the target with the back “ E ” detector of the telescope and both break-up detectors situated at 240 mm. In the 31° configuration, these distances changed to 256 mm for the E detector and 230 mm for the dE and breakup detectors. Altogether, this provided an angular resolution of 0.7° per strip in each configuration and a total angular acceptance within the recoil telescope of 11° for the 31° configuration and 12° for the 106° configuration. Such

an angular arrangement intrinsically possesses a low detection efficiency for higher multiplicity events, such as multiplicity 4 ($m4$) events, in which the recoil α particle and all three decay products are detected. This decrease in statistics, however, was deemed acceptable due to the ability to examine relative state population and thus begin to experimentally postulate spin-parity assignments for states of interest.

In order to counteract the much higher rate of the competing $^{12}\text{C}(p, p')$ reactions overwhelming the (p, α) event triggers, a 1-in-10 rate reduction was incorporated into the trigger logic for multiplicity 1 ($m1$) events using a rate divider. This was also implemented in conjunction with “veto” $500 \mu\text{m} \times 50 \times 50 \text{ mm}^2$ 16-strip DSSDs, which only utilized the front 16-strip readouts to effectively function as single-sided strip detectors, placed behind the telescope and breakup detectors enabling the removal of high-energy p -background events in software. Together, these strategies allowed for an improvement in the observation of breakup from the $^9\text{B} \rightarrow ^8\text{Be} + p$ decay channel.

Use of recoil telescope detectors in each configuration enabled tagging of recoil α -particles through characteristic energy loss between dE and E detectors. Additionally, a further particle selection step was utilised through Catania plots [14,23–25] allowing for the removal of any possible contaminant channels as well as confirmation of the reaction channel. This particle identification and channel selection directly enables missing-mass spectra to be constructed, which, when coupled with event multiplicity selection permits high-precision event reconstruction.

Examination of specific ^9B decay channels is accomplished through further break-up decay gating during multiplicity 3 ($m3$) events, in which the recoil α -particle and a combination of two of three ^9B decay products ($\alpha + \alpha + p$) are detected. During the coincident detection of the recoil α and two particles in the breakup detectors, permutations of possible 2α and $\alpha + p$ breakups are reconstructed in order to obtain a 91.8 keV ^8Be binding energy signature. If within allowed tolerances, events can then be utilized to plot only proton-decaying ^9B excited states (i.e., those populating the ^8Be (g.s.)). This specifically enables removal of strongly α -decaying states (i.e., those decaying via $^5\text{Li} + \alpha$), such as the dominant $5/2^-$ state, allowing for the weakly populated $1/2^+$ state to be identified with greater certainty.

As cross validation for collected spectra, identification of contaminant processes, and for generation of efficiency profiles and energy-dependent resolution curves, simulations were performed using the RESOLUTION8 Monte Carlo package developed at Birmingham [26,27]. Background from three and four-body phase space contributions were obtained through ROOT [28] using the TGENPHASESPACE class. The phase-space backgrounds were employed with the energy-dependent resolution curves extracted from Resolution8, required for Gaussian convolution to raw R -matrix line shapes, to improve the accuracy of performed fits.

A custom R -matrix software, ARGONAUT [29], capable of producing sequential decay-strength profiles, was created alongside a bound-imposed gradient-descent fitting algorithm, REVERSE SISYPHUS [30], to optimize all R -matrix fits to data. For all states, the centroid energy, width, and scale were given

as input parameters for fitting, except in the case of the ground state where the state width was fixed.

During the fitting procedure, missing-mass spectrum data were passed into REVERSESISYPHUS, which was coupled to ARGONAUT. Initial excitation energy and width parameters input into the gradient-descent algorithm were obtained from literature and scaling parameters through initial hand fitting. The gradient-descent algorithm then iteratively optimized these values with use of a chi-squared loss function which it aimed to minimise. To maintain physical sensibility, all excitation and width parameters had bounds imposed on them to negatively impact the loss function when they were breached. This would result in the return of a large gradient preventing the algorithm optimizing to parameter values outside the imposed bounds. Known states in ${}^9\text{B}$ were allowed to vary up to $\pm 1\sigma$ in excitation energy and width as defined by currently available ENSDF data [31]. Included $1/2^+$ states were bounded by an excitation range of 0.5–2.0 MeV and a width range of 200–1500 keV. Scale parameters were bounded by a lower value of zero and an arbitrary upper limit which would not affect fitting. This procedure was repeated for all relevant testing hypotheses to evaluate all possible $1/2^+$ candidate combinations.

Altogether a total of four spectra were fitted using this method:

- (1) The $m3$ 31° missing-mass data.
- (2) The $m3$ 106° missing-mass data.
- (3) The combined $m3$ 31° and 106° missing-mass data (referred to as the combined missing-mass data).
- (4) The ${}^8\text{Be}$ decay-gated combined $m3$ 31° and 106° missing-mass excitation data (referred to as the breakup-gated missing-mass data).

Each spectrum was fitted a total of three times corresponding to each of the proposed hypotheses:

- (1) The presence of a single $1/2^+$ state; at either ≈ 0.8 or ≈ 1.8 MeV.
- (2) The presence of two $1/2^+$ states at 0.8 and 1.8 MeV.
- (3) The absence of a $1/2^+$ state within this region.

In each iteration of hypothesis testing, the absence of any $1/2^+$ state was taken as the null hypothesis and the dual- and single-state observations were alternate hypotheses. Such rigorous fitting and examination were undertaken to conclusively examine all possible hypotheses and definitively rule out the observation of both states, either state, or no states. In each case, given that the hypotheses are nested models of one another, a χ^2 difference test [32] was also performed allowing for a definitive acceptance or rejection of hypotheses. From this testing, the most statistically significant hypothesis, and hence R -matrix fit, can then be identified. A table of all known states included during calculations is provided in Table I.

III. RESULTS AND ANALYSIS

Initial simulations performed indicated contamination of the ${}^9\text{B}$ missing-mass spectra predominantly arise within multiplicity 1 ($m1$) events. No contributions were observed from ${}^{12}\text{C}(p, p')$ reactions populating excited states within ${}^{12}\text{C}$

TABLE I. List of known states and their properties utilised during R -matrix calculations and gradient-descent fitting to data. Values quoted are taken from currently available ENSDF data [31] unless otherwise stated.

J^π	E_x (MeV)	Γ (keV)
$3/2^-$	0.0	0.54
$5/2^-$	2.345 ± 0.011	81 ± 5
$5/2^+$	2.751 ± 0.025	614 ± 37
$1/2^-$	2.78 ± 0.16	3130 ± 200
$3/2^-^a$	$3.82 \pm_{0.22}^{0.23}$	$1330 \pm_{360}^{620}$
$3/2^+^b$	4.8 ± 0.3	1200 ± 200

^aThe 3.8 MeV state centroid and width are taken from reference [11].

A Spin-parity assignment taken from reference [11] is combined with those presented in reference [33] utilising mirror symmetry. As such a value of $J^\pi = 3/2^-$ is used for the current work.

^bSpin-parity assignment is taken from the experimental rotational band fitting in reference [4].

above the alpha-decay threshold. Instead, contaminant processes were identified arising from target impurities, such as ${}^{13}\text{C}(p, \alpha)$ populating the 4.77 MeV 3^+ state in ${}^{10}\text{B}$ resulting in a peak at $E_x = 0.98$ MeV in the ${}^9\text{B}$ missing-mass spectrum. Experimentally, a strong background of α particles was also observed in $m1$ spectra, impacting fitting. Given complicated possible contamination to $m1$ spectra and the necessary requirement for breakup reconstruction, only $m3$ events were used during subsequent analysis. Comparison between all multiplicity ($m1+$), $m3$, and $m3$ with ${}^9\text{B}$ breakup gating excitation spectra for both angular arrangements are shown in Fig. 2. Due to the limited statistics within both $m3$ breakup-gated spectra, the choice to combine the results was taken to improve the veracity of performed R -matrix fitting.

Telescope particle identification plots with imposed α -particle gates for the 31° and 106° configurations are shown in Figs. 3(a) and 4(a) respectively. Corresponding Catania plots for both gates are then shown in Figs. 3(b) and 4(b). The background is seen to be much larger in data collected for the 31° arrangement; however, it is removed following multiplicity selection and recoil gating, illustrated in both Catania plots. The elongation of states within Figs. 3(a) and 4(a) most likely arises due to nonuniformity in front detector thickness, as similar effects are seen in the data from Ref. [34] for an identical detector. This does not result in problems during missing-mass reconstruction, however, due to complete energy deposition within both stages of the telescope and the fact that PID plots are exclusively used for recoil identification.

Reconstruction of particles recorded within the breakup detectors to obtain the ${}^8\text{Be}$ binding energy, produces the Q -value plots shown in Fig. 5. Both spectra show the anticipated 91.8 keV binding energy peak associated with the α decay of the ${}^8\text{Be}$ ground-state, denoted by the blue dashed line. Red dot-dashed lines indicate the ${}^8\text{Be}$ binding energy gate tolerances applied to such events, corresponding to a $\pm 2\sigma$ limit. The steeper background near the origin of Fig. 5(a) arises due to the α decay of ${}^9\text{B}$ states leading to incorrect attempted particle combinations. The higher excitation range accessible in ${}^9\text{B}$ with the 31° configuration, illustrated in Fig. 2, allows

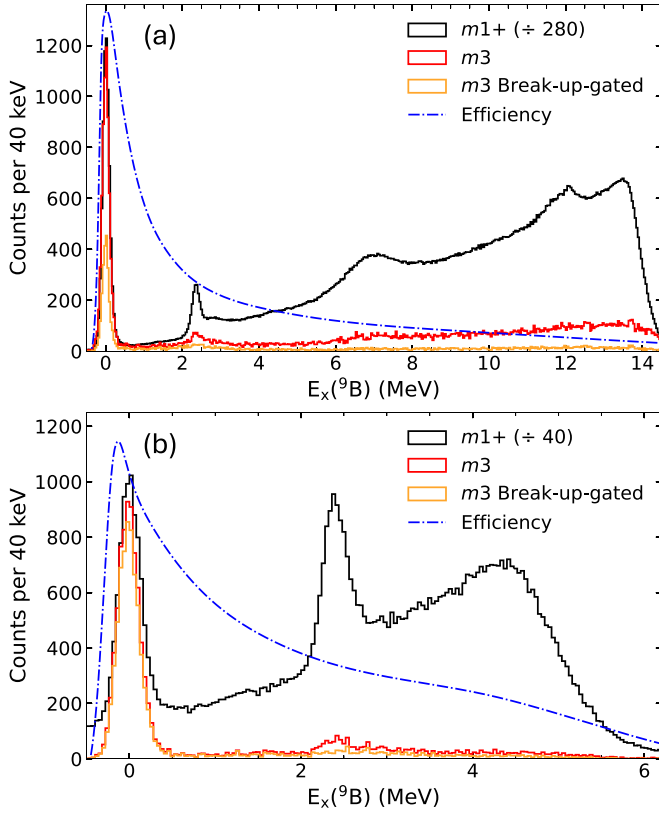


FIG. 2. All multiplicity ($m1+$), multiplicity 3 ($m3$), and breakup-gated $m3$ ${}^9\text{B}$ missing-mass excitation spectra for the (a) 31° detector configuration and (b) 106° detector configuration. Multiplicity 1+ counts are scaled down by factors of 40 and 280 respectively. The blue dot-dashed line corresponds to the arbitrarily-scaled normalised efficiency curve for $m3$ spectra generated from Monte Carlo simulations.

for detection of the 2^+ state within ${}^8\text{Be}$ during p decay. This is evidenced with the peak centered at 3 MeV in Fig. 5(a) and the lack of such a prominent identical state within Fig. 5(b).

A. 31° recoil data

“Single,” “dual,” and “neither” state R -matrix fits, and their associated reduced χ^2 values, for the 31° data are shown in Fig. 6. Here it is identified that the greatest agreement arises from a single-state hypothesis, with a reduced χ^2 of 2.31 compared to the null hypothesis reduced χ^2 of 2.36. Evaluation of a χ^2 difference test between the single-state and neither-state fits allows for a rejection of the null hypothesis with a $>99\%$ confidence level at a p value of 0.0091. Thus the single state fit shown in Fig. 6 a is the most statistically significant for this angle. The extracted resonance parameters of this fit are a centroid energy of 2.00 MeV, relative to the ${}^9\text{B}$ ground-state following correction to the minimal discrepancy from the expected energy, and a width of 430 keV. Chi-squared sensitivity for each parameter is evaluated, under which a change of one from the optimized chi-square value provides uncertainty, as shown in Fig. 7. This gives resonance values of $E_x = 2.00 \pm 0.05$ MeV and $\Gamma = 430_{-110}^{+130}$ keV.

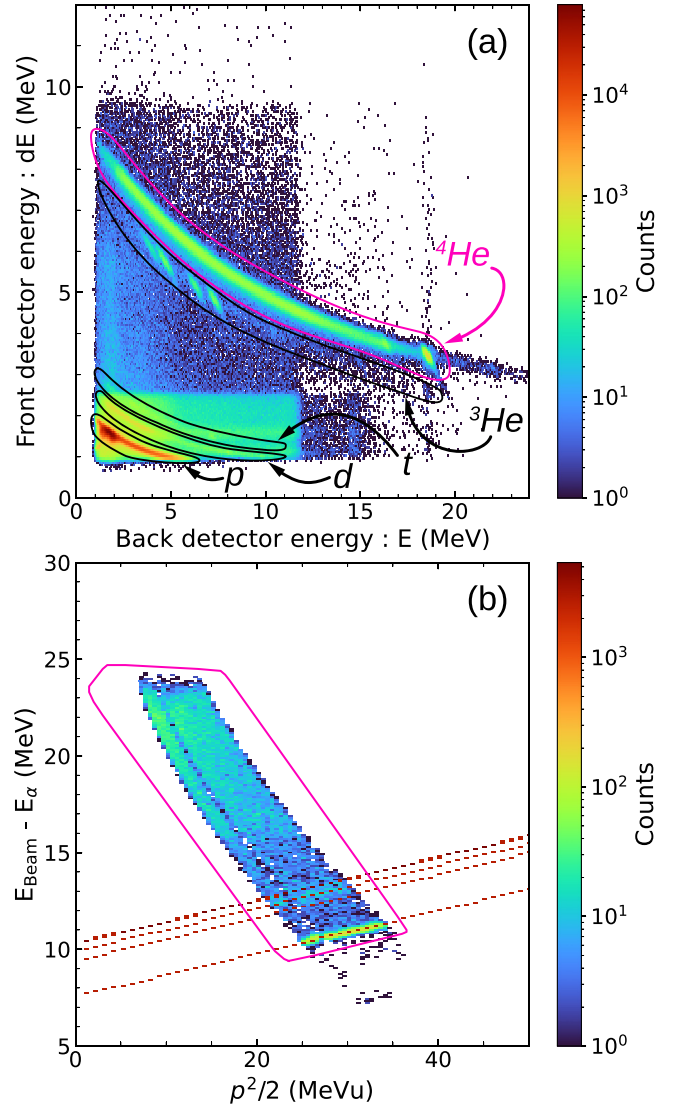


FIG. 3. (a) Recoil telescope dE - E plot for the 31° configuration showing particle identification capabilities based on characteristic energy loss with the magenta α -gate superimposed. Additional p , d , t , and ${}^3\text{He}$ lines are also indicated by black outlines. These arise from ${}^{12}\text{C}(p, p){}^{12}\text{C}$, ${}^{12}\text{C}(p, d){}^{11}\text{C}$, ${}^{12}\text{C}(p, t){}^{10}\text{C}$, and ${}^{12}\text{C}(p, {}^3\text{He}){}^{10}\text{B}$ events respectively. The magenta outline of figure (a) encompasses all ${}^9\text{B}$ events, with those below the ${}^9\text{B}$ ground state excluded. Unwanted events which might pass through are also removed following a gate applied to the Catania plot. (b) Corresponding multiplicity 3 Catania plot for events within the α gate of the recoil telescope. The solid magenta outline in (b) denotes the $\alpha + {}^9\text{B}$ reaction gate, with the linear red dotted lines corresponding to the expected loci of the first four excited states in ${}^9\text{B}$, including a 1.86 MeV $1/2^+$ state. The heat-map color scale indicates intensity (counts).

The dual-state fit shows the poorest agreement to data, with an almost negligible contribution from the low-lying candidate to the combined excitation profile. This near-zero contribution is similarly observed in other dual state R -matrix fits due to strong contributions from the three and four-body phase space background, highlighted as the yellow dashed line. This minimal contribution strongly suggests such a state

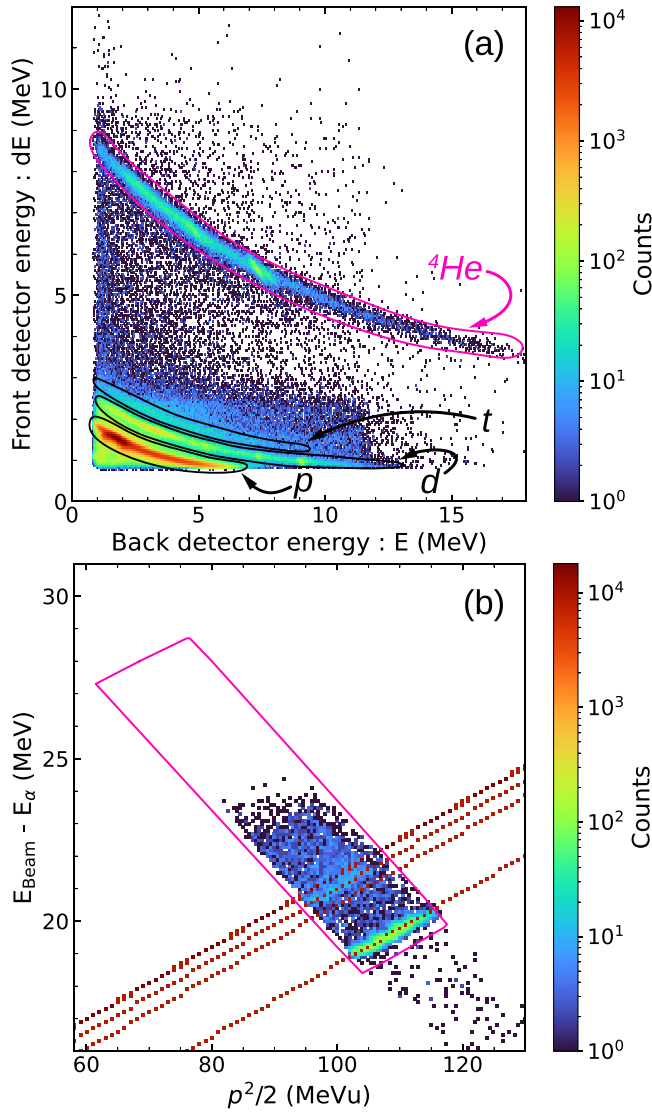


FIG. 4. (a) Recoil telescope dE - E plot for the 106° configuration showing particle identification capabilities based on characteristic energy loss with the magenta α -gate superimposed. Additional p , d , and t lines are also indicated by black outlines. These arise from ${}^{12}\text{C}(p, p){}^{12}\text{C}$, ${}^{12}\text{C}(p, d){}^{11}\text{C}$, and ${}^{12}\text{C}(p, t){}^{10}\text{C}$ events respectively. (b) Corresponding multiplicity 3 Catania plot for events within the α gate of the recoil telescope. The solid magenta outline in (b) denotes the $\alpha + {}^9\text{B}$ reaction gate, with the linear red dotted lines corresponding to the expected loci of the first four excited states in ${}^9\text{B}$, including a 1.86 MeV $1/2^+$ state. The heat-map color scale indicates intensity (counts).

cannot be present within this excitation region, further refuting its existence.

B. 106° recoil data

Single-, dual- and neither-state fits for the 106° data are shown in Fig. 8. Comparison against Fig. 6 immediately highlights a strong decrease in profile strength around the 1.6–2 MeV region, suggesting a lack of resonance intensity within this region. This is confirmed upon examination of the

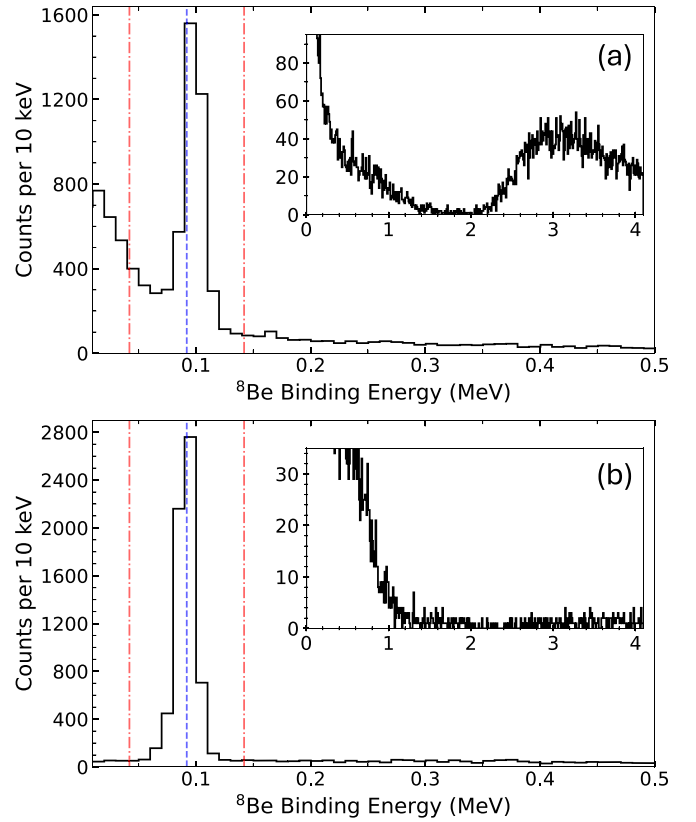


FIG. 5. Breakup reconstruction of ${}^8\text{Be}$ binding energy for (a) 31° and (b) 106° detector configurations. The blue dashed lines denote the known 91.8 keV ${}^8\text{Be}$ binding energy and red dot-dashed lines indicate the utilized binding energy gate. Inset axes in each panel show full ${}^8\text{Be}$ binding energy up to 4 MeV to examine any detection of the 3.03 MeV 2^+ state.

R -matrix fits in Fig. 8 where the null hypothesis produces a reduced χ^2 of 2.06 and the single and dual hypotheses produce a reduced χ^2 of 2.10 and 2.15 respectively. Chi-square difference tests performed between single-, dual-, and neither-state fits give p values for the single- and dual-state hypotheses of 0.351 and 0.541 respectively. This indicates an inability to reject the null hypothesis at any reasonable confidence level, indicating that the neither-state hypothesis fit shown in Fig. 8(b) is the most statistically significant. Therefore the current work reports no observation of a resonance at this α -recoil angle.

C. Combined angular data

1. Missing mass

Given the known weakly populated nature of the first excited state and the reduced statistics of the current work, efficiency-corrected data from both angles were combined through summation of counts and analyzed alongside individual fits. The ${}^9\text{B}$ missing-mass excitation spectrum with single-, dual-, and neither-state fits for combined statistics are shown in Fig. 9. Examination of the reduced χ^2 for each fit immediately indicates a strong preference for a state situated around 1.80 MeV. Difference tests for the obtained χ^2

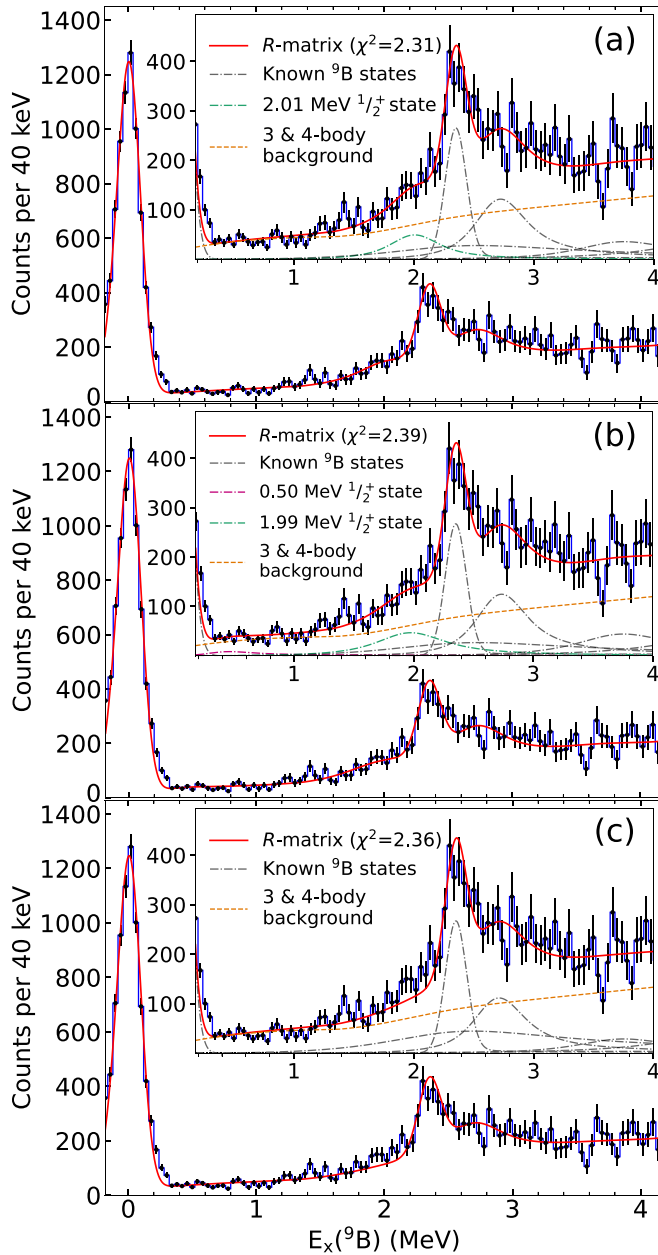


FIG. 6. *R*-matrix fits for 31° ^9B missing-mass excitation spectrum corresponding to (a) single-state, (b) double-state, and (c) no-state hypotheses. *R*-matrix fits are generated by ARGONAUT and optimized through a gradient-descent fitting routine REVERSE SISYPHUS. Known states are shown by the grey dot-dashed lines, three- and four-body background contributions by the yellow dashed line, and generated $1/2^+$ states by the green and magenta dot-dashed lines.

between all hypotheses highlight that the fits in both Figs. 9(a) and 9(b) are statistically significant at a $>99\%$ confidence level compared to Fig. 9(c). A further χ^2 difference test between 9(a) and 9(b) also allows confirmation that a single-state fit is the most statistically significant, with the dual-state hypothesis rejected. The corresponding observed state possesses an excitation energy of 1.79 MeV, after ground-state centroid shift correction, and a width of 790 keV. As before, extraction of the

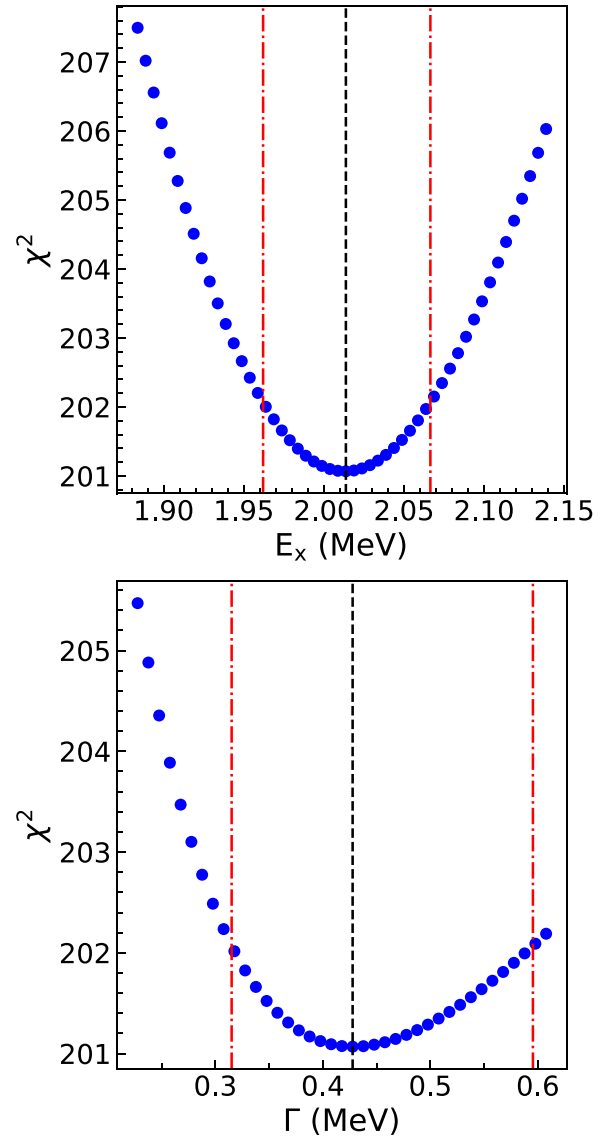


FIG. 7. Sensitivity of χ^2 to changes in observed state excitation energy, E_x , and width, Γ , for the 31° ^9B missing-mass excitation spectrum. Red dot-dashed lines denote values of E_x and Γ that correspond to a change from the minimized χ^2 by 1.

uncertainties of state properties is achieved under independent variation of these values and subsequent examination of χ^2 sensitivity as shown in Fig. 10. Together this provides an excitation energy and width of 1.79 ± 0.08 MeV and 790^{+150}_{-120} keV for the observed resonance. The shift in centroid energy away from the observed value of 2.00 MeV within the 31° data likely arises from the increased statistics under combination of the individual angle data. The resulting greater statistics will allow for a better constraint to the 2.345 MeV state during fitting, which will help to reduce the strong correlation observed between the $5/2^-$ and $1/2^+$ states in the 31° data. Overall, this leads to an improved capability to fit to a weak $1/2^+$ state in the combined missing-mass spectrum. Additionally, by combining these profiles, a more detailed phase-space background presence arises, altering the possible location of the first excited state in fitting; the interplay of

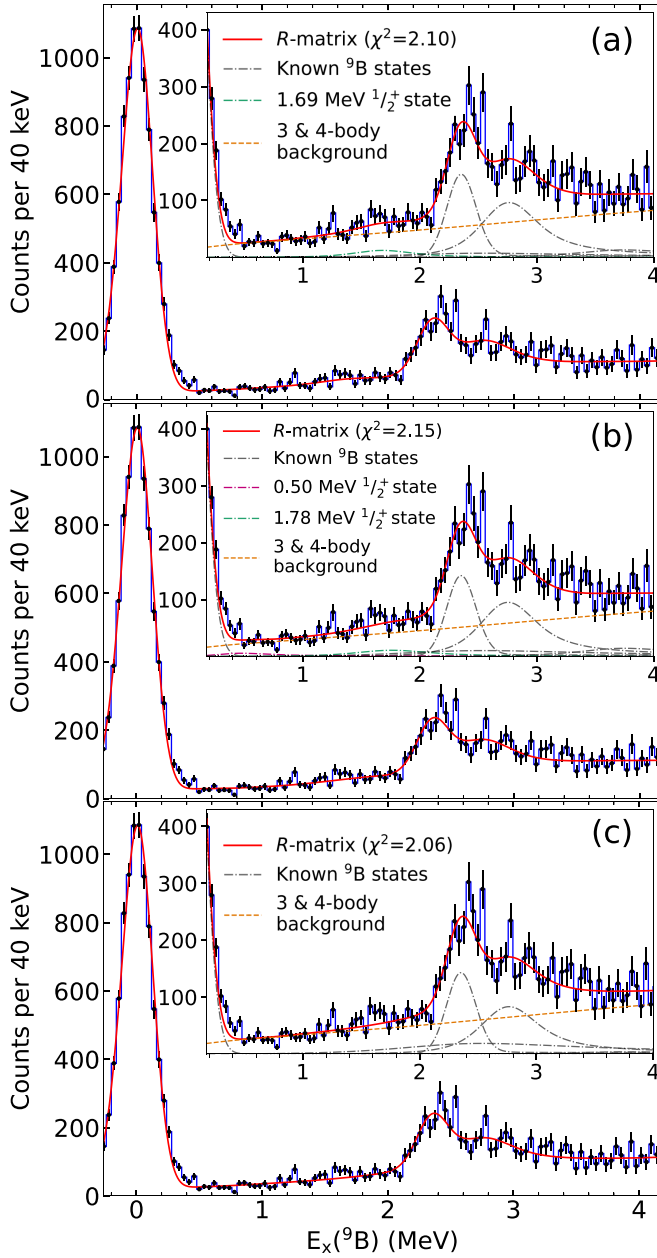


FIG. 8. R -matrix fits for 106° ${}^9\text{B}$ missing-mass excitation spectrum corresponding to (a) single-state, (b) double-state, and (c) no-state hypotheses. R -matrix fits are generated by ARGONAUT and optimized through the gradient-descent fitting routine REVERSE SISYPHUS. Known states are shown by the grey dot-dashed lines, three- and four-body background contributions by the yellow dashed line, and generated $1/2^+$ states by the green and magenta dot-dashed lines.

other states across the excitation spectrum is also likely able to result in the observed shift of the state centroid and width during fitting.

2. Break-up-gated missing mass

By repeating the analysis on the missing-mass spectrum but with an additional gate on the ${}^8\text{Be}$ ground-state from the decay breakup reconstruction, the results shown in Fig. 11

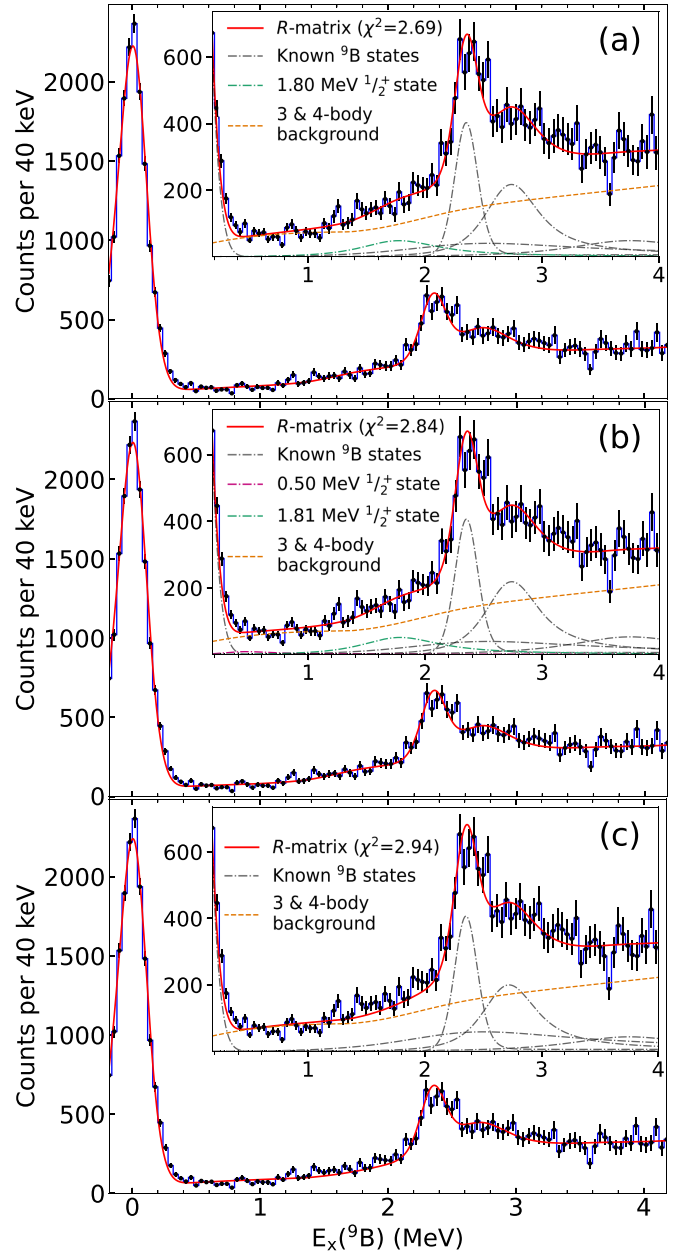


FIG. 9. R -matrix fits for combined 31° and 106° ${}^9\text{B}$ missing-mass excitation spectrum corresponding to (a) single-state, (b) double-state, and (c) no-state hypotheses. R -matrix fits are generated by ARGONAUT and optimized through the gradient-descent fitting routine REVERSE SISYPHUS. Known states are shown by the grey dot-dashed lines, three- and four-body background contributions by the yellow dashed line, and generated $1/2^+$ states by the green and magenta dot-dashed lines.

are obtained. Here it is seen that the single-state fit shows the greatest statistical significance. As identified in the combined missing-mass excitation spectrum, R -matrix fit optimization indicates the presence of a state at an excitation energy of 1.85 MeV, although with a larger width of 920 keV. This difference likely arises from a decrease in statistics as a result of breakup detection constraints when compared with the combined missing-mass excitation spectrum in Fig. 9. This is

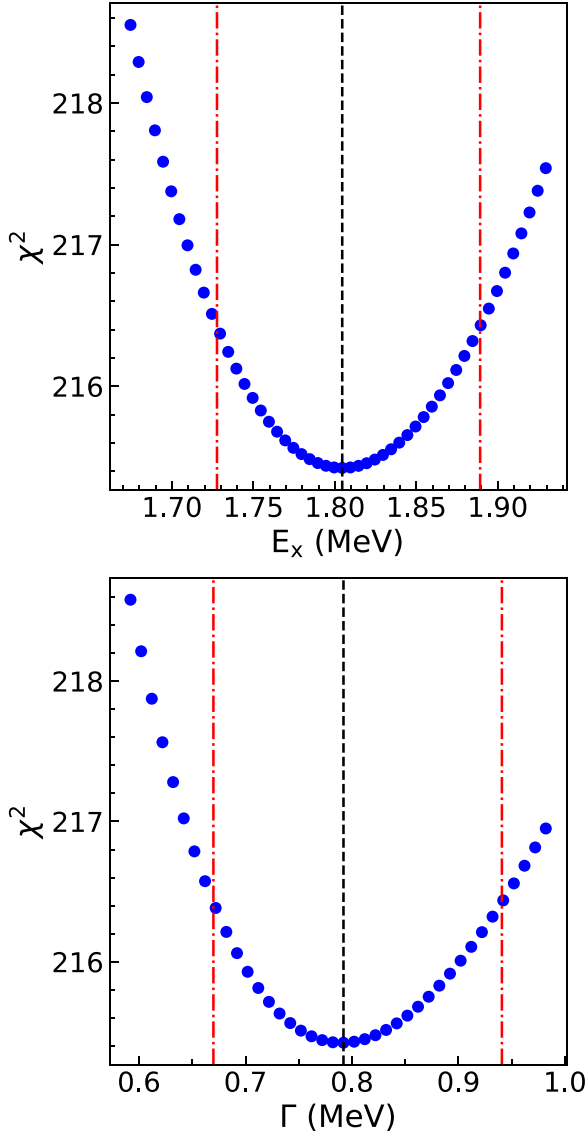


FIG. 10. Sensitivity of χ^2 to changes in observed state excitation energy, E_x , and width, Γ , for the combined ${}^9\text{B}$ missing-mass excitation spectrum. Red dot-dashed lines denote values of E_x and Γ that correspond to a change from the minimized χ^2 by 1.

different to the smaller width obtained during fitting of the 31° data in Fig. 6(a) as a result of state masking by the neighboring 2.35 MeV $5/2^-$ state. As previously, sensitivity of the χ^2 is measured for each state property, shown in Fig. 12, allowing for the extraction of uncertainties. From this a reported excitation energy and width of 1.85 ± 0.07 MeV and $920 \pm_{130}^{160}$ keV are obtained. This means state properties extracted from both missing-mass and breakup-gated missing-mass spectra are in agreement within one standard deviation, while the resonance from the 31° data lies within two standard deviations. A tabulation of all of the observed resonance parameters from the current work is given in Table II.

IV. DISCUSSION

The sensitivity of the state width to the statistics level of the breakup-gated data, as well as the sensitivity of the centroid to

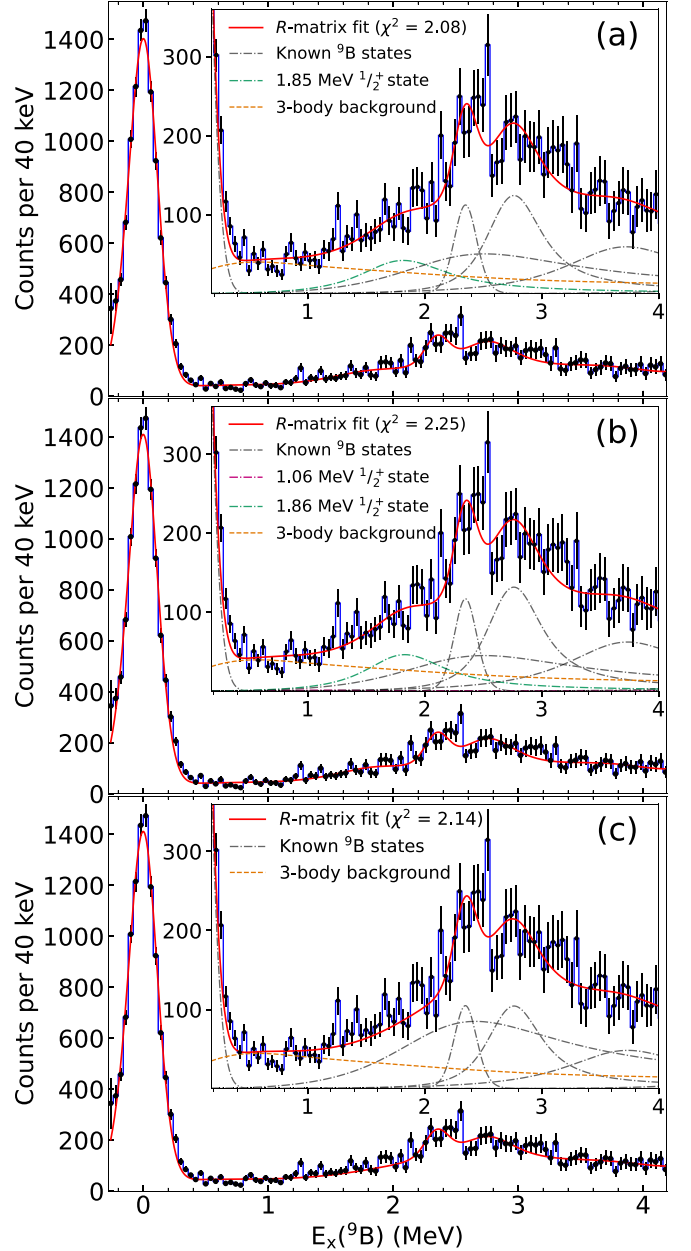


FIG. 11. R -matrix fits for combined 31° and 106° ${}^9\text{B}$ breakup-gated missing-mass excitation spectrum corresponding to (a) single-state, (b) double-state, and (c) no-state hypotheses. R -matrix fits are generated by ARGONAUT and optimized through the gradient-descent fitting routine REVERSESISYPHUS. Known states are shown by the grey dot-dashed lines, three-body background contributions by the yellow dashed line, and generated $1/2^+$ states by the green and magenta dot-dashed lines.

TABLE II. Resonance excitation energy, E_x , and width, Γ , values for the observed state within 31° , combined, and breakup-gated missing-mass spectra obtained from R -matrix fitting.

Dataset	E_x (MeV)	Γ (keV)
31°	2.00 ± 0.05	$430 \pm_{110}^{130}$
Combined	1.79 ± 0.08	$790 \pm_{120}^{150}$
Breakup-gated	1.85 ± 0.07	$920 \pm_{130}^{160}$

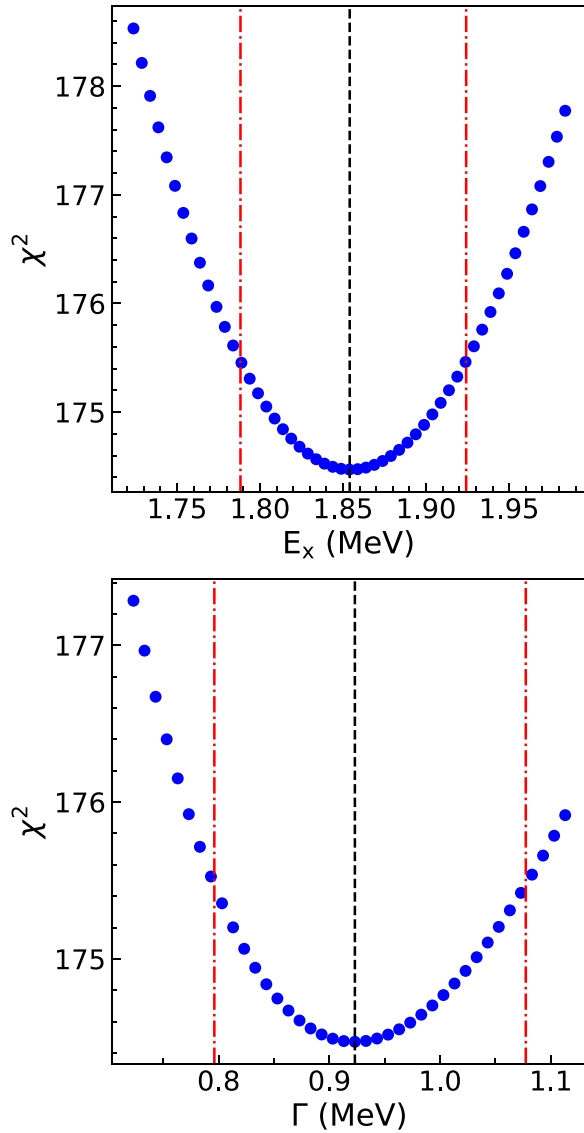


FIG. 12. Sensitivity of χ^2 to changes in observed state excitation energy, E_x , and width, Γ , for the combined ${}^9\text{B}$ forward-gated missing-mass excitation spectrum. Red dot-dashed lines denote values of E_x and Γ that correspond to a change from the minimized χ^2 by 1.

the neighboring $5/2^-$ state within nongated data, indicate that just one single result cannot be taken. To avoid these issues, a weighted average was calculated from the combined and breakup-gated resonance results to produce a final result of $E_x = 1.83 \pm 0.05$ MeV and $\Gamma = 850 \pm {}^{110}_{88}$ keV at a confidence level of 99.1%. The 31° resonance result is neglected in this average as it is already incorporated into that of the combined data resonance. Comparison to experiments reporting a 1.8 MeV candidate performed in the last 25 years show the result obtained in the current work is in agreement with those literature results, as highlighted in Fig. 13. Combination of those results with that presented in the current work yields weighted average resonance parameters of $E_x = 1.84 \pm 0.04$ MeV and $\Gamma = 740 \pm {}^{77}_{66}$ keV. A point of note from performed

R -matrix fitting is that in all cases the single-state hypothesis resulted in a higher-lying excitation state as opposed to a lower one. Furthermore all dual-state fits were always successfully and unambiguously rejected. This provides further evidence in resolution to the long-standing dilemma showing that a $1/2^+$ candidate does not appear to lie at ≈ 0.8 MeV, narrowing the possible range of excitation energies in future searches. Indeed, as previously shown [19], any contribution in this low-energy region is likely due to ghost-peak or phase-space background contributions, which inherently prohibit the existence of a low-lying state with anything but near-zero population.

Although unable to extract full angular distributions in the current work, theoretical distorted-wave Born approximation (DWBA) calculations were performed in FRESKO [35] to postulate possible spin-parity assignments to the state of interest. DWBA transfer calculations describing triton exchange with differing ℓ values in the ${}^{12}\text{C}(p, \alpha)$ reaction are shown in Fig. 14. Additionally, the compound nucleus angular distribution for the ${}^9\text{B}$ ground state is also included. Modeling of the compound nucleus angular distribution was achieved by assuming an isotropic distribution in the center-of-mass frame (well justified due to the high excitation populated in ${}^{13}\text{N}$ and therefore the high level density) with the absolute cross section obtained from PACE4 [36,37]. One should note that the veracity of DWBA calculations does begin to decrease away from the first maxima and so becomes more qualitative for larger angles.

Considering again the R -matrix fits for the single-state hypothesis within the 31° and 106° data, while the gradient-descent algorithm is able to assign a state to the 31° data, it is unable to provide any contribution for the 106° fit. This highlights that the resonance observed in the current work shows relatively strong population at 31° but is weakly populated at 106° . For any definitive selection to be made regarding the angular momentum transition, a greater number of recoil detection angles is required across the 31° – 106° range, particularly for angles closer to the zero degrees direction. This is also not considering that the most probable reaction channel here is through compound nucleus production instead of triton transfer; a process which does not allow for the inference of state spin-parity. Calculation of the ground-state relative populations at 106° and 31° yields a ratio of 0.204 ± 0.085 , which aligns more with the ratio of 0.796 from the compound nucleus cross section as opposed to the ratio from the t -transfer cross section of 0.0006. Likewise, for the observed 1.83 MeV state, a ratio of 0.226 ± 0.122 disagrees with calculated t -exchange ratios of 0.0013, 0.0006, and 0.0082 from $\ell = 0, 1$, and 2 transitions respectively. This suggests a different reaction mechanism, such as 31° – 106° $\text{Be}({}^3\text{He}, t)$ charge exchange, is better suited for spin-parity assignments than the ${}^{12}\text{C}(p, \alpha)$ reaction. Alternatively, the ${}^{12}\text{C}(p, \alpha)$ resonant scattering pathway, as proposed by Sherr and Fortune, but utilizing an active-target time projection chamber (TPC) to deal with the low energy final-state products, might also yield improved results by proceeding through an isolated, well-defined spin-parity state in ${}^{13}\text{N}$ where $\ell = 0$ decay to ${}^9\text{B}(1/2^+)$ is preferred due to the penetrability.

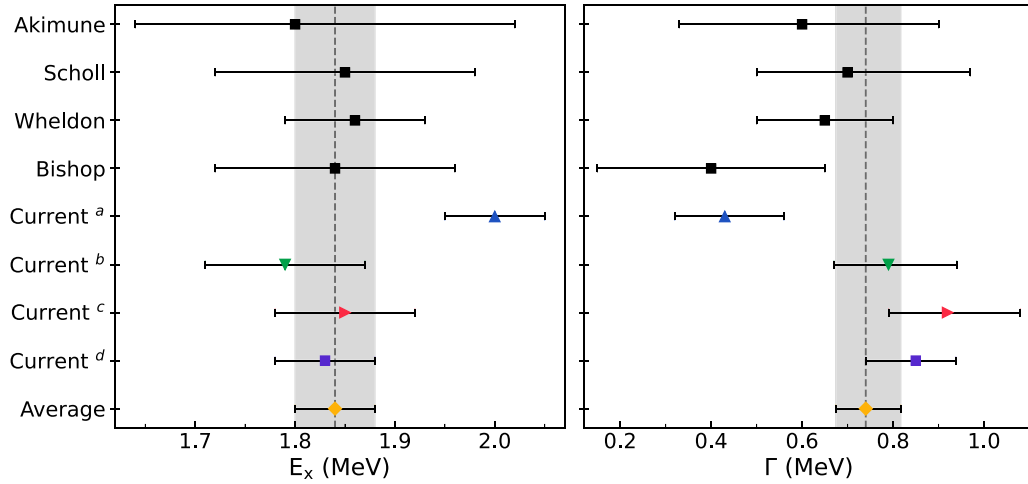


FIG. 13. Published excitation energy and width results for observed 1.8 MeV states in ${}^9\text{B}$ since 2000 [11,12,14–16], including results from the current work. An average of all square points is also provided—represented by the lowest diamond symbol—to denote the global average of results published to date including from the current work. The current result denoted *a* is from *R*-matrix fitting to the 31° missing-mass data, *b* the combined missing-mass data, *c* the breakup-gated missing-mass data, and *d* the weighted average of the state properties from the combined and breakup-gated missing-mass results.

V. CONCLUSION

To summarize, a recent experiment conducted at the Birmingham MC40 Cyclotron using the ${}^{12}\text{C}(p, \alpha){}^9\text{B}$ reaction was performed. From coincident detection of recoil α particles and breakup decay products, signatures of a resonance are found at an excitation energy of $E_x = 1.83 \pm 0.05$ MeV, possessing a width of $\Gamma = 850 \pm_{88}^{110}$ keV with a confidence level of 99.1%. This reported observation is consistent with previous measurements over the last 25 years suggesting that a state exists in ${}^9\text{B}$ at a weighted average excitation of $E_x = 1.84 \pm 0.03$ MeV and possesses a width of $\Gamma = 740 \pm_{66}^{77}$ keV. This result confirms an inverted Thomas-Ehrman shift relative to the analog state in ${}^9\text{Be}$, improving our understanding of the

charge independence of the nuclear force and the structural properties of the state. No evidence of a resonance within the 0.8–1.0 MeV region is found, with single-state fits at a higher centroid energy being the most statistically significant. This strongly indicates that states below ≈ 1 MeV can be ruled out in the search for the ${}^9\text{B}(1/2^+)$ analog state. Although unable to provide direct spin-parity assignments, investigations into relative population of the observed 1.83 MeV resonance between 106° and 31° data are performed. Compared against population ratios from DWBA calculations, triton transfer is shown to be unlikely. Thus, dominated by the compound nucleus and fusion evaporation pathway, the accuracy of any transfer assignment in the current work is limited and requires

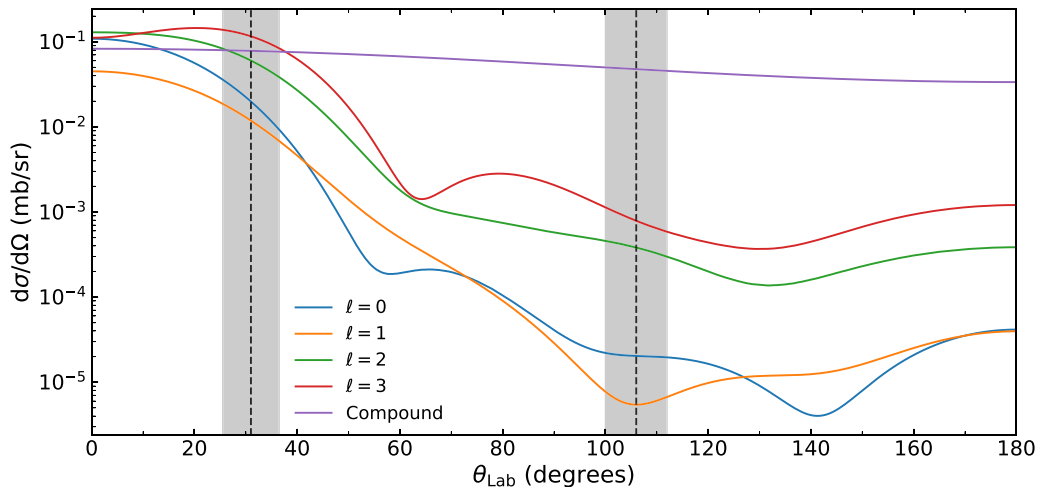


FIG. 14. DWBA calculations performed in FRESKO [35] for the ${}^{12}\text{C}(p, \alpha)$ triton transfer reaction with $\ell = 0, 1, 2, 3$. The compound nucleus angular distribution for the ${}^9\text{B}$ ground state, obtained using PACE4, is also overlaid. Relevant recoil detection angles are denoted by the dashed lines and the full angular coverage by the grey shaded regions.

a different population mechanism to be explored for definitive angular distribution measurements.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [38].

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