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First Experiment with HELIOS: The Structure of ^{13}B

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A first experiment is reported that makes use of a new kind of spectrometer uniquely suited to the study of reactions with radioactive beams in inverse kinematics, the helical orbit spectrometer, HELIOS. The properties of some low-lying states in the neutron-rich $N = 8$ nucleus ^{13}B were studied with good resolution. From the measured angular distributions of the (d, p) reaction and the relative spectroscopic factors, spin and configuration assignments of the first- and third-excited states of this nucleus can be constrained.

In light nuclei with large neutron excess, the ordering of single-particle states and the nuclear shells are different from those in nuclei near stability. The gap between the $0p_{1/2}$ and $1s_{1/2}$ orbits vanishes in light neutron-rich systems and $N = 8$ ceases to be a magic number. The ground states of the $T_z = 3/2$ nuclei ^{11}Be and ^{15}C with 7 and 9 neutrons have $J^\pi = 1/2^+$, while the $T_z = 1/2$ nuclei with the same number of neutrons, ^{13}C and ^{17}O, have the "normal" spins of $1/2^-$ and $5/2^+$, respectively. For the 8-neutron systems, the halo nuclei ^{11}Li ($T_z = 5/2$) and ^{12}Be ($T_z = 2$) each have large $(1s_{1/2})^2$ components in their ground-state wave function. In contrast, the $T_z = 1$ nucleus ^{14}C has very little such admixture, as does ^{15}N, with $T_z = 1/2$. Thus the $T_z = 3/2$ nucleus ^{13}B with 8 neutrons is on the borderline between the two regimes. The ground state has $J^\pi = 3/2^-$, and the properties of low-lying positive-parity states contain information about the $1s_{1/2}$ and $0d_{5/2}$ single-particle energies and the residual interaction.

Information on excited states of ^{13}B stems largely from the work of Middleton and Pullen [1] who measured the ^{11}B$(t, p)^{13}$B reaction, identifying the first four excited states in ^{13}B clustered around 3.6 MeV, and two more states at $\sim$4.8 MeV. From the shapes of the angular distributions Middleton and Pullen suggested some constraints on the parities of the excited states as shown in Fig. 1. In particular, they proposed that the states at 3.48 and 3.68 MeV have even parity [$\ell = 1$ in (t, p)] which would favor spin assignments between $1/2^+$ and $5/2^+$. More recently, additional information on ^{13}B was obtained by Guimarães *et al.* [2] who measured neutron knockout on ^{14}B and suggested that the 3.48-MeV state was $3/2^+$, and the 3.68-MeV state $5/2^+$ on the basis of a comparison of the data with theoretical calculations; Ota *et al.* [3] measured the proton-adding ^{12}Be$(\alpha, t)^{13}$B reaction and saw a

strong $\ell = 0$, $1/2^+$ state at 4.83 MeV interpreted as a proton intruder state; Iwasaki *et al.* [4] suggested $3/2^-$ for the state at 3.53 MeV from a lifetime measurement, an assignment that is consistent with the odd parity result from [1]. These assignments also seem consistent with the recent measurement of Guess *et al.* [5] who saw significant Gamow-Teller strength in the ^{13}C$(t, {}^3$He$)^{13}$B reaction.

The (d, p) reaction is a powerful tool for studying the spectroscopic overlaps of a single neutron added to a target. With short-lived beams it has to be measured in inverse kinematics, posing technical challenges, especially when states are closely spaced in energy. In order to help clarify the structure of ^{13}B and obtain assignments of spins and spectroscopic strengths to the states of this nucleus, we have measured the neutron-adding ^{12}B$(d, p)^{13}$B reaction in
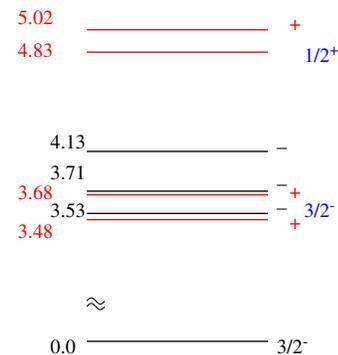

FIG. 1 (color online). The observed levels in ^{13}B, up to $\sim$5-MeV excitation, from various sources. The negative- and positive-parity states of Ref. [1] are indicated [black and light gray (red)] with a "−" or "+" on the right-hand margin. The recent spin assignments [3,4] are in dark gray (blue) on the right-hand side.

inverse kinematics as a first application of the helical orbit spectrometer (HELIOS) [6]. A beam of ^{12}B ($T_{1/2} = 20$ ms) was produced using a primary ^{11}B beam, from the ATLAS accelerator at Argonne National Laboratory, with an intensity of up to 50 p nA at 81 MeV to bombard a cryogenic deuterium gas cell by the method described in [7]. It yielded a secondary ^{12}B beam, on target, of approximately 10^5 ions/s at 75 MeV. The results of an earlier measurement of this reaction, carried out using the traditional experimental approach with an array of segmented silicon detectors, has recently been published [8]. There were indications of large transfer strength near the 3.6-MeV even-parity doublet, but the resolution of that experiment was not sufficient to draw any further conclusions.

The separation of the closely spaced doublet served as a stringent test of the capabilities of HELIOS to obtain high-resolution data in inverse kinematics with short-lived beams at ATLAS. HELIOS consists of a superconducting solenoidal magnet with a 2.35-m long, 0.9-m diameter bore and maximum central field strength of 2.7 T. In the present measurement the magnetic field was 1.05 T. The beam was incident along the magnetic axis and passed through the hollow array of position sensitive (along the beam direction) silicon detectors placed between 350 and 700 mm upstream from the target. The ^{12}B beam, after passing through the array, bombarded a 73-μg/cm^2-thick CD$_2$ target. In inverse kinematics, protons corresponding to small center-of-mass angles are emitted in the backward hemisphere. In the magnetic field these protons follow helical trajectories and return to the axis in a single cyclotron period, where they are detected in the silicon array with their energy, flight time, and distance from the target determined [6]. In HELIOS, the energy dispersion by angle is translated by the trajectories in the magnetic field into position dispersion along z, the axis of the magnet. Coincidences with recoiling ^{13}B ions were required in order to minimize backgrounds from the C component of the CD$_2$ target as well as from contamination by the primary ^{11}B beam. The recoil ions were detected in a Si telescope consisting of ΔE and E detectors of thickness 80 and 500 μm, covering laboratory angles between 0.5° and 2.8°.

The laboratory proton energies for $\sim$3.6 MeV excitation in ^{13}B, for an incident ^{12}B energy of 75 MeV and for protons at forward center-of-mass angles, are in the range of $\sim$0.5–3 MeV. Protons from the inverse $d(^{11}$B$,p)^{12}$B reaction at $E(^{11}$B$) = 81$ MeV to states at 2.62 and 3.39 MeV, which are known to have large spectroscopic factors, have proton energies close to those for the ^{13}B doublet over the entire angle range. Data with the ^{11}B beam were taken to provide reference angular distributions and a calibration of efficiencies (sensitive to threshold effects at the very low proton energies).

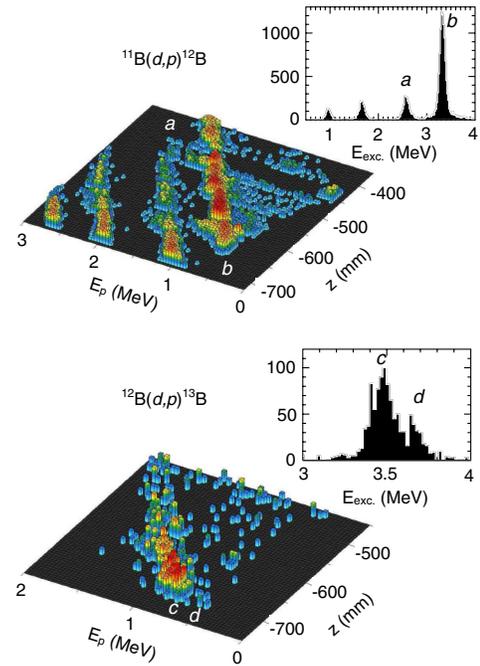The relation between position and energy in the data is shown in Fig. 2 for the two beams, and represents a partial

FIG. 2 (color online). Raw data from ^{11}B$(d,p)^{12}$B (top) and ^{12}B$(d,p)^{13}$B (bottom). The three-dimensional plots (with units displayed logarithmically) in the E_p vs z plane show ridges that correspond to different excited states of the final nucleus. The insets show the projection of the data onto excitation energy in the final nucleus. The states labeled a and b in the upper image correspond to the 2.62- and 3.39-MeV states of ^{12}B, while in the lower one the labels c and d are the 3.48/3.68-MeV doublet studied in ^{13}B. The range in z corresponds to angles of $\sim$10°-30° in the center of mass.

set of detectors. The prominent ridges in yield in the E_p vs z plane, most dramatic in the high-statistics ^{11}B data on top, represent different final states, and projections onto excitation energy are shown in the insets.

For both reactions, the ground state was outside the spectrometer acceptance. The observed excitation-energy resolution is approximately 100-keV FWHM, showing a significant improvement over the resolution reported in [8] of $\sim$300 keV, and the two components of the positive-parity doublet in ^{13}B are distinct, as seen in the lower inset of Fig. 2. The excitation-energy resolution contains contributions from the spread in the beam energy, the intrinsic silicon-detector resolution, and a small contribution from the proton energy loss in the target.

The yields for the two reactions were extracted in equal bins of position along z, which in HELIOS correspond to equal solid-angle elements in the center-of-mass system. In this commissioning experiment, the electronic thresholds of the silicon detectors varied and, for the lowest proton energies (near 0.8 MeV), some of the detectors had reduced efficiency. The detector efficiency was determined by making use of the ^{11}B$(d,p)^{12}$B data. This reaction had been analyzed in terms of the distorted wave Born approxi-

mation (DWBA) [9], and the present angular distribution data were required to match the shape of DWBA calculations with three different optical-model parameter sets [10]. To assign ℓ values and extract relative spectroscopic factors, we compared yields in each detector for the two reactions: two states in ^{12}B with known angular distributions from the ^{11}B$(d,p)^{12}$B reaction were compared to the doublet in ^{13}B measured via the ^{12}B$(d,p)^{13}$B reaction. The efficiencies extracted for the 2.62- and 3.39-MeV states in ^{12}B, where the proton energies are within $\sim$100 keV of the ^{13}B doublet being studied, give similar efficiencies at the $\sim$30% level. The angular distributions thus derived are shown in Fig. 3. The 3.48-MeV member of the ^{13}B doublet is clearly $\ell = 0$ in character (it is very similar in shape to that for the 2.62-MeV ^{12}B state), while the much weaker 3.68-MeV member of the doublet has an $\ell = 2$ shape.

The absolute beam intensity was not measured in this commissioning experiment and we do not quote absolute cross sections. However, the *relative* cross sections for the states measured with the same beam are correct and ratios of spectroscopic factors with one beam can be obtained by dividing the measured cross sections by the appropriate DWBA calculations. Such comparisons were carried out with three parameter sets obtained from the literature [10] and gave consistent results for the ratios at the <20% level.

For the 3.48-MeV $\ell = 0$ state in ^{13}B, a small $\ell = 2$ component cannot be excluded ($S_{\ell=2}/S_{\ell=0} \lesssim 5\%$). It should be noted that for the known $\ell = 0$ state at 2.62 MeV in ^{12}B there must be a contribution from the
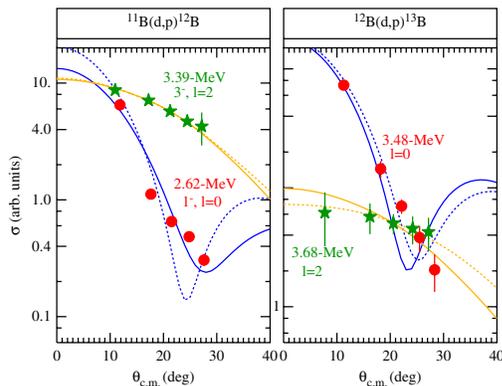

FIG. 3 (color online). The left-hand figure shows angular distributions for the ^{11}B$(d,p)^{12}$B reaction measured with HELIOS for two states known to be populated with $\ell = 0$ and 2. The normalization procedure is described in the text and this plot used the $\ell = 2$ transition for reference. The solid stars (green) are the HELIOS data for the $\ell = 2$ transition to the 3.39-MeV state, used as a basis of normalization, and the solid dots (red) are the $\ell = 0$, 2.62-MeV state. The solid lines and the dashed lines are DWBA calculations with two different sets of parameters. On the right, the data for the ^{12}B$(d,p)^{13}$B doublet at 3.48 and 3.68 MeV are shown with the same normalization. The conventions on the symbols and curves are the same as on the left-hand side. Angles, $\theta_{c.m.}$, are in the center of mass.

unresolved 0^+ state at 2.72 MeV with a known spectroscopic factor of $\sim$0.2, and this will contribute on the order of $\sim$10% of the cross section around 10°, well within the overall uncertainties. For the 3.68-MeV $\ell = 2$ state in ^{13}B, the maximum $\ell = 0$ component is less than $\sim$2% of that for the 3.48-MeV state. The negative-parity excited states in ^{11}B are expected to have very small spectroscopic factors [11]. We do not see these, and can place limits on the supposed negative-parity states in ^{13}B at 3.53 and 3.71 MeV, as having $S < 5\%$–10% of that for the 3.48-MeV $\ell = 0$ transition.

Shell-model calculations predict that the lowest positive-parity state in ^{13}B ($1/2^+$) should be populated in the (d, p) reaction by an almost pure $\ell = 0$ transition, that the lowest $3/2^+$ state should have approximately equal admixtures of $\ell = 0$ and $\ell = 2$, and that the lowest $5/2^+$ state must be a pure $\ell = 2$ transition. This comparison strongly suggests spin assignments of $J^\pi = 1/2^+$ and $5/2^+$ for the states at 3.48 and 3.68 MeV, respectively. The calculations discussed here were obtained with the WBP interaction of Ref. [12] in a $0\hbar\omega$ basis for positive (negative) parity states in ^{12}B (^{13}B), and in a $1\hbar\omega$ basis for negative (positive) parity states in ^{12}B (^{13}B). These interactions have been used recently for understanding the ^{11}Be$(d,p)^{12}$Be [13] and ^{13}C$(t,^3$He$)^{13}$B [5] reaction data.

The calculated percentage of the spectroscopic strength in the lowest state of a given spin compared to the sum over the first 10 states with that spin is 78% (^{12}B 1^-, $s_{1/2}$), 94% (^{12}B 3^-, $d_{5/2}$), 94% (^{13}B $1/2^+$, $s_{1/2}$), 30% (^{13}B $3/2^+$, $s_{1/2}$), 38% (^{13}B $3/2^+$, $d_{5/2}$), and 25% (^{13}B $5/2^+$, $d_{5/2}$). Thus the energies of the first state in the first three cases are expected to be a good measure of the effective single-particle energies for these orbitals.

Table I summarizes a comparison between experiment and predictions for the ratios of spectroscopic factors $S_{\ell=0}/S_{\ell=2}$ of particular $\ell = 0$ dominated and $\ell = 2$ dominated transitions from (d,p) reactions on ^{11}B, ^{12}C [14], and ^{12}B. The experimental values for the first two targets are in good agreement with the predictions. However, for the ^{12}B$(d,p)^{13}$B reaction, the spectroscopic factor for the $\ell = 2$ dominated transition to the 3.68-MeV state is considerably weaker than predicted by theory (though the agreement is better assuming a $J^\pi = 5/2^+$ assignment than $3/2^+$). The shell-model calculations predict the $3/2^+$ and $5/2^+$ states to be 60 keV apart, but there seems to be no other known even-parity state below 4.8 MeV. Comparisons of spectroscopic factors between the calculations and the experimental measurements are shown in Fig. 4. It is evident that the first two even-parity states in ^{13}B are much closer together in the experiment than in the calculation. The 3.48-MeV state is consistent with the $1/2^+$ of the shell-model calculations. While the 3.68-MeV level could be either $3/2^+$ or $5/2^+$, the absence of an $\ell = 0$ component in the angular distribution, as well as the better fit in the ratio as discussed above in the context of

TABLE I.   Comparison of ratios of spectroscopic factors for the strongest $\ell = 0$ and $\ell = 2$ states.

| Reaction | J^π, Excitation [Theory] (MeV) | | $S_{\ell=0}/S_{\ell=2}$ | |
	$\ell = 0$	$\ell = 2$	Experiment	Theory
^{11}B$(d,p)^{12}$B	1^-, 2.62 [1.98]	3^-, 3.39 [2.99]	1.0 ± 0.3[a]	0.82
^{12}C$(d,p)^{13}$C	$1/2^+$, 3.09 [2.49]	$5/2^+$, 3.85 [3.10]	1.23 ± 0.30[b]	1.02
^{12}B$(d,p)^{13}$B	$1/2^+$, 3.48 [2.99]	$3/2^+$, 3.68 [3.95]	13 ± 4[a]	1.84
^{12}B$(d,p)^{13}$B	$1/2^+$, 3.48 [2.99]	$5/2^+$, 3.68 [4.00]	8 ± 3[a]	2.94

[a]This work. [b]See Ref. [14].

Table I, tends to favor the latter assignment. The observed energies of the first states of a given spin indicate that the effective single-particle energies for even-parity states are too low in the calculation compared to experiment. The experimentally observed fragmentation of strength in the $3/2^+$ and $5/2^+$ states is not predicted correctly and therefore more strength is to be expected above 4 MeV in ^{13}B.

In conclusion, we have used the realization of a new spectrometer concept to study the ^{12}B$(d,p)^{13}$B reaction in inverse kinematics. The design of HELIOS provides sufficient experimental center-of-mass energy resolution to separate the transitions to the closely spaced 3.48- and 3.68-MeV positive-parity excited states in ^{13}B. The results suggest that these levels are the predicted $1/2^+$ and $5/2^+$

states in ^{13}B. However, the spectroscopic factor of the suggested $5/2^+$ state, compared to that for the $1/2^+$ state, is smaller than predicted by theory. The absolute excitation energies, as well as the ordering of the states, are not in good agreement with shell-model predictions, and a predicted $3/2^+$ state is not observed below 4.8 MeV. It is possible that this state could correspond to a strong transition at 5.1-MeV excitation seen in a prior measurement of ^{12}B$(d,p)^{13}$B [8], although further experimental scrutiny is required to verify this suggestion. It is clear that HELIOS, especially with the planned implementation of a full Si detector array, is a powerful device for the study of reactions in inverse kinematics, with both short-lived and stable beams.
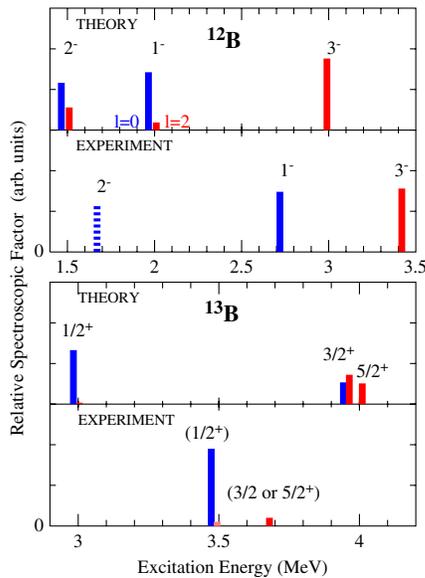
FIG. 4 (color online).   Energies and spectroscopic factors for $\ell = 0$ and 2 (d,p) transitions from theory and experiment, with ^{12}B on top and ^{13}B on bottom. Solid bars are experimental values from the present measurement, the dashed bar is from other work. Only relative values of spectroscopic factors are meaningful within each plot, and the two colors denote the two ℓ values as indicated. The small $\ell = 2$ component shown as the experimental result for the 3.48-MeV state is a limit.

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[1] R. Middleton and D. Pullen, Nucl. Phys. **51**, 50 (1964).
[2] V. Guimarães *et al.*, Phys. Rev. C **61**, 064609 (2000).
[3] S. Ota *et al.*, Phys. Lett. B **666**, 311 (2008).
[4] H. Iwasaki *et al.*, Phys. Rev. Lett. **102**, 202502 (2009).
[5] C. J. Guess *et al.*, Phys. Rev. C **80**, 024305 (2009).
[6] A. H. Wuosmaa *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **580**, 1290 (2007).
[7] B. Harss *et al.* Rev. Sci. Instrum. **71**, 380 (2000).
[8] H. Y. Lee *et al.*, Phys. Rev. C **81**, 015802 (2010).
[9] Accepted values are from the analysis of J. E. Monahan *et al.*, Phys. Rev. C **3**, 2192 (1971).
[10] C. M. Perey and F. G. Perey, Phys. Rev. **132** 755 (1963); J. P. Schiffer *et al.*, Phys. Rev. **164**, 1274 (1967); K. W. Corrigan *et al.*, Nucl. Phys. **A188**, 164 (1972).
[11] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967); private communication.
[12] E. K. Warburton and B. A. Brown, Phys. Rev. C **46**, 923 (1992).
[13] R. Kanungo *et al.*, Phys. Lett. B **682**, 391 (2010).
[14] S. E. Darden *et al.*, Nucl. Phys. **A208**, 77 (1973).