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Letter

Search for the γ decay of the narrow near-threshold proton resonance in ^{11}B

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A B S T R A C T

The γ decay of the elusive narrow, near-threshold proton resonance in ^{11}B was investigated at Laboratori Nazionali di Legnaro (INFN) in a particle-γ coincidence experiment, using the ^{6}Li(^{6}Li,pγ) fusion-evaporation reaction and the GALILEO-GALTRACE setup. No clear signature was found for a possible E1 decay to the $1/2^-_1$, first-excited state of ^{11}B, predicted by the Shell Model Embedded in the Continuum (SMEC) with a branching of $0.98^{+167}_{-69}\times10^{-3}$ with respect to the dominant particle-decaying modes. The statistical analysis of the γ-ray spectrum provided an average upper limit of 2.37×10^{-3} for this γ-ray branching, with a global significance of 5σ. On the other hand, by imposing a global confidence level of 3σ, a significant excess of counts was observed for $E_\gamma = 9300(20)$ keV, corresponding to a resonance energy of 11429(20) keV (namely 200(20) keV above the proton separation energy of ^{11}B) and a γ-ray branching of $1.12(35)\times10^{-3}$. This result is compatible with the SMEC calculations, potentially supporting the existence of a near-threshold proton resonance in ^{11}B.

Atomic nuclei are open many-body quantum systems characterized by bound states and unbound resonances, located above particle-separation energies [1–4]. In light nuclear systems, with a limited number of nucleons (A < 20), narrow resonances may appear in the proximity of particle-emission thresholds [5–9]. These *near-threshold states* are relevant to understand the onset of collectivization and clusterization phenomena in light nuclei, as a consequence of the coupling between bound and scattering states in the continuum [10]. Moreover, near-threshold states play a key role in nucleosynthesis reactions occurring in stars. The most famous example is the Hoyle state in ^{12}C, located only 287 keV above the α-decay threshold [11], which boosts the burning of ^{4}He nuclei in stellar environments and explains the abundance of ^{12}C and heavier elements in the Universe. The existence of a near-threshold state in the neighbouring ^{11}B system, located just above the proton separation energy, was postulated after the possible observation of the β^-−delayed proton emission process in the ^{11}Be, one-neutron-

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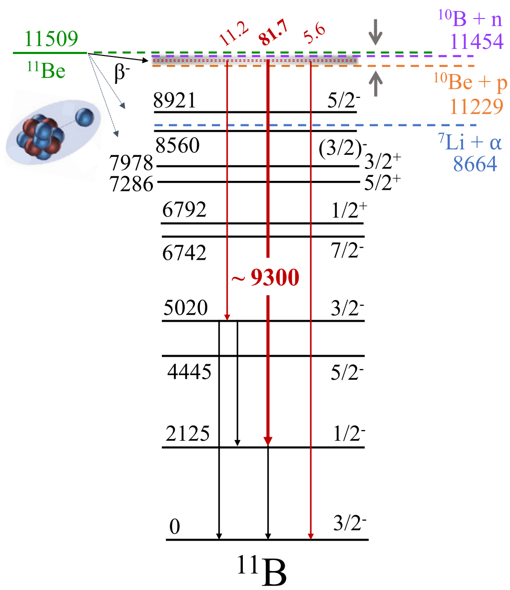

Fig. 1. Partial level scheme of ^{11}B showing the α, p and n decay thresholds, and the ground state of ^{11}Be, located at 8664, 11229, 11454, and 11509 keV respectively, relative to the ground state of ^{11}B. The 280-keV narrow window available for proton emission after β^- decay of ^{11}Be is indicated by grey arrows. The location of the near-threshold resonance is displayed by the shaded bar, with red arrows showing the expected dominant γ-ray decays, with intensities given by the SMEC calculations [19] (see text for details).

halo nucleus [12–14]. Proton emission is an unusual phenomenon in neutron-rich nuclei as it carries the final system away from the valley of stability, resulting in an extremely rare decay mechanism. Along with ^{11}Be, the β^-−delayed proton emission is energetically allowed in the neutron-rich ^{19}C and ^{31}Ne halo nuclei only, where the decaying neutron is quasi free [15]. Yet, ^{11}Be offers the most favourable condition for observing this process. With a β^- Q-value of 11509 keV and a proton-separation energy in ^{11}B of 11229 keV, a 280-keV energy window is available for the β^-−delayed proton decay, as schematically illustrated in Fig. 1. Due to the narrow phase space, theoretical calculations predict a β^-−delayed proton emission branching of 3×10^{-8} [15], which is at odds with experimental results on the β^- decay of ^{11}Be, reporting a proton-decay intensity of $1.3(3) \times 10^{-5}$ [12], $8.3(9) \times 10^{-6}$ [13], and $< 2.2 \times 10^{-6}$ [14]. Despite the experimental discrepancies on the strength of the β^-−delayed proton decay of ^{11}Be, the supposedly large emission rate could be explained if the decay proceeds through a narrow resonant state in ^{11}B, located slightly above the proton-emission threshold. Such a state should resemble the structure of the proton-decay threshold, with a dominant (^{10}Be $\otimes$ p) core−proton coupled configuration and negligible contributions from the other (^{10}B $\otimes$ n) and (^{7}Li $\otimes$ α) decay channels, the thresholds of which are at 11454 keV and 8664 keV, respectively (see Fig. 1).

In Ref. [12], the energy of the near-threshold proton resonance in ^{11}B was originally proposed to be located 196(20) keV above the proton separation energy, at $E_x = 11425(20)$ keV, with a proton emission width Γ_p = 12(5) keV and spin-parity ($1/2^+$,$3/2^+$). More recently, the same collaboration reported an energy E_{res} = 11400(20) keV, hence 171(20) keV above the proton threshold with $J^\pi = 1/2^+$ and $\Gamma_p = 4.5(11)$ keV, as observed in a ^{10}Be(p,p') experiment [16]. In the same work, a possible spin-parity J^π = $3/2^+$ was ruled out according to the data fit results. At the same time, a near-threshold states was also reported in a ^{10}Be(d,n) → ^{10}Be+p experiment [17], with an energy E_{res} = 11440(40) keV, namely 211(40) keV above the proton threshold. The existence and the structure of a near-threshold proton resonance in ^{11}B was theoretically predicted and described by the Shell Model Embedded in the Continuum (SMEC) [10,18,19], which points to the appearance of near-threshold states as an universal phenomenon in light nuclei. In this approach, atomic nuclei are treated as open quantum systems, including couplings between bound and scattering states through an energy-dependent effective Hamiltonian. In this context, near-threshold resonances are expected to gain collectivity due to the mixing with shell-model bound states. In ^{11}B, the SMEC calculates the $1/2_3^+$ near-threshold state to be located 142 keV above the proton separation energy [18], with an E1 γ-ray branching to the $1/2_1^-$ state at 2125 keV of $0.98^{+167}_{-69} \times 10^{-3}$ with respect to the particle-decay modes [19]. The rather large γ-decay branching predicted by the SMEC opens up the possibility to probe the existence of the near-threshold proton resonance in ^{11}B by searching for its γ-ray decay, as a complementary tool to particle-spectroscopy experiments [16,17]. In this work, for the first time, the ≈ 9300-keV, $1/2_3^+ \to 1/2_1^-$ γ-ray transition, predicted by the SMEC to dominate the electromagnetic decay of the near-threshold state, was searched for.

The experiment was performed at Laboratori Nazionali di Legnaro (INFN), using the ^{6}Li(^{6}Li,pγ) fusion-evaporation reaction and the GALILEO HPGe array [20] coupled to the GALTRACE silicon detectors [21]. The ^{6}Li beam was accelerated at 9 MeV by the TANDEM-XTU and slowed down to 7 MeV by using a Ni degrader. The beam impinged on a ^{6}LiF target 0.5-mg/cm^2 thick, evaporated onto a 150 µg/cm^2 Cu backing. Boron-11 nuclei were populated by the evaporation of one proton from the ^{12}C compound nucleus, with a total cross section of 84 mb, estimated with the PACE code [22]. It is important to note that the ^{6}Li+ ^{6}Li, fusion-evaporation reaction was already employed in Ref. [23] to populate the excitation energy region around 11 MeV in ^{11}B, where the near-threshold proton resonance is expected to be located. In this work, the selectivity on the reaction channel of interest was achieved by detecting the emitted protons feeding states in ^{11}B. Protons originating from fusion-evaporation reactions on ^{19}F nuclei, present in the target, are suppressed by almost an order of magnitude, being the ^{6}Li beam energy below the Coulomb Barrier for the ^{6}Li+ ^{19}F system. Charged particles were identified with 3 GALTRACE detectors, consisting of pixel-type silicon layers mounted in a ΔE-E telescopic configuration. The thin ΔE detector had a thickness of 200 µm, while the E detector was 1.5-mm thick. They were both divided into 60 pads, 4×4-mm^2 wide, for a total active area of 50×20 mm^2. The GALTRACE detectors were placed at ≈ 5 cm from the target, covering an angular range between 47° and 59° with respect to the beam direction. Protons were measured in coincidence with γ rays de-exciting ^{11}B nuclei by the GALILEO setup, comprising 10 HPGe triple-cluster detectors [24] at backward angles and 20 single, coaxial HPGe crystals [25] at forward angles. All the HPGe detectors were equipped with BGO anti-Compton shields.

Charged particles evaporated from the ^{12}C compound nucleus and punching through the first thin silicon layer were identified by using the ΔE-E method, hence correlating the loss of energy measured in the ΔE detector with the energy deposited in the thick E layer. This is depicted in the panel a) of Fig. 2, where protons and deuterons are indicated. On the other hand, low-energy charged particles stopped in the ΔE layer were identified by Pulse Shape Analysis techniques, correlating the maximum derivative of the signal pulse (I_{max}) with the particle energy [26,27]. This is shown in panel b) of Fig. 2, where protons, deuterons and α particles can be distinguished. The high granularity of the GALTRACE detectors enabled to measure the proton scattering angles which, along with the measured energies, were used to reconstruct the kinematics of the ^{6}Li(^{6}Li,pγ) reaction, on an event-by-event basis, to obtain the excitation energy spectrum of ^{11}B. The direction of the recoiling ^{11}B nuclei was also obtained and used to reconstruct the relative angle between ^{11}B products and the emitted γ rays to achieve a better Doppler correction of γ-ray spectra. The Doppler-corrected-, γ-ray spectrum, measured in coincidence with protons punching through the ΔE layer of GALTRACE, is shown in panel c) of Fig. 2. These events correspond to a ^{11}B excitation energy lower than ≈ 10 MeV. The γ-ray transitions belonging to ^{11}B and connecting the states shown in Fig. 1

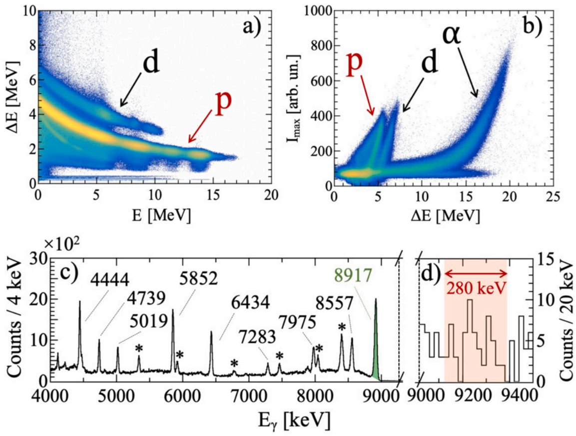

Fig. 2. (a) Two-dimensional matrix correlating the particle energy loss in the ΔE layer of GALTRACE with the energy E deposited in the thick layer. Identified protons and deuterons are indicated. (b) Two-dimensional matrix correlating the maximum derivative of the signal pulse (I_{max}) with the particle energy deposited in the ΔE layer of GALTRACE [26,27]. Identified protons, deuterons and α particles are labelled accordingly. (c) Doppler-corrected γ-ray spectrum measured in coincidence with protons punching through the ΔE layer of GALTRACE. Identified transitions in ^{11}B are marked. The 8917-keV γ ray, depopulating the $5/2^-_2$ resonance at 8921 keV (used in the analysis for cross section normalization) is indicated in green. First-escape peaks are marked by stars. (d) Doppler-corrected γ-ray spectrum measured in coincidence with protons stopped in the ΔE layer of GALTRACE. The 280-keV region of interest, where the γ-decay of the near-threshold proton resonance to the $1/2^-_1$ state is expected, is shown in red (see text for details).

are labelled accordingly. The 8917-keV transition, used as a reference for the analysis presented in this work, is highlighted in green (see discussion below). On the other hand, protons feeding the excitation energy region of ^{11}B around 11 MeV, where the near-threshold resonance state is expected to be located, are emitted with energies below 5 MeV and they are fully stopped in the ΔE detectors of GALTRACE (see panel b) of Fig. 2). In this experiment, the γ-ray decay of the possible near-threshold state in ^{11}B was investigated by searching for a high-energy transition deexciting a state located in the ^{11}B excitation energy range of 11229-11509 keV, and feeding the $1/2^-_1$, first excited state at 2125 keV (see Fig. 2). The corresponding γ-ray energy range (280-keV wide) would be 9100-9380 keV, as shown in red in panel d) of Fig. 2, where the Doppler-corrected γ-ray spectrum gated on low-energy protons stopped in the ΔE layers of GALTRACE is presented. Since no evidence of a clear γ-ray peak was found in the 280-keV region of interest (ROI) displayed in panel d) of Fig. 2, the γ-ray spectrum was analysed using the statistical method described by Gilmore [28], to search for a significant excess of counts over the background. This method relies on the assumption of a Gaussian distribution for background events. The ROI was sampled by a 120-keV moving window, at steps of 20 keV between 9100 keV and 9400 keV. The width of the sampling window was chosen according to the measured FWHM of the 8917-keV peak shown in green in panel c) of Fig. 2, lying close to the energy of the ROI. The FWHM is 41 keV, corresponding to $\sigma_{(\mathrm{FWHM})} \approx 18$ keV. Therefore, a conservative $\sigma_{(\mathrm{FWHM})} = 20$ keV was assumed in the ROI, and a $\pm 3\sigma_{(\mathrm{FWHM})}$ moving window (equivalent to 120 keV) was defined to account for the majority of the total peak area. For each sampled region, the measured number of counts G was compared with the one of the sum of the background regions B, selected at the left and right sides of the moving window with a width of 60 keV each. The net counts $C = G - B$ were considered significant if larger than the critical limit L_C defined in Ref. [28] by

$$L_C = k_\alpha \sqrt{[B(1 + n/2m)]}, \tag{1}$$

where n and m are the number of bins of the sampling window and background regions, respectively. The k_α parameter of Eq. (1) is a predetermined level of confidence, corresponding to the number of standard deviations σ for a given probability interval α. In this work, a global confidence level of 5σ was imposed, which corresponds to a local confidence level of 5.4σ for each sampling window, as neither the energy nor the intensity of the γ ray of interest are known. The local confidence level was established based on the Bonferroni correction, which accounts for the so-called look-elsewhere effect [29]. Under this assumption, no significant excess of counts was found in any of the energy regions sampled by the moving window. As a consequence, upper limits (L_U) for the γ-ray decay in the ROI, defined in Ref. [28], were evaluated by

$$L_U = C + k_\alpha \sqrt{[C + B(1 + n/2m)]}. \tag{2}$$

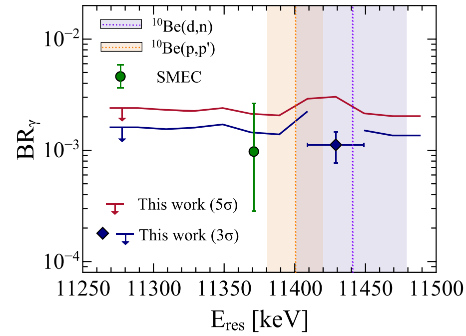

Fig. 3. Results obtained in the current experiments for the γ-ray branching of the near-threshold proton resonance in ^{11}B to the $1/2^-_1$ state, plotted as a function of the measured resonance energy. Experimental values are obtained assuming the same cross section for the population of the near-threshold state and the $5/2^-_2$ state at 8921 keV (see text for details). The red line corresponds to upper limits obtained with a global 5σ significance. The blue point is the result for a global 3σ confidence level, for which a significant excess of counts was found at E_γ = 9300(20) keV (E_{res} = 11429(20) keV). Upper limits with a global 3σ significance are shown by a blue line for the other energy regions sampled by the moving window. The resonance energy predicted by the SMEC and the calculated γ-ray branching are shown by the green point [19]. The resonance energies proposed in Refs. [16,17] are displayed by dashed orange and purple lines, respectively, with errors indicated by shaded coloured areas.

The corresponding upper limits for the γ-ray branching ratios were obtained using Eq. (2) with respect to the measured number of counts in the 8917-keV γ-ray peak (see panel c) of Fig. 2), depopulating the $5/2^-_2$ state in ^{11}B at 8921 keV with a γ-ray branching of 95%, and considering the same population cross section for the hypothetical resonance. Such an assumption is based on the statistical character of the decay of the compound nucleus formed in our ^{6}Li(^{6}Li,p) reaction. This is evidenced by the results of Ref. [23] in which the same reaction was studied, obtaining similar cross sections for different excited states up to $\approx$ 9 MeV within a factor of 1.5-2.0 at most. It is important to stress that a difference in the population cross sections between the near-threshold state and the $5/2^-$ state at 8921 keV, if any, would result only in a linear scaling of the obtained γ-ray branching ratio, without affecting the statistical analysis presented in this work. The results are shown in Fig. 3 by a solid red line, where the γ-ray branching ratio BR_γ is shown against the energy of the resonant state E_{res} obtained by

$$E_{res} = E_\gamma + E(1/2^-_1) + E_r. \tag{3}$$

In Eq. (3), E_γ is the centroid of each sampling window, $E(1/2^-_1)$ is the energy of the $1/2^-_1$ state at 2125 keV and E_r = 4 keV is the recoil energy of ^{11}B calculated by $E^2_\gamma/2mc^2$. On average, for a global confidence level of 5σ, an upper limit of 2.37×10^{-3} for the γ-ray decay from the near-threshold proton resonance region to the $1/2^-_1$ state in ^{11}B can be then assumed with respect to the particle-decay branching. On the other hand, by lowering the global significance down to 3σ, corresponding to a local confidence level of 3.6σ, one region with net counts C

larger than the critical limit L_C was found for $E_\gamma = 9300(20)$ keV. This corresponds to an excitation energy $E_{res} = 11429(20)$ keV, obtained by Eq. (3), lying 200(20) keV above the proton separation energy and shown by the blue point in Fig. 3. The energy of the resonant state is consistent with $E_{res} = 11440(40)$ keV and $E_{res} = 11400(20)$ keV, reported in Refs. [16,17] and shown by orange and purple dot lines in Fig. 3, respectively, with errors displayed by shaded coloured areas. The corresponding γ-ray branching to the $1/2_1^-$ state of ^{11}B, obtained in this work, is $BR_\gamma = 1.12(35) \times 10^{-3}$. In the other energy regions sampled by the moving window, no significant excess of counts was found with a global 3σ confidence level, and upper limits for the γ-ray branching are shown by a solid blue line in Fig. 3.

Our results are compared with SMEC calculations reported in Refs. [18,19] and shown by the green point in Fig. 3. In these works, for $1/2^+$ spin-parity states, couplings to the $[^{10}\mathrm{Be}(0^+) \otimes \pi(s_{1/2})]$ one-proton channel and the $[^{10}\mathrm{B}(3^+) \otimes n(d_{5/2})]$ one-neutron channel were considered. The strongest collectivization induced by the mixing with shell-model states was calculated for the $1/2_3^+$, near-threshold state at 142 keV above the proton separation energy, corresponding to a resonance energy of 11371 keV. Its wave function was found to be dominated by the (^{10}Be $\otimes$ p) core−proton coupled configuration, with only a little contribution from the other particle-decaying channels located nearby. The calculated γ-decay width for this near-threshold resonance is 14.32^{+25}_{-16} eV only, with the 81.7% of the strength carried by a ≈9300-keV, E1 decay to the $1/2_1^-$, first excited state of ^{11}B at 2125 keV [19]. The latter corresponds to a γ-ray branching of $0.98^{+167}_{-69} \times 10^{-3}$ with respect to the particle-decay modes, which is in good agreement with the experimental value obtained in this work for a global 3σ confidence level. The SMEC value was obtained by tuning the effective Hamiltonian to the known electromagnetic properties of ^{11}B [19]. The other γ-ray decays from the near-threshold state are predicted by the SMEC calculations to be the 6405-keV, E1 transition to the $3/2_2^-$ state at 5020 keV (11.2%) and the 11425-keV, E1 transition to the $3/2_2^-$ ground state (5.6%) (see Fig. 1).

In summary, the γ-ray decay of a possible near-threshold proton resonance in ^{11}B was searched for in a dedicated experiment employing the ^{6}Li(^{6}Li,pγ) fusion-evaporation reaction and the GALILEO-GALTRACE γ-particle coincidence arrays at Laboratori Nazionali di Legnaro (INFN). The statistical analysis of the γ-ray spectrum of ^{11}B provided upper limits for the γ-ray decay of the resonance to the $1/2_1^-$, first excited state, within the allowed 280-keV excitation energy region, considering a global 5σ and 3σ confidence level. A significant excess of counts is found only for a global 3σ confidence level, for $E_\gamma = 9300(20)$ keV. This corresponds to a resonance energy of 11429(20) keV, namely 200(20) keV above the proton separation energy of ^{11}B, in agreement with the location recently proposed by particle-spectroscopy experiments [16,17]. In such a case, the measured γ-ray branching is $BR_\gamma = 1.12(35) \times 10^{-3}$. This result is consistent with calculations from the Shell Model Embedded in the Continuum (SMEC) [19], therefore it potentially supports the existence of a near-threshold proton resonance in ^{11}B, although, with limited statistical confidence − with a global 5σ confidence level, the effect is not present. It follows that higher precision experimental data are needed to firmly conclude on the existence of the near-threshold resonance on the basis of its γ-ray decay. Such a sensitivity could be provided by γ-tracking array, such as AGATA or GRETA [30,31], coupled to efficient and highly segmented charged-particle detectors (e.g., GRIT or ORRUBA [32,33]), thus allowing one to study in detail the electromagnetic decay properties of narrow resonances, such as near-threshold states, and the impact of the continuum on the nuclear shell structure.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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