Letter

Single-particle properties of the near-threshold proton-emitting resonance in ^{11}B

Nguyen Le Anh [*]
Department of Theoretical Physics, Faculty of Physics and Engineering Physics, University of Science, Ho Chi Minh City, Vietnam; Vietnam National University, Ho Chi Minh City, Vietnam; and Department of Physics, Ho Chi Minh City University of Education, 280 An Duong Vuong, District 5, Ho Chi Minh City, Vietnam

Bui Minh Loc [†]
Center for Exotic Nuclear Studies, Institute for Basic Science (IBS), Daejeon 34126, Korea

Naftali Auerbach [‡]
School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

Vladimir Zelevinsky [§]
Facility for Rare Isotope Beams, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

(Received 2 June 2022; accepted 10 November 2022; published 18 November 2022)

The excitation function of proton elastic scattering from ^{10}Be at keV energy is calculated using the method of self-consistent Skyrme Hartree-Fock in the continuum. The calculation successfully reproduces the narrow near-threshold proton-emitting resonance ($E_x = 11.4$ MeV, $\Gamma = 6$ keV, and quantum number $J^\pi = 1/2^+$) in ^{11}B relevant to the β-delayed proton emission of ^{11}Be. This supports the recent experimental result of Ayyad *et al.* at the ReA3 reaccelerator facility of the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The resonance is interpreted as the $s_{1/2}$ single-proton resonance state in the Skyrme Hartree-Fock mean-field theory.

DOI: 10.1103/PhysRevC.106.L051302

Introduction. The study of loosely bound states of atomic nuclei close to the drip lines and beyond is one of the major current directions of nuclear science [1]. At the limits of nuclear stability, rare decay processes were discovered for weakly bound nuclei, especially for nuclei with the halo structure (see [2] for a review).

A very particular case is the β-delayed proton emission (βp) that was theoretically predicted for the halo nucleus ^{11}Be in Refs. [3,4] with unexpectedly high intensity [4]. The decay was indirectly observed in Refs. [5–7]. The existence of a narrow resonance in ^{11}B was suggested to explain this observation [5,8]. However, there was no suitable level in ^{11}B known at that time. There have been several attempts of theoretical calculations to confirm the resonance in ^{11}B and to estimate the $\beta^- p$ decay branching ratio in ^{11}Be [9–12]. These studies and general interest in underlying physics are also related to the search for the so-called neutron dark decay mode proposed in Ref. [13] in order to explain the existing discrepancy between two different methods of neutron lifetime measurements (see [14] for a review). If the dark neutron decay is possible for the unbound nucleon, then it should occur also for the quasibound neutron in a nucleus with sufficiently low neutron binding energy, and ^{11}Be is the most promising nucleus for such studies [15].

Recently, $\beta^- p$ decay was directly observed for the first time in the $^{11}\text{Be} \rightarrow {}^{10}\text{Be} + \beta^- + p$ [16]. The result showed that $\beta^- p$ decay is the sequence of the disintegration proceeding via an intermediate near-threshold narrow resonance in the β^- decay product ^{11}B* at an energy $E_r = 196(20)$ keV above the proton separation energy, with a total width of $\Gamma_p = 12(5)$ keV, and spin-parity quantum numbers $J^\pi = (1/2^+, 3/2^+)$. Moreover, a dedicated experiment employing the ^{10}Be(p, p) reaction was performed later by the same collaboration at the ReA3 reaccelerator NSCL facility [17]. The experimental result indicated a very narrow resonance ($\Gamma_p = 4.4$ keV) with $J^\pi = 1/2^+$ located 182 keV above the proton separation energy. Another experimental result was reported in Ref. [18]. The existence of the new resonance in ^{11}B immediately has a significant impact on nuclear astrophysics [19]. In this Letter, we point out the nature and the key feature of the resonance.

Using an appropriate optical potential for the keV-energy scattering, it is straightforward to calculate the excitation function of the elastic scattering ^{10}Be(p, p). The detailed calculation for the nuclear structure can be directly linked to the problem of scattering without introducing additional

[*] anhnl@hcmue.edu.vn
[†] buiminhloc@ibs.re.kr
[‡] auerbach@tauex.tau.ac.il
[§] Zelevins@frib.msu.edu

approximations, especially in the very-low-energy region where the coupling to the inelastic excitations can be neglected. In the pioneering work Ref. [20], the Hartree-Fock (HF) single-particle potential was expressed as an equivalent optical potential. The version of the optical potential obtained from the HF calculations using the Skyrme effective interaction was long ago demonstrated to be an appropriate formalism for the keV-energy region [21,22]. Not only the background cross section but also the positions and widths of single-particle resonances could be predicted. Recently, the method was successfully applied to the study of keV-nucleon radiative capture reactions in nuclear astrophysics [23–25]. In this work, the Skyrme HF in the continuum method is applied to reproduce the near-threshold resonance in ^{11}B recently found in Ref. [17].

Method. The solution starts with the Skyrme HF calculation for the ground state of ^{10}Be using the `skyrme_rpa` computer program provided in Ref. [26]. The versions of Skyrme interactions used in this study include SkM* [27], SGII [28], SLy4 [29], and SAMi [30]. The local equivalent optical potential within the Skyrme HF formalism (called the Skyrme HF optical potential) $V(E, r)$, is obtained following the method of Ref. [21]:

$$V(E,r) = \frac{m^*(r)}{m}\left\{V_{\rm HF}(r) + \frac{1}{2}\frac{d^2}{dr^2}\left(\frac{\hbar^2}{2m^*(r)}\right) - \frac{m^*(r)}{2\hbar^2}\left[\frac{d}{dr}\left(\frac{\hbar^2}{2m^*(r)}\right)\right]^2\right\} + \left[1 - \frac{m^*(r)}{m}\right]E, \quad (1)$$

where $m = m_p A/(A-1)$ with m_p being the proton mass. The large part of the center-of-mass correction that is important in the case of light nuclei is taken into account. $V_{\rm HF}(r)$ and $m^*(r)$ are the mean-field potential and the effective proton mass within the Skyrme HF approach, respectively [31]. At the keV energy, the nuclear central potential $V(E, r)$ is real and depends weakly on the incident energy. The center-of-mass correction, the rearrangement term, and the nonlocal effect are included in the Skyrme HF optical potential [21,22]. Note that the one-body Coulomb potential that plays an important role in the low-energy scattering is obtained self-consistently in the calculation.

The partial scattering equation

$$\left\{\frac{\hbar^2}{2m}\left[-\frac{d^2}{dr^2} + \frac{\ell(\ell+1)}{r^2}\right] + V(E,r) - E\right\} \times \chi_\ell(E,r) = 0, \quad (2)$$

is solved with the Skyrme HF optical potential in Eq. (1) to obtain the scattering phase shifts and the excitation function using a computer program such as `ECIS06` [32]. The s-wave scattering ($\ell = 0$) dominates at the energy of our interest. The width of the resonance $\Gamma(E_r)$ is calculated from the derivative of the phase shift $\delta_{\ell=0}(E)$ with respect to energy at the position of the resonance E_r,

$$\Gamma(E_r) = 2\left[\frac{d}{dE}\delta_{\ell=0}(E)\right]^{-1}. \quad (3)$$

TABLE I. The scaling factor λ in calculations with different Skyrme interactions. The values of λ are very close to unity. The calculated resonance width is about 5.5–6.0 keV.

Skyrme interaction	λ	Γ (keV)
SkM* [27]	1.004	5.43
SGII [28]	1.028	5.97
SLy4 [29]	0.984	6.09
SAMi [30]	0.998	5.99

Discussion. Without any adjustment, the Skyrme HF calculation provides a good description of the background cross section and the resonance with the single-particle properties. The resonance recently found by Ayyad *et al.* [17] is located at 182 keV, that is close to the $s_{1/2}$ single-particle resonance with $J^\pi = 1/2^+$.

Our calculations with the SkM* and SAMi interactions show the resonance in the appropriate energy region. Outside the resonance, the calculation agrees well with experimental data. In general, the Skyrme HF calculation cannot predict exactly the location of the unknown resonance in ^{10}Be(p, p). Therefore, the nuclear central part of the Skyrme HF optical potential is slightly scaled by the factor λ, that is close to unity (Table I), in order to correct the resonance position to 182 keV. In the case of SLy4 and SGII interactions, the calculations with $\lambda = 1$ do not show the resonance in the energy region. As the resonance is just a few hundred keV above the threshold, it is possibly shifted to the subthreshold energy by using SLy4 and SGII versions. However, with the slight correction (Table I), the resonance at 182 keV appears for all selected variants of the Skyrme interactions.

It is expected that the width of a near-threshold resonance is narrow. Indeed, the calculated resonance widths are 5–6 keV with different Skyrme interactions as seen in Table I. The calculations with and without the adjustment for the case of SAMi interaction are shown in Fig. 1 as an example. The calculations with different Skyrme interactions using the values of λ in Table I cannot be distinguished in Fig. 1. Only the phase shift of the s wave is shown in Fig. 1(b) as the contributions of other waves are negligible. The resonance energy, $E_r = 166$ keV, and the width, $\Gamma = 4.05$ keV (the dotted line in Fig. 1), are obtained with $\lambda = 1$.

When λ is applied, the dispersion of the volume integrals with different Skyrme interactions is reduced from 530 to 260 MeV fm^3. However, at low energy, the incoming particle does not feel the whole potential but only the surface of the potential. It is obtained more precisely by observing the accumulation of the volume integral, which is the value of volume integral as a function of the relative distance r as shown in Fig. 2. Within large distances from 5 to 15 fm, only the effect of the Coulomb potential survives. From where the nuclear potential plays a noticeable role, the difference in the calculations, applying different Skyrme interactions, can be observed as shown in Fig. 2(a). When the value of λ is adjusted to correct the resonance location, the calculations get close, as shown in Fig. 2(b). The dispersion of the accumulation of the volume integral at the nuclear surface ($r = 2.35$ fm) is

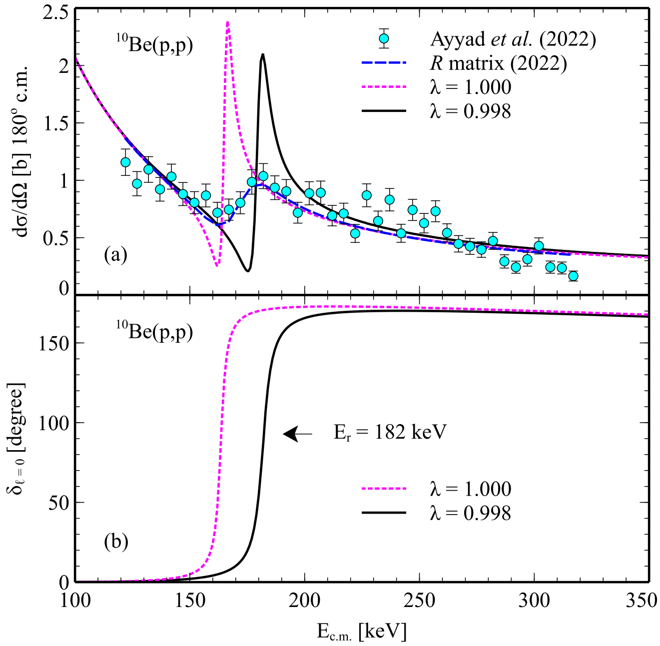

FIG. 1. Calculated excitation function (a) and s-wave phase shift (b) in the center-of-mass frame for ^{10}Be(p, p) elastic scattering. The calculation with SAMi interaction is shown as an example. The experimental data and the R-matrix fitting (the blue-dashed line) are taken from Ayyad *et al.* [17].

reduced from 630 to 440 MeV fm^3. It is worth emphasizing that the slight change in the HF potential caused by the scaling factor λ preserves the calculated single-particle structure and nuclear properties.

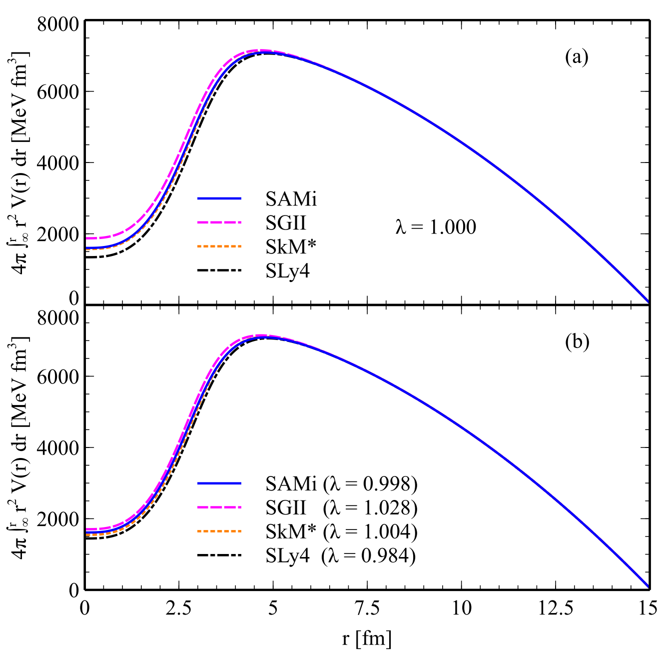

FIG. 2. The accumulation of the volume integral of the total potential. The calculations with different Skyrme interactions are convergent after the adjustment of the potential depth to correct the resonance position at 182 keV.

The width of the calculated resonance is about one-half of the experimental data. The reason is that only the corresponding single channel (^{10}Be $+p$) is considered. The calculated width is, therefore, the proton partial (escape) width only. The spreading contribution that will increase the width can be obtained by the coupled channels calculation. It is important that the channel (^{7}Li $+\alpha$) has its threshold at 8.66 MeV, which is 2.56 MeV below the proton-emission threshold of ^{11}B. A good understanding of α clusterization in light nuclei that is beyond the scope of the present calculation is required for a fully consistent treatment. We can also mention that the corresponding measurements are currently under preparation at FRIB.

Conclusions and outlook. The experimental result [17] of the near-threshold resonance in ^{11}B relevant to the β-delayed proton emission of ^{11}Be is interpreted as the $s_{1/2}$ single-particle resonance predicted by the Skyrme HF calculation. Its simple structure is given by [^{10}Be($0^+_{\rm g.s.}$) + $p(s_{1/2})$]. The calculated width of this resonance is $\Gamma = 6$ keV and quantum numbers are $J^\pi = 1/2^+$. The experiment in Ref. [17] is crucial for localizing the exact position of this resonance.

The final result of calculations does not depend on the choice of the version of the Skyrme interactions. The Skyrme HF calculation is an excellent tool for describing the scattering process including low-lying single-particle resonances in the keV-energy region in light nuclei. As the resonance has mainly a single-particle nature, the mean-field approach, without a configuration mixing, seems to be an appropriate instrument for the analysis. Going to heavier nuclei, one has to expect, along with the stronger Coulomb effects, the growing role of the pairing interaction as demonstrated for low-lying $s_{1/2}$ neutron resonances by Hamamoto and Mottelson [33].

Certainly, the energy density functional does not deal with the continuum; it is not intended to describe precise positions and widths of low-energy resonances. The possibility of describing the data by a very small variation of the parameters (the introduction of the scaling factor λ) is a nice and practically convenient feature of the suggested theoretical description. The value of λ is very sensitive to the position of the low-lying resonance, which is a well-known general feature of quantum problems at the threshold of the continuum. In addition, it was checked that this approach works well for low-lying proton resonances in ^{12}C(p, p) and ^{14,15}O(p, p).

The great current interest in experiments at rare isotope beam facilities around the world and in corresponding reaction theory is important for progress in understanding unusual features of exotic nuclei in relation to nuclear structure, astrophysics, and the standard model of particle physics. Another branch of this physics is related to the role of clusters in the physics of light and medium-weight nuclei; this will be studied in the upcoming FRIB experiment on the decay of ^{11}Be into ^{7}Li and α particle.

Acknowledgment. B.M.L. was supported by the Institute for Basic Science (IBS-R031-D1).

[1] C. W. Johnson, K. D. Launey, N. Auerbach, S. Bacca, B. R. Barrett, C. R. Brune, M. A. Caprio, P. Descouvemont, W. H. Dickhoff, C. Elster, P. J. Fasano, K. Fossez, H. Hergert, M. Hjorth-Jensen, L. Hlophe, B. Hu, R. M. I. Betan, A. Idini, S. König, K. Kravvaris *et al.*, White paper: from bound states to the continuum, J. Phys. G: Nucl. Part. Phys. **47**, 123001 (2020).

[2] M. Pfützner, M. Karny, L. V. Grigorenko, and K. Riisager, Radioactive decays at limits of nuclear stability, Rev. Mod. Phys. **84**, 567 (2012).

[3] M. Horoi and V. Zelevinsky, in April Meeting, American Physical Society, Philadelphia, PA, 2003, abstract U10.001 (unpublished).

[4] D. Baye and E. M. Tursunov, β delayed emission of a proton by a one-neutron halo nucleus, Phys. Lett. B **696**, 464 (2011).

[5] K. Riisager, O. Forstner, M. Borge, J. Briz, M. Carmona-Gallardo, L. Fraile, H. Fynbo, T. Giles, A. Gottberg, A. Heinz, J. Johansen, B. Jonson, J. Kurcewicz, M. Lund, T. Nilsson, G. Nyman, E. Rapisarda, P. Steier, O. Tengblad, R. Thies *et al.*, ^{11}Be(βp), a quasi-free neutron decay? Phys. Lett. B **732**, 305 (2014).

[6] M. J. G. Borge, L. M. Fraile, H. O. U. Fynbo, B. Jonson, O. S. Kirsebom, T. Nilsson, G. Nyman, G. Possnert, K. Riisager, and O. Tengblad, Rare βp decays in light nuclei, J. Phys. G: Nucl. Part. Phys. **40**, 035109 (2013).

[7] K. Riisager, M. J. G. Borge, J. A. Briz, M. Carmona-Gallardo, O. Forstner, L. M. Fraile, H. O. U. Fynbo, A. G. Camacho, J. G. Johansen, B. Jonson, M. V. Lund, J. Lachner, M. Madurga, S. Merchel, E. Nacher, T. Nilsson, P. Steier, O. Tengblad, and V. Vedia, Search for beta-delayed proton emission from ^{11}Be, Eur. Phys. J. A **56**, 100 (2020).

[8] K. Riisager, The strength of beta-decays to the continuum, Nucl. Phys. A **925**, 112 (2014).

[9] A. Volya, Assessment of the beta-delayed proton decay rate of ^{11}Be, Europhys. Lett. **130**, 12001 (2020).

[10] J. Okołowicz, M. Płoszajczak, and W. Nazarewicz, Convenient Location of a Near-Threshold Proton-Emitting Resonance in ^{11}B, Phys. Rev. Lett. **124**, 042502 (2020).

[11] J. Okołowicz, M. Płoszajczak, and W. Nazarewicz, β^{-}p and $\beta^{-}\alpha$ decay of the ^{11}Be neutron halo ground state, J. Phys. G: Nucl. Part. Phys. **49**, 10LT01 (2022).

[12] W. Elkamhawy, Z. Yang, H.-W. Hammer, and L. Platter, β-delayed proton emission from ^{11}Be in effective field theory, Phys. Lett. B **821**, 136610 (2021).

[13] B. Fornal and B. Grinstein, Dark Matter Interpretation of the Neutron Decay Anomaly, Phys. Rev. Lett. **120**, 191801 (2018).

[14] F. E. Wietfeldt and G. L. Greene, Colloquium: The neutron lifetime, Rev. Mod. Phys. **83**, 1173 (2011).

[15] M. Pfützner and K. Riisager, Examining the possibility to observe neutron dark decay in nuclei, Phys. Rev. C **97**, 042501(R) (2018).

[16] Y. Ayyad, B. Olaizola, W. Mittig, G. Potel, V. Zelevinsky, M. Horoi, S. Beceiro-Novo, M. Alcorta, C. Andreoiu, T. Ahn, M. Anholm, L. Atar, A. Babu, D. Bazin, N. Bernier, S. S. Bhattacharjee, M. Bowry, R. Caballero-Folch, M. Cortesi, C. Dalitz *et al.*, Direct Observation of Proton Emission in ^{11}Be, Phys. Rev. Lett. **123**, 082501 (2019).

[17] Y. Ayyad, W. Mittig, T. Tang, B. Olaizola, G. Potel, N. Rijal, N. Watwood, H. Alvarez-Pol, D. Bazin, M. Caamaño, J. Chen, M. Cortesi, B. Fernández-Domínguez, S. Giraud, P. Gueye, S. Heinitz, R. Jain, B. P. Kay, E. A. Maugeri, B. Monteagudo *et al.*, Evidence of a Near-Threshold Resonance in ^{11}B Relevant to the β-Delayed Proton Emission of ^{11}Be, Phys. Rev. Lett. **129**, 012501 (2022).

[18] E. Lopez-Saavedra, S. Almaraz-Calderon, B. W. Asher, L. T. Baby, N. Gerken, K. Hanselman, K. W. Kemper, A. N. Kuchera, A. B. Morelock, J. F. Perello, E. S. Temanson, A. Volya, and I. Wiedenhöver, Observation of a Near-Threshold Proton Resonance in ^{11}B, Phys. Rev. Lett. **129**, 012502 (2022).

[19] A. Sieverding, J. S. Randhawa, D. Zetterberg, R. J. deBoer, T. Ahn, R. Mancino, G. Martínez-Pinedo, and W. R. Hix, Role of low-lying resonances for the ^{10}Be$(p,\alpha)^{7}$Li reaction rate and implications for the formation of the solar system, Phys. Rev. C **106**, 015803 (2022).

[20] D. Vautherin and M. Vénéroni, Potential scattering by a nuclear Hartree-Fock field, Phys. Lett. B **26**, 552 (1968).

[21] C. B. Dover and N. Van Giai, Low-energy neutron scattering by a Hartree-Fock field, Nucl. Phys. A **177**, 559 (1971).

[22] C. B. Dover and N. Van Giai, The nucleon-nucleus potential in the Hartree-Fock approximation with Skyrme's interaction, Nucl. Phys. A **190**, 373 (1972).

[23] N. Le Anh and B. Minh Loc, Bound-to-continuum potential model for the (p,γ) reactions of the CNO nucleosynthesis cycle, Phys. Rev. C **103**, 035812 (2021).

[24] N. Le Anh, P. Nhut Huan, and B. Minh Loc, Potential model within a bound-to-continuum approach for low-energy nucleon radiative capture by ^{12}C and ^{16}O, Phys. Rev. C **104**, 034622 (2021).

[25] N. Le Anh and B. Minh Loc, Low-energy ^{7}Li$(n,\gamma)^{8}$Li and ^{7}Be$(p,\gamma)^{8}$B radiative capture reactions within the Skyrme Hartree-Fock approach, Phys. Rev. C **106**, 014605 (2022).

[26] G. Colò, L. Cao, N. Van Giai, and L. Capelli, Self-consistent RPA calculations with Skyrme-type interactions: The `skyrme_rpa` program, Comput. Phys. Commun. **184**, 142 (2013).

[27] J. Bartel, P. Quentin, M. Brack, C. Guet, and H.-B. Håkansson, Towards a better parametrisation of Skyrme-like effective forces: A critical study of the SkM force, Nucl. Phys. A **386**, 79 (1982).

[28] N. Van Giai and H. Sagawa, Spin-isospin and pairing properties of modified Skyrme interactions, Phys. Lett. B **106**, 379 (1981).

[29] E. Chabanat, P. Bonche, P. Haensel, J. Meyer, and R. Schaeffer, A Skyrme parametrization from subnuclear to neutron star densities Part II. Nuclei far from stabilities, Nucl. Phys. A **635**, 231 (1998).

[30] X. Roca-Maza, G. Colò, and H. Sagawa, New Skyrme interaction with improved spin-isospin properties, Phys. Rev. C **86**, 031306(R) (2012).

[31] D. Vautherin and D. M. Brink, Hartree-Fock calculations with Skyrme's interaction. I. Spherical nuclei, Phys. Rev. C **5**, 626 (1972).

[32] J. Raynal, ECIS06 code, distributed by the NEA DATA Bank, Paris, France; ECIS72 is described in "Optical model and coupled-channels calculations in nuclear physics", in *Computing as a Language of Physics*, ICTP International Seminar Course, Trieste, Italy (IAEA, Vienna, 1971), p. 281.

[33] I. Hamamoto and B. R. Mottelson, Weakly bound $s_{1/2}$ neutrons in the many-body pair correlation of neutron drip line nuclei, Phys. Rev. C **69**, 064302 (2004).