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Precise γ-ray intensity measurements in ^{10}B

E. A. McCutchan,[1,2] C. J. Lister,[1,3] M. Elvers,[4,5] D. Savran,[4,6,7] J. P. Greene,[1] T. Ahmed,[8] T. Ahn,[4] N. Cooper,[4] A. Heinz,[4] R. O. Hughes,[8] G. Ilie,[4,9] B. Pauerstein,[8] D. Radeck,[4,5] N. Shenkov,[8] and V. Werner[4]
[1] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2] *National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York 11973, USA*
[3] *Department of Physics and Applied Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[4] *Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511, USA*
[5] *Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[6] *ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*
[7] *Frankfurt Institute for Advanced Studies FIAS, D-60438 Frankfurt am Main, Germany*
[8] *Department of Physics, University of Richmond, Richmond, Virginia 23173, USA*
[9] *National Institute for Physics and Nuclear Engineering, P.O. Box MG-6 Bucharest-Magurele, Romania*

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Precise electromagnetic transition matrix elements in ^{10}Be and ^{10}C have provided surprisingly stringent tests of modern *ab initio* calculations using realistic nuclear forces. The analog transition in ^{10}B can further constrain these new calculations and probe the symmetry of the wave functions across the $A = 10$ multiplet. We report on a careful measurement of the γ-ray intensities from states populated in the ^{10}B(p,p') reaction at 10 MeV, including a determination of the key $E2$ branch from the $J = 2$ $T = 1$ state at 5164 keV to the $J = 0$ $T = 1$ state at 1740 keV of 0.16(4)%.

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Ab initio calculations of light nuclei, using Hamiltonians based on realistic two-body nucleon-nucleon forces and empirical three-body forces have been one of the major triumphs of nuclear structure in the last decade [1,2]. They are leading to a more profound understanding of nuclear structure; the origin of the mean field, the source of the spin-orbit and tensor forces, and the causes of correlations like pairing and α clustering. A wide variety of experiments have tested the veracity of the new wave functions, including measuring rms radii [3], spectroscopic factors [4], knockout reaction probabilities [5], and electromagnetic transition rates [6,7].

Electromagnetic transitions have proven to be a difficult challenge for the new theories [7] as they are sensitive to cancelations between many small components in the wave functions. The mixing induced by three-body forces has a surprisingly strong effect on predicted transition rates, to a point where these rates may eventually become a significant constraint for three-body formulations in the future. We have recently precisely measured the $A = 10$ nuclei ^{10}Be [6] and ^{10}C [7] in order to study isospin effects and eventually investigate charge-symmetry breaking. We found that the electric quadrupole radiation from the first excited 2^+ state is an almost pure isoscalar motion, corresponding to tumbling of the di-α core. The isovector influence of the two neutrons in ^{10}Be, or the two protons in ^{10}C is surprisingly small. Counterintuitively, the isovector contribution is destructive in ^{10}C, and the extra charge leads to slower radiation of photons. This is in agreement with the original shell model of Cohen and Kurath [8,9] but is difficult to reproduce in our modern *ab initio* calculations [7]. In order to understand this issue better, one needs to complete the set of measurements in the $A = 10$ isotriplet by accurately determining the equivalent transition in ^{10}B. Naively, this should be the average of the ^{10}C and ^{10}Be matrix elements. Deviations from this value can only arise from explicit charge symmetry breaking and imply an explicit isotensor contribution from the wave functions to the decays.

The measurements of the matrix element in the even-even nuclei ^{10}Be and ^{10}C are straightforward as the state of interest, the first excited $J^\pi = 2^+$ state, is bound in both cases and decays 100% by γ-ray emission, so the matrix element is inversely proportional to the square root of the half-life. Consequently, a precise measurement of the lifetime of the state directly provides the quadrupole matrix element. The $T = 1$ analog transition in $T = T_z = 0$ ^{10}B lies high in excitation energy (5164 keV) and is particle unbound, so is more difficult to study and needs three good measurements: the width of the state (equivalent to the lifetime), the particle decay branch, and the γ-ray branch, in order to obtain the matrix element. Currently, for the $T = 1$, 2^+ state in ^{10}B, the width is reasonably well known [10,11], at the 7% level, the α-decay branch moderately well known [12,13], at the 25% level, but the γ-ray branch has several conflicting published results and the most recent data evaluation [14] reports only an upper limit of <0.5% for the transition of interest.

In this Brief Report we present a new study of ^{10}B in which we clarify the sources of disagreement between previous γ-ray studies, measure this key γ-ray branching ratio, and determine an $E2$ matrix element for the $T = 1$, $J = 2 \rightarrow 0$ decay. The $B(E2)$ value is not sufficiently precise to strongly constrain the new theories. However, we can assess what new measurements are needed to make a determination that is really challenging to theory. In the course of this work, we also remeasured the relative intensities of γ rays from two additional bound states of ^{10}B, improving the precision of the γ-ray branching ratios and thus, many other electromagnetic matrix elements.

Excited states in ^{10}B were populated in the (p,p') reaction using a 10 MeV proton beam provided by the ESTU Tandem

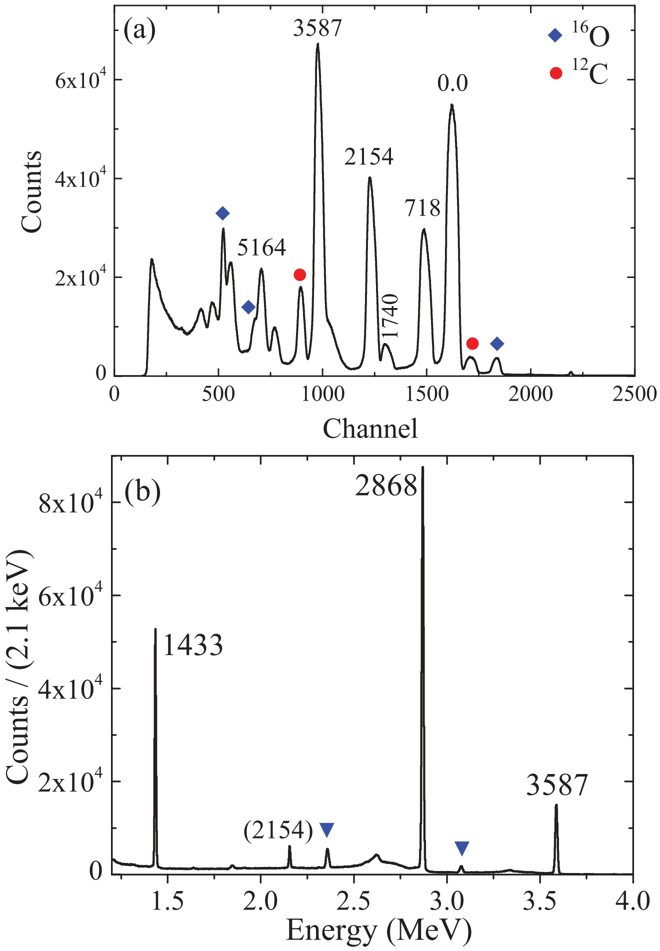

FIG. 1. (Color online) (a) Particle spectrum from one silicon detector. Levels in ^{10}B are labeled by their energy in keV. Symbols indicate states in ^{12}C and ^{16}O. (b) γ-ray spectrum from a gate on population of the 3587-keV level in the proton spectrum. Depopulating transitions are labeled by their energy in keV. Triangles indicate single escape peaks.

accelerator at the Wright Nuclear Structure Laboratory (WNSL) at Yale University. A ~300 μg/cm^2 self-supporting ^{10}B target was used. A beam current of ~28 pnA yielded a $p\gamma$ coincidence rate of ~2.5 kHz. Scattered protons were detected in five Si surface-barrier detectors, four positioned at backward angles, ~130° to the beam direction, and one at 90°. γ rays were detected by nine Compton-suppressed Clover detectors. Data were acquired simultaneously with three triggers: $p\gamma$ coincidences, downscaled γ singles and downscaled particle singles. The experimental setup and sorting procedure are described in more detail in Ref. [15].

An example of a particle spectrum from a single Si detector is given in Fig. 1(a). Several excited states in ^{10}B are observed, including the $J^\pi = 3^+$ ground state, 1^+ 718-, 0^+ 1740-, 1^+ 2154-, 2^+ 3587-, and 2^+ 5164-keV levels. A few states in ^{16}O and ^{12}C are also observed, resulting from contamination in the target. A sample of the γ-ray spectrum obtained by gating on population of the 3587-keV level in the proton spectrum is given in Fig. 1(b). These spectra are incredibly clean with very little background or contamination. Also, the statistics in the spectra are sufficient such that the uncertainty in the intensity of strong decay branches is dictated by knowledge of the γ-ray efficiency of the Clover detectors.

The γ-ray branches from the 1^+, 2154-keV and 2^+, 3587-keV levels were measured in a number of experiments, as summarized in Table I. The adopted values [14] are taken from the values recommended by Ref. [19] (see Ref. [19] for a description of their weighting procedure and values included in the average from a private communication). The results of the present measurement are given in Table I and provide a considerable reduction in uncertainty compared with the prior individual studies. For both levels, the statistics were sufficient that the γ-ray branches could be measured in coincidence with each individual Si detector; the results in Table I are then a weighted average of five individual measurements. The evaluated branches for both the 2154- and 3587-keV levels favor the results of Ref. [19], as these are quoted to the highest precision. In fact, the results from the present work are in very close agreement with those of Ref. [18].

There has been some controversy concerning the decay branches from the 5164-keV level, particularly for the 3423-keV γ-ray transition corresponding to the $T = 1, 2^+$ to $T = 1, 0^+$ transition. The results from prior measurements on the γ-ray branches from the 5164-keV level are summarized in Table II. The determination of the 3423-keV γ-ray intensity is complicated by two factors. First, a nearby 5182-keV wide resonance ($\Gamma = 110$ keV) has a broad γ decay centered at 3439 keV. The total γ decay from this $T = 0$, 1^+ state is small, 5×10^{-4}%, thus only affects the measurement if the state is strongly populated in a given reaction. The second complication is the fact that the 3423-keV γ-ray can be masked by the double-escape (DE) peak from the 4444-keV γ

TABLE I. Branching ratios for the 2154-keV and 3587-keV levels in ^{10}B.

E_i (keV)	E_γ (keV)	E_f (keV)	Present work	Evaluated [14]	Ref. [16]	Ref. [17]	Ref. [13]	Ref. [18]	Ref. [19]	Ref. [20]
2154	2154	0.0	17.5(4)	21.1(16)	16	27(7)	24	17.5(20)	20.2(14)	
	1436	718	24.8(5)	27.3(9)	29	26(6)	23	26.3(20)	28.6(20)	
	414	1740	57.7(6)	51.6(16)	55	47(5)	53	56.2(20)	51.2(31)	
3587	3587	0.0	16.7(3)	19(3)			12	16.6(20)	24.2(17)	18.9(27)
	2868	718	66.0(5)	67(3)			76	68.2(20)	63.8(19)	67.0(29)
	1847	1740	<1				<0.3	<5	<1	<3
	1433	2154	17.3(3)	14(2)			12	15.4(20)	12.0(9)	14.1(16)

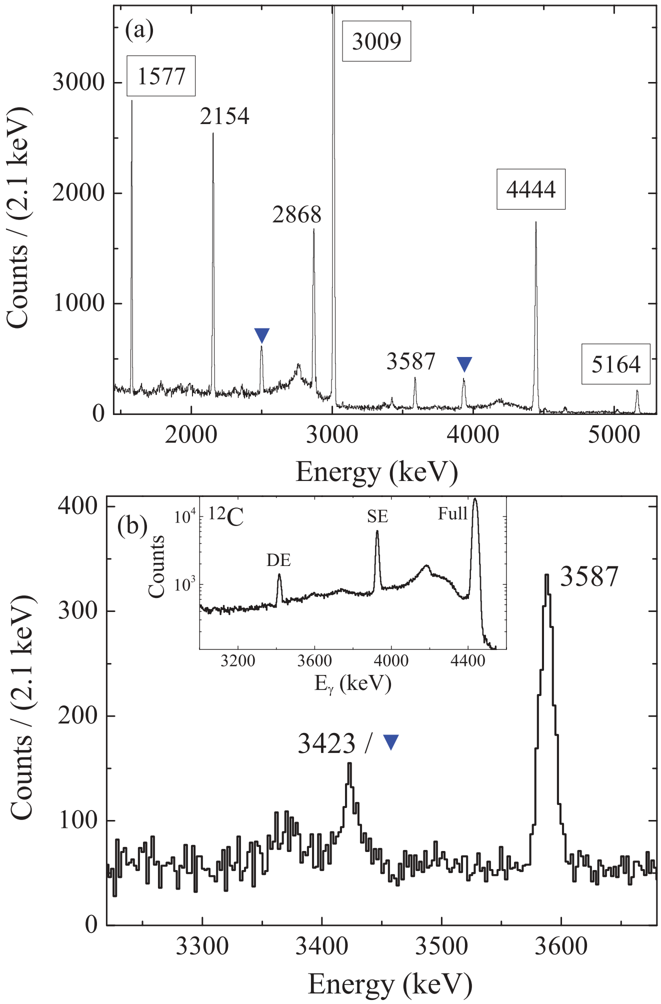

FIG. 2. (Color online) γ-ray spectra from a gate on population of the 5164-keV level in the proton spectrum. Spectra are shown in the regions (a) 1500 keV to 5200 keV and (b) around the 3423-keV transition. γ rays are labeled by their energy in keV; those in boxes are transitions directly depopulating the 5164-keV level whereas others are transitions from lower energy levels populated in the decay. Diamonds indicate escape peaks. The 3009-keV transition shown in (a) is plotted off-scale on the ordinate (actual peak height is approximately 9000 counts). The inset in (b) shows a proton gate on the inelastic excitation of the 2_1^+ state in ^{12}C in log scale. See text for explanation.

ray which also depopulates the 5164-keV level. The original measurement by Forsyth *et al.* [21] determined a 2% branch for the 3423-keV transition. This measurement used the ^{6}Li(α,γ) reaction which suffered from contamination by the 5182-keV resonance. A subsequent measurement by Paul *et al.* [23], using the ^{10}B(p,p') reaction (which does not strongly populate the 5182-keV resonance), observed no indication of a 3423-keV γ-ray and set a limit for its decay branch at <0.5%. To clarify this discrepancy, Ref. [24] repeated the measurement using again the ^{6}Li(α,γ) reaction. To separate the 3423-keV γ ray from that of the DE peak of the 4444-keV transition, the γ-ray spectrum was measured at 0° where the two peaks were separated by ~10 keV due to differing Doppler shifts. They observed the 3423-keV branch and measured its intensity as 0.7(2)%. Finally, Ricken *et al.*, [25] used the ^{9}Be(p,γ) reaction, did not observe the 3423-keV γ-ray branch and placed a limit of <0.6% on its intensity.

Figure 2 gives the proton-gated spectrum from the decay of the 5164-keV level as measured in the present work. The strong decay branches are illustrated in Fig. 2(a) and the measured branches given in Table II. The present work shows some disagreement with the prior measurements, particularly for the transitions to the 718-keV and 2154-keV levels. An expanded view of the spectrum around the 3423-keV transition is given in Fig. 2(b). A peak at 3423-keV is clearly observed, however, as discussed previously, this transition is contaminated by the DE peak from the 4444-keV γ ray. In this particular instance, the presence of a ^{12}C contaminant in the experiment is fortuitous, as the strong 4438.0-keV transition from the decay of the 2_1^+ level provides an excellent calibration point for understanding the DE peak of the 4444-keV transition in ^{10}B. Using the 4438-keV transition, the shape of its DE peak and the ratio of the full energy peak to the DE peak intensity were determined; the quality of this spectrum is illustrated in the inset of Fig. 2(b). The energies are similar enough, that this information can be used to determine the DE peak intensity of the 4444-keV transition and subtract it from the total intensity observed for the 3423-keV γ ray. Following this procedure, we arrive at a γ-ray branch of 0.16(4)% for the 3423-keV transition. The correction for the DE peak was large, approximately 400 counts out of the total 550 counts measured in the 3423-keV peak, and so reduced the statistical precision considerably. The uncertainty of this γ-branching ratio can be significantly improved, realistically to better than 10%, if a new measurement is made using a spectrometer with better pair-suppression and higher overall efficiency, such as Gammasphere.

The width of the 5164-keV state has been measured by several authors [12,21,26] with considerable scatter between the reported values. Spear *et al.* [10] added a more recent determination, 400 ± 60 meV, and recognized an error in the analysis of some earlier works, which led to a considerable improvement in consistency. The most recent determination by Gyürky *et al.* [11] 366 ± 38 meV, is consistent with Spear's finding and the weighted combination of results is now 387 ± 27 meV, a 7% determination. The leading systematic source of error in the two latter studies was the absolute efficiency calibration of the γ-ray detector. With current technology [27], the uncertainty can be reduced to less than 1%.

The 5164-keV state is unbound against breakup into ^{6}Li + α. The α-decay branch has been measured in two studies. Alburger *et al.* [12] made a very careful study of this state following the ^{11}B(^{3}He,α)^{10}B reaction. They measured both the α-decay branch with α-α-recoil coincidences, and the γ-ray branches in α-γ coincidences. They obtained breakup branches Γ_α/Γ of 0.12(4) and 0.14(4), respectively, averaging to 0.13(4). A less precise value of 0.27(15) was inferred by Segel *et al.* [13] using the ^{10}B(p,p') reaction and absolute measurement of the yield of coincident γ rays. The evaluated result [14] is a weighted average of the two measurements yielding $\Gamma_\alpha/\Gamma = 0.16(4)$; a 25% uncertainty which needs

TABLE II. Branching ratios for the 5164-keV level in ^{10}B.

E_i (keV)	E_γ (keV)	E_f (keV)	Present work	Evaluated [14]	Ref. [21]	Ref. [22]	Ref. [23]	Ref. [24]	Ref. [25]
5164	5164	0.0	5.3(5)	4.4(4)	5(1)	7		4.4(4)	
	4444	718	31.7(12)	22.6(6)	24(3)	27		22.4(6)	
	3423	1740	0.16(4)	<0.5	2(1)		<0.5	0.7(2)	<0.6
	3009	2154	55.5(16)	65.3(9)	69(5)	57		64.8(9)	
	1577	3587	7.3(5)	7.8(3)		9(2)	4.5(10)	7.7(3)	

improving to produce a stringent test of theory. Using contemporary technology like the superconducting solenoid, HELIOS [28], where both γ-emitting and α-decaying recoil nuclei can be collected with near-identical efficiency, a much more precise determination of the α branch, probably below the 5% level, should be straightforward.

Combining the width, the α branch and the new γ branch from the present work now yields a $B(E2;\, 2^+ \rightarrow 0^+)$ value of 6.1(22) e^2fm^4 between the $T = 1$ states, a significant improvement over the evaluated value [14] of < 19 e^2fm^4. The new $B(E2)$ strength can be compared with the values recently measured in ^{10}C and ^{10}Be of 8.8(3) e^2fm^4 and 9.2(3) e^2fm^4, respectively. Naively, one would expect the ^{10}B value to be the simple average of the ^{10}C and ^{10}Be values. The *ab initio* Green's function Monte Carlo prediction [7] with the IL7 three-body potential lies somewhat higher at 11.4(6) e^2fm^4. In this context, the current value of 6.1(22) e^2fm^4 is surprisingly low, and thus interesting, but until the precision of the γ and α branches is improved, it is not statistically significant. New measurements of these quantities are planned using the current technologies of Gammasphere and HELIOS with a goal of determining this key decay rate at a level of $<10\%$.

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