Observation of a Near-Threshold Proton Resonance in ^{11}B

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A near-threshold proton resonance in ^{11}B at $E_{\mathrm{ex}} = 11.44 \pm 0.04$ MeV is observed via the reaction $^{10}\mathrm{Be}(d,n)^{11}\mathrm{B} \to {}^{10}\mathrm{Be} + p$ in inverse kinematics, measured with a beam of the radioactive isotope ^{10}Be. The resonance energy at $E_{\mathrm{res}} = 211(40)$ keV is consistent with a proton signal observed by Ayyad *et al.* in the β-delayed proton decay of ^{11}Be. By comparison to a distorted wave Born approximation calculation, a 0.27(6) spectroscopic factor is extracted and a tentative ($\ell = 0$) character is assigned for this resonance. The significant cross section in the proton-transfer (d,n) reaction, as well as the observation of its proton-decay signal, point to the threshold-resonance character of this state. The position of this state, its structure, and strong coupling to the s-wave continuum represent an ideal case to study quantum near-threshold many-body dynamics of unstable states. The presence of this state is an important step toward understanding the excessively large beta-delayed proton-decay branch of ^{11}Be.

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The development of a quantum many-body approach capable of treating structure and dynamics of bound, resonance, and scattering states is an ongoing goal of nuclear physics and other fields [1]. Since Ikeda *et al.* [2] observed that α-cluster states can be found in the proximity of the α-particle decay threshold, the understanding of near-threshold resonances [3] has become of crucial importance. Moving toward drip lines, or high excitation energies, the continuum physics becomes critical, making the description of the nucleus as an open quantum system necessary.

Weakly bound states become strongly perturbed by virtual excitations into the continuum leading to significant changes in the spectra that models without continuum physics cannot reproduce [4–6]. The perturbation from the continuum is most significant exactly at thresholds and for those channels where Coulomb and centrifugal barriers are minimized [7]. This "pressure" from the continuum [8,9] leads to localization of strongly coupled states near the decay threshold of the respective channels and impacts their wave functions [10].

Coupling to the reaction continuum and explicit decay dynamics modify the structure of states and their spectroscopic factors in relation to different reaction channels [11]. In particular some states become "aligned" or superradiant [11] and accumulate most of the continuum coupling to the decay channel, thus exhausting the decay width into that channel. Such an alignment in the Hilbert space is likely to reduce coupling and decay width of superradiant states into other orthogonal channels.

Recent theoretical developments [12–15] include interactions with the continuum. However, questions on the behavior, structure, and properties of the many-body systems close to the emission threshold remain open, making the experimental studies of near-threshold states and their characteristics crucial for constraining the theoretical efforts.

Of particular recent interest has been the suggestion of a near-threshold proton-resonance state in ^{11}B. The surprisingly high branching ratio of the $^{11}\mathrm{Be} \to {}^{10}\mathrm{Be}$ β-delayed proton decay of the halo nucleus ^{11}Be observed by Riisager *et al.* [16] led to speculations about possible physics beyond the standard model. The significant discrepancy in the neutron lifetime measurements [17,18] compelled examinations of ^{11}Be neutron halo decay [16,19]. As a nonexotic explanation, it has been proposed a resonant enhancement mechanism through a strong, narrow state in ^{11}B.

Subsequently, Ayyad *et al.* [20] observed a sharp proton signal in the β decay of ^{11}Be, indicative of a $J^{\pi} = (1/2^{+}, 3/2^{+})$ resonance at $E_{\mathrm{res}} = 196$ keV, consistent with the resonant-enhancement picture. In contrast to the arguments for the existence of a near-threshold proton resonance, Riisager *et al.* [21] repeated their experiment and failed to confirm their earlier observation of the $^{11}\mathrm{Be} \to {}^{10}\mathrm{Be}$ β-delayed proton decay, adding controversy to the question of whether such state exists or to which degree it could enhance the β-delayed proton decay.

Several theoretical studies have been aimed toward understanding the nature of the possible near-threshold proton resonance in ^{11}B, its structure, and its role in the beta-delayed process [22–26].

The role that an intermediate resonance can play in the beta-delayed proton decay was examined in Ref. [23], where it was pointed out that the quoted rate is difficult to explain and the list of possible intermediate states narrows down to a $\ell = 0$, $1/2^+$ state, with large proton spectroscopic factor, small α strength, and located in a very narrowly defined energy region above the proton-decay threshold.

Isospin mixing with an isobaric analog state and potential for a virtual transition or via a tail of an isobaric analog state are also questions of significant interest. Interaction with the continuum was suggested in Ref. [22] as the reason for the appearance of this near-threshold resonance and its reduced coupling to the α channel. Finally, it should be mentioned that the region of interest is exactly at the neutron threshold, but due to its being a higher angular momentum channel, the neutron decay is not expected to impact the discussion.

In this Letter, we report on the direct observation of a near-threshold proton-emitting resonance state in ^{11}B at $E_{\rm ex} = 11.44 \pm 0.04$ MeV ($E_{\rm res} = 211(40)$ keV), populated via the $^{10}{\rm Be}(d,n)$ reaction in inverse kinematics and observed through its proton decay.

The experiment was carried out at the John D. Fox accelerator laboratory of Florida State University, where the primary beam of ^{9}Be was delivered by the Tandem-Linac accelerator at an energy of 40.9 MeV. The beam bombarded a thin-window gas cell filled with deuterium gas at 350 Torr, which was kept at liquid nitrogen temperature inside the RESOLUT radioactive beam facility [27]. The magnetic and electric elements of RESOLUT were used to select a beam of ^{10}Be produced via the $^9{\rm Be}(d,p)^{10}{\rm Be}$ reaction. The secondary beam of ^{10}Be with an energy of 39 MeV was focused into the reaction chamber and onto a 517 $\mu{\rm g/cm}^2$ thick CD_2 target, with a beam purity $\geq 90\%$, at a rate of about ~6000 particles per second.

The reaction of interest, $^{10}{\rm Be}(d,n)^{11}{\rm B}$, is well-suited to selectively populate the low-lying proton resonances of low-angular momentum. The proton-decay products from these resonances were detected in a compact detector system designed to register coincidences between the charged particles and the heavy reaction residues. It is important to point out that protons from low-lying resonances arrived to our detector system with energies ≥ 1 MeV, since the present measurement was performed in inverse kinematics.

The heavy reaction residues and the unreacted beam were detected in an ionization chamber (IC) placed 25.4 cm downstream from the target position, filled with isobutane gas at 136 Torr, which was contained by an entrance Kapton window of 8 μm thickness. The IC consisted of 4 independent sections, labeled “X” (40 mm), “Y” (40 mm), “ΔE” (80 mm), and “E” (200 mm). The use of the position-sensitive “X” and “Y” sections in the IC allowed the determination of the position of the reaction residues. The design of the IC has been described in Ref. [28].

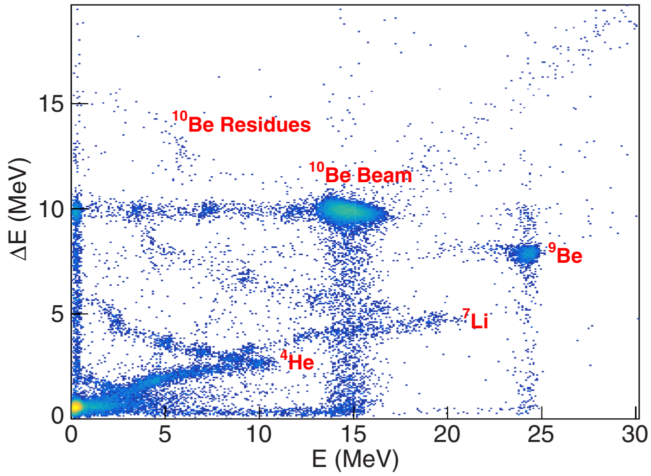

FIG. 1. Spectrum in the ionization chamber (IC) obtained using the E-ΔE sections during the present $^{10}{\rm Be}(d,n)^{11}{\rm B}^* \to {}^{10}{\rm Be} + p$ measurement. The location of the ^{10}Be recoils is well separated from the direct ^{10}Be beam. Other components present in the spectrum are the primary ^{9}Be beam as well as He and Li breakup channels.

An energy calibration for the ionization chamber was obtained by comparing signals of the unreacted ^{9}Be and ^{10}Be components in the different sections of the IC to the expected energy deposition calculated with the program LISE++ [29]. A typical spectrum of signals in the IC is shown in Fig. 1, where correlations of the signals in the E and ΔE sections are observed. The direct ^{10}Be beam is well separated from the region of reaction residues from the $^{11}{\rm B} \to {}^{10}{\rm Be} + p$ decay. Other particle components observed in the IC are those corresponding to scattered particles of the primary ^{9}Be beam, as well as ^{7}Li and ^{4}He, produced from breakup channels.

The light charged particles were detected in a set of S1 and S2 type double-sided silicon detectors [30] of thickness 68 and 1000 μm, respectively, placed in a forward ΔE–E telescope configuration at a distance of 8.6 and 15.6 cm, respectively, from the target, covering a combined angular range of $\theta_{\rm lab} = 7°$–$22°$. The silicon detectors were calibrated using a standard ^{228}Th α source.

The main event trigger was derived from signals in either silicon detector. A spectrum of the charged particles measured in the silicon detectors is shown in Fig. 2. The α particles (^{4}He), deuterons (d), and protons (p) are clearly separated into bands of their respective characteristic energy losses.

States in ^{11}B and their subsequent charged-particle decay were studied via the $^{10}{\rm Be}(d,n)^{11}{\rm B}^* \to \alpha/p$ reaction. These events were identified by requiring coincidences between the silicon detector array and heavy reaction residues in the ionization chamber. For events from the $^{11}{\rm B}^* \to {}^{10}{\rm Be} + p$ decay, the ^{10}Be recoils in the ionization chamber were first

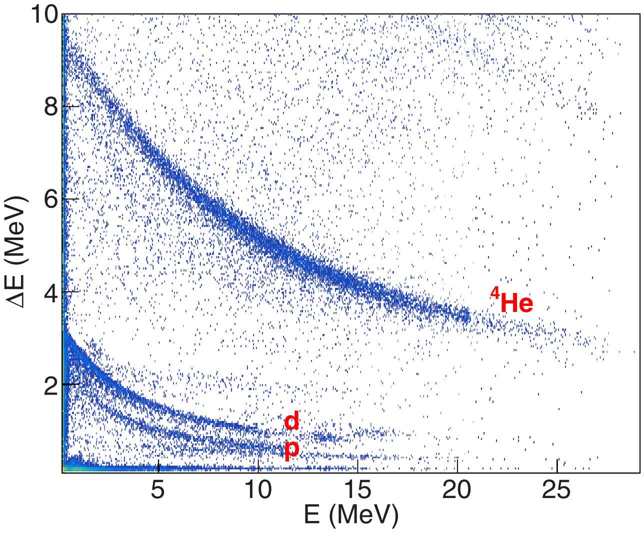

FIG. 2. E–ΔE spectrum obtained in the silicon-detector telescope. Bands of α particles (^{4}He), deuterons (d), and protons (p) are visible and well separated from each other.

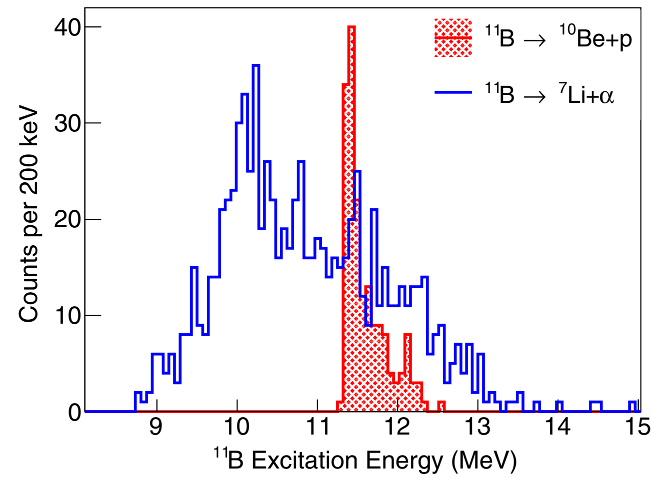

FIG. 3. Excitation energy spectrum in ^{11}B reconstructed from the $^{11}\mathrm{B}^* \to {}^{10}\mathrm{Be} + p$ (red) and $^{11}\mathrm{B}^* \to {}^{7}\mathrm{Li} + \alpha$ (blue). A prominent near-threshold peak at $E_{ex} = 11.44 \pm 0.04$ MeV is visible in the proton spectrum.

identified by their energy loss signals in a two dimensional E–ΔE spectrum using the last two sections (ΔE and E) in the IC. However, as shown in Fig. 1, some residues of interest were stopped before reaching the E section of the IC due to their low energy. Those events were further identified and selected by their signal correlations between the Y and ΔE sections of the IC.

The ^{11}B excitation spectra were then reconstructed using an invariant mass analysis for the two outgoing fragments ($^{11}\mathrm{B}^* \to {}^{10}\mathrm{Be} + p$, or $^{11}\mathrm{B}^* \to {}^{7}\mathrm{Li} + \alpha$), where the position and energy signals from the IC and silicon array were used to reconstruct their 4 vectors through the expressions

$$P^\mu({}^{11}B^*) = P^\mu({}^{10}Be) + P^\mu(p), \quad \text{or}$$
$$P^\mu({}^{11}B^*) = P^\mu({}^{7}Li) + P^\mu(\alpha). \qquad (1)$$

The extracted invariant mass was then used to determine the excitation energy in ^{11}B through

$$E_{\mathrm{ex}} = \sqrt{P^\mu({}^{11}B^*)P_\mu({}^{11}B^*)} - M({}^{11}B_{\mathrm{g.s.}}), \qquad (2)$$

where $M({}^{11}B_{\mathrm{g.s.}})$ is the mass of the ^{11}B ground state (g.s.).

The reconstructed excitation-energy spectrum for the $^{11}\mathrm{B}^* \to {}^{10}\mathrm{Be} + p$ reaction is shown in red in Fig. 3. Its main characteristic is the presence of a prominent peak at $E_{\mathrm{ex}} = 11.44 \pm 0.04$ MeV of excitation energy in ^{11}B ($E_{\mathrm{res}} = 211(40)$ keV). The location of this peak agrees well with the energy of the predicted proton resonance state in ^{11}B suggested by Refs. [16,20].

A Monte Carlo (MC) simulation was performed to determine the coincidence detection efficiency between the charged particles measured in the silicon detectors and reaction residues measured in the IC. A coincidence efficiency of ~15% was determined for the proton peak at $E_{\mathrm{ex}} = 11.44$ MeV in ^{11}B. After taking into account the number of counts in the peak, amount of incident beam, target thickness, and detection efficiency, a cross section of $\sigma_R = 17.8$ mb $\pm$ 3.5 mb (stat) was calculated for the state at $E_{\mathrm{ex}} = 11.44$ MeV shown in red in Fig. 3.

A distorted wave Born approximation (DWBA) calculation for the $^{10}\mathrm{Be}(d,n)$ reaction was performed with the code FRESCO [31], using entrance and exit potentials taken from Zhang *et al.* [32] and Koning and Delaroche [33], respectively. The population of the state at $E_{\mathrm{ex}} = 11.44(4)$ MeV was obtained in the weak-binding approximation, assuming spin parity $1/2^+$.

Since our experiment only detected the decay proton emitted from the 211 keV resonance, the proton-branching ratio enters in the extraction of the (d,n) cross section. Under the assumption of a 100% proton decay, we extract a spectroscopic factor of $C^2S = 0.27(6)$ for the population of the resonance. The ~ 20% systematic uncertainty is mainly due to the choice of radius for the Woods-Saxon potential, consistent with arguments provided in Ref. [34]. For comparison, Ayyad *et al.* [20] analyzed the line shape of the proton signals to extract a proton width of 12(5) keV, and, relative to the calculated single-particle width of 44 keV, extracted a spectroscopic factor $C^2S \approx 0.34$.

While the neutron of the (d,n) reaction remains undetected here, its energy distribution can be experimentally obtained as "missing" energy in the event kinematics. Since the reaction Q value of the (d,n) reaction populating the resonance is fixed, the detected sum energy of the proton and the reaction residue carry an imprint of the unobserved neutron energy of the event. The neutrons emitted in the inverse-kinematics (d,n) reaction have a strong energy

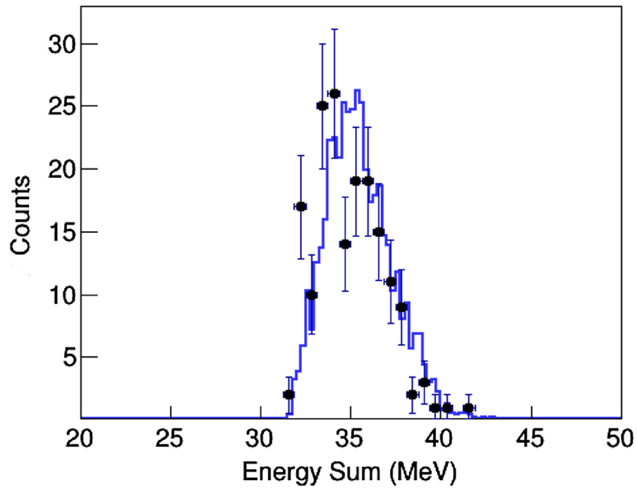

FIG. 4. Energy-sum signals of ^{10}Be $+ p$ events for the 11.44 MeV state, compared with a Monte Carlo simulation (in blue) that takes into account the DWBA-calculated angular distribution of the ^{10}Be$(d,n)^{11}$B* reaction. A value of $\ell = 0$ fits well the experimental data.

variation as a function of the emission angle, so that this energy dependence also carries information about the angular distribution of the unobserved neutron. The sum-energy signals corresponding to the $E_{\rm ex} = 11.44(4)$ MeV peak are displayed in Fig. 4. They are compared to a MC simulation of the event kinematics based on the DWBA calculation of the (d,n) neutron-angular distribution for $\ell = 0$. The experimental distribution is consistent with the DWBA angular distribution, which strongly peaks in the "forward" angles of the center of mass system, but $\ell = 1$ or 2 could not be excluded from these data alone. An analogous analysis for similar experimental conditions is described in Ref. [35].

Given that the barrier-penetrability value for an angular momentum transfer of $\ell = 1$ or 2 would be orders of magnitude smaller than for $\ell = 0$ [36] for the 211 keV resonance energy, we assume that the observed proton emission would not be able to compete with the kinematically favored α emission for these ℓ values and tentatively assign $\ell = 0$ to this resonance, leading to a spin-parity assignment of $J^\pi = (1/2^+)$ to the state at $E_{\rm ex} = 11.44(4)$ MeV. This value is in agreement with the predicted $\ell = 0$ suggested by Ref. [22].

The excitation energy spectrum for the ^{11}B$^* \to {}^7$Li $+ \alpha$ decay, was also reconstructed in the present analysis. The corresponding spectrum is shown in blue in Fig. 3, where α-unbound states from the threshold at 8.864 MeV up to $\sim$13 MeV are observed. A coincidence detection efficiency of about 5% was determined for the α decay at $E_{\rm ex} \sim$ 11.4 MeV in ^{11}B.

The obtained α spectrum agrees well with the previously measured ones by Refs. [37,38]. In particular, we observe a peak at $E_{\rm ex} = 11.45$ MeV, observed before by Cusson [39], Ahmed *et al.* [37], and Curtis *et al.* [38] in studies of the ^{11}B $\to {}^7$Li $+ \alpha$-decay channel. In the spectra of Fig. 3, this peak itself is located slightly above the proton-decaying structure. None of the previous studies resolved both states, or were able to determine their α-decay or p-decay branching ratios.

The question of whether the proton-decaying state at $E_{\rm ex} = 11.44 \pm 0.04$ MeV also exhibits an α-decay branch remains unresolved from our experiment. Under the assumption that the protons and α particles are emitted from the same resonance, an upper limit of $\leq 40\%$ α-branching ratio was determined after considering the respective detection efficiencies. The more likely situation is that both signals originate from different states, a dominantly proton-decaying $(1/2^+)$ state at 11.44 MeV and an α-decaying state at 11.45 MeV. Further experiments capable of resolving both states and determining the α- and proton-decay strengths for both states are called for.

An interesting aspect of the observed proton-resonant state is that it lies very close to the neutron-emission threshold ($S_n = 11.454$ MeV) in ^{11}B. For the $(1/2^+)$ resonance of interest, the neutron-decay channel ^{11}B$(1/2^+) \to {}^{10}$B$(3^+) + n$ requires at least $\ell = 2$ and should therefore be suppressed and of lower importance at the decay-energy threshold. It was also pointed out in Ref. [22] that the $\ell = 0$ neutron-aligned resonance is expected to be realized in the $5/2^+_6$ state.

The mechanism of the β-delayed proton decay through an intermediate resonance has been analyzed in Ref. [23], where it was pointed out that the strongest resonant enhancement would come from a contribution of the $T = 3/2$ isobaric analog state. Experimentally, the analog state has been identified with the $1/2^+$ state at 12.554 MeV [40], more than 1 MeV above the energy window relevant to β decay. One may be led to speculate whether the threshold-resonance mechanism also leads to an admixture of $T = 3/2$ amplitude to the resonance observed in this Letter and thus enhance the β-delayed proton-decay rate.

A study of the mirror nucleus ^{11}C is called for. A measurement of the ^{10}C(d,p) reaction will populate the $s_{1/2}$ state in ^{11}C, mirror of the one in ^{11}B reported in this Letter. Given that the proton-decay threshold in ^{11}C is $\sim$2.5 MeV lower than the one in ^{11}B, such an experiment would allow to determine whether or not the characteristics of the resonance reported in this Letter emerge from an interaction with the continuum as a near-threshold effect.

In summary, we report the observation of a near-threshold proton resonant state in ^{11}B at $E_{\rm ex} = 11.44(4)$ MeV with a tentative spin-parity assignment of $(1/2^+)$, populated via the ^{10}Be(d,n) reaction in inverse kinematics and observed through its proton decay. The cross section confirms a strong single-proton character for this resonant state, with a spectroscopic factor of $C^2S = 0.27(6)$, essentially consistent with the value of 0.34 extracted by Ayyad *et al.* [20]. The value of 0.27(6) could be systematically affected by the presence of an α-decay branch from this state, which our experiment did not observe, but for which it established an upper limit of 40% branching ratio. The properties of this state are consistent with the predictions for a near-threshold proton resonance.

The conclusive observation of the near-threshold proton resonance measured in this Letter favors the ^{11}Be → ^{10}Be β-delayed proton decay via an intermediate resonance enhancement mechanism in ^{11}B over more exotic explanations.

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Note added.—During production of our Letter, we became aware of Ref. [41].

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Correction: A typographical error in the reaction given in the first sentence of the abstract was introduced during the proof cycle and has been fixed.