γ-ray spectroscopic study of self-conjugate ^{10}B nucleus with inelastic proton scattering

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Abstract. A γ-ray spectroscopic study of ^{10}B is reported. Excited states in ^{10}B were populated in inelastic proton scattering and their γ-decays were measured with the ELIFANT array, a state-of-the-art spectrometer with large volume $LaBr_3$:Ce and $CeBr_3$ detectors placed in anti-Compton shields and having unprecedented efficiency for high-energy γ rays. A few weak transitions were observed in the experiment, namely $M3$ transition between $J^\pi, T = 0^+_1$, 1 isobaric analog state to the $J^\pi, T = 3^+_1$,0 ground state and $E2$ transition between the $J^\pi, T = 2^+_1$,0 state and the isobaric analog state. The results are compared to a new set of *ab initio* no-core shell model calculation using the newest version of the local position-space chiral N^{3}LO nucleon-nucleon interaction, which correctly reproduces the spectrum of the excited states in ^{10}B, a problem of the theory in previous years.

1 Introduction

The properties of light nuclei are described either within *ab initio* many-body theories [1] or using cluster models [2]. Nowadays, there is renewed interest in experimental states in light nuclei, for a review see Ref. [3], which is due to the intensive development of the *ab initio* models, as well as to the increasing amount of information related to α clustering in ground and excited states. Experimental studies in the $A = 10$ nuclei provide a number of examples for cluster degrees of freedom [4–10]. Cluster-like *vs* shell-model-like basis configurations in light nuclei are described on an equal footing using the antisymmetrized molecular dynamics models [11]. On the other hand, the correct description of the spectrum of the lowest-lying states in ^{10}B has been a long-standing problem for *ab initio* calculations, see Ref. [12] and references therein.

We have carried out a γ-ray spectroscopic study of ^{10}B, using inelastic proton scattering [3, 13, 14]. The γ decay of the $J^\pi, T = 0^+_1$,1 isobaric analog state (IAS) was found to proceed through competing $M3$ and $M1$ transitions to the 3^+_1 ground state (gs) and the lowest lying $J^\pi, T = 1^+_1$,0 excited state. Here we discuss this finding due to clustering effects in both, the IAS and the gs.

2 Experimental Details

In the present experiment, excited states of ^{10}B were populated by an inelastic proton scattering reaction. The 8.5 MeV proton beam was generated at the 9-MV Tandem accelerator of IFIN-HH with an intensity of 0.8 nA. A 30-mg/cm^2 self-supporting ^{10}B target with a 99.24% enrichment was used. Excited states from the target were detected by using the ELIFANT array with large volume $LaBr_3$:Ce and $CeBr_3$ detectors [15] placed in anti-Compton shields of ROSPHERE array [16] and having unprecedented efficiency for high-energy γ rays [17]. Two HPGe detectors were used for tagging the residues. Collimator cones were mounted in front of the BGO's to reduce the direct hit intensity. The DELILA digital data acquisition system was used to control V1730 and 1725 CAEN digitizers [18] and for data collection [19]. The single γ-ray spectra and coincidence γ-ray spectrums were reported

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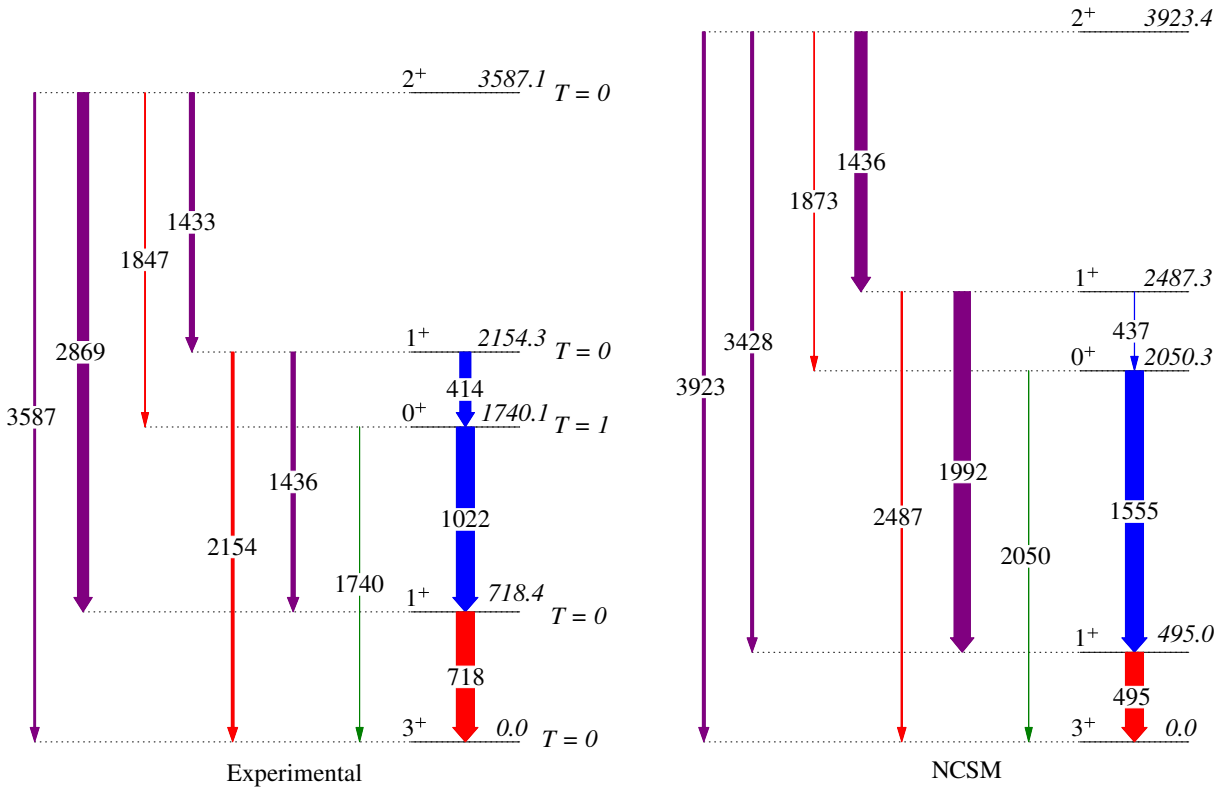

Figure 1. Experimental bound states of ^{10}B are compared with theoretical *ab initio* no-core shell model calculation using the newest version of the local position-space chiral N^{3}LO nucleon-nucleon interaction. Experimental and calculated branching ratios for $M1$s (blue), $E2$s (red), and $M3$ (green) transitions are reported proportionally to arrow widths. Spin, isospin, parties, and branching ratios are taken from Ref. [13].

in Refs. [13, 20]. The branching ratios of the bound states in ^{10}B were obtained via γ-ray spectroscopy as explained in detail in Ref. [3].

3 Results and Discussion

A primary goal of this experiment was the configuration of the suggested weak transitions in ^{10}B [21], especially between the IAS and the gs a quest of the $0^+_1,1 \rightarrow 3^+_1,0$ $M3$ transition, here the first number denotes the spin/parity of the state and its occurrence in the energy spectrum, and the second one is the isospin quantum number. This transition was observed unambiguously [13]. The branching ratio of the $M3/M1$ γ decay is $2.5(1)\times10^{-4}$, yet a correction of about 10% related to summing-up effects needs to be introduced, which will be discussed in a forthcoming paper [22]. The $A = 10$ isobaric multiplet can be described by two α particles with two orbiting nucleons, *e.g.*, two neutrons in the case of ^{10}Be, a proton and a neutron for ^{10}B, and two protons for ^{10}C. Clustering was reported for the $0^+_1,1$ gs in ^{10}Be [23] which indicates that similar effects should be expected in the other nuclei of the triplet. In addition, a highly deformed rotational molecular band was observed in ^{10}Be built on the $0^+_2,1$ state at 6.18 MeV and understood as built on the α:2n:α configuration [10]. In ^{10}B, the 2^+ state at 8.9 MeV, the isobaric analog of the $0^+_2,1$ state at 7.542 MeV in ^{10}Be, was found to be a highly clustered state and was suggested as a member of the α:np:α rotational band [24], which is built on $0^+_2,1$ state at 7.542 MeV [10, 11, 25]. Clustering was found for the 3^- state at 8.9 MeV in ^{10}B, confirming the idea that clustering effects penetrate in different configurations in the $A = 10$ isobaric triplet.

The explanation for the competing $M3$ transition in ^{10}B might be related to clustering effects in both the IAS and gs which results in its enhancement such that it starts to compete with the $0^+_1,1 \rightarrow 1^+_1,0$ $M1$ transition. This opens a new problem for theory to describe.

The spectrum of the ^{10}B excited states was calculated using the N^{3}LO interaction [13, 26], which uses delocalization of the potential. The NCSM calculations correctly reproduce the $3^+,0$ gs and the excited bound states in ^{10}B without involving 3N forces, contrary to numerous previous attempts, for a review see Ref. [12].

An *ab initio* no-core shell model (NCSM) [27] calculation with the newest version of the local position-space chiral N^{3}LO NN interaction was performed [26]. In the NCSM, the nuclear A-body Hamiltonian is defined as [27]:

$$H = \frac{1}{A}\sum_{i<j}^{A}\frac{\left(\boldsymbol{p}_i - \boldsymbol{p}_j\right)^2}{2m} + \sum_{i<j}^{A} V_{ij}^{NN}, \qquad (1)$$

where $\boldsymbol{p}_i$ and $\boldsymbol{p}_j$ denote the nucleon's momentum in the laboratory frame, m is the mass of the nucleon's, and V_{ij}^{NN} is the NN interaction. The Hamiltonian in equation (1) is then diagonalized in the Hilbert space spanned by the harmonic oscillator basis which is referred to as the model space. In the actual NCSM calculations, one has to truncate the model space due to limited computation resources which is often realized by the maximum many-body harmonic oscillator (HO) excitation energy $N_{\max}$. In this work, we took $N_{\max} = 8$, which was large enough to reproduce the converged calculations of $A \sim 10$ nuclei [28]. An optimal HO frequency of $\hbar\Omega = 20$ MeV was used in the numerical calculation corresponding to the energy minima of the ^{10}B gs. The NCSM calculations were performed using the highly parallel code BIGSTICK [29].

The calculated branching ratios in figure 1 describe reasonably well the measured branching ratios. However, there are a number of differences. The most intense transition in the γ decay of the $1_2^+,0$ state is the $M1$ transition to the IAS, while in the NCSM calculations, this is hindered, and the most intense transition is the $M1/E2$ $1_2^+,0 \rightarrow 1_1^+,0$ transition. While the NCSM calculations yields highest intensity for the $2_1^+,0 \rightarrow 1_2^+,0$ $M1/E2$ transition although that is this case the difference is not that striking. The intensity of the $2_1^+,0 \rightarrow 0_1^+,0$ transition is well reproduced in the NCSM calculation. The branching ratios of the bound states in ^{10}B were calculated, as displayed in figure 1, where they are compared to the experimental data obtained in a coincidence γ-ray spectroscopic experiment [13]. Considering the branching ratios of the decay transitions, *e.g.*, the enhancement of the $1_2^+,0 \rightarrow 0_1^+,1$ and $1_2^+,0 \rightarrow 3_1^+,0$ transitions and the hindrance of the $1_2^+,0 \rightarrow 1_1^+,0$ transition compared to the NCSM calculation, one might suggest that there is a higher degree of clustering in the $1_2^+,0$ state compared to the $1_1^+,0$ state. This is further supported by the fact that the $2_1^+,0 \rightarrow 1_1^+,0$ transition is enhanced and the $2_1^+,0 \rightarrow 1_2^+,0$ and $2_1^+,0 \rightarrow 3_1^+,0$ transitions are hindered compared to the NCSM calculation, thus suggesting similar structure of the $1_1^+,0$ and $2_1^+,0$ states on one hand and the $3_1^+,0$ and $1_2^+,0$ states on the other. Note that the IAS $\rightarrow$ gs $M3$ transition is strongly underestimated in the NCSM calculations which might be due to the fact that possible clustering effects are not well taken into account in the model.

4 Conclusions

The spectroscopic study of ^{10}B provided more precise information about the branching ratios of the γ decay of the bound states. The comparison with NCSM calculation using the N^{3}LO interaction demonstrates a reasonable agreement with the experimental values. A weak $M3$ transition between the IAS and the gs was observed, which is totally unexpected because $M3$ transitions are usually hindered. Its enhancement is suggested to be due to clustering effects in both, the IAS and the gs.

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References

[1] H. Hergert, A guided tour of *ab initio* nuclear many-body theory, Front. Phys. **8**, 379 (2020). 10.3389/fphy.2020.00379

[2] I. Lombardo, D. Dell'Aquila, Clusters in light nuclei: history and recent developments, Riv. Nuovo. Cim. **46**, 521 (2023). 10.1007/s40766-023-00047-4

[3] A. Kuşoğlu, D.L. Balabanski, Renewed Interest in Spectroscopy of the Lightest Doubly-Odd $N = Z$ Nuclei, Quantum Beam Sci. **7**, 28 (2023). 10.3390/qubs7030028

[4] W. von Oertzen, Two-center molecular states in ^{9}B, ^{9}Be, ^{10}Be, and ^{10}B, Z. Phys. A **354**, 37 (1996). 10.1007/s002180050010

[5] W. von Oertzen, Dimers based on the $\alpha + \alpha$ potential and chain states of carbon isotopes., Z. Phys. A **357**, 355 (1997). 10.1007/s002180050255

[6] P. Descouvemont, Microscopic study of α clustering in the ^{9,10,11}Be isotopes, Nucl. Phys. A **699**, 463 (2002). https://doi.org/10.1016/S0375-9474(01)01286-6

[7] N. Soić, S. Blagus, M. Bogovac, S. Fazinić, M. Lattuada, M. Milin, D. Miljanić, D. Rendić, C. Spitaleri, T. Tadić et al., ^{6}He + α clustering in ^{10}Be, Europhys. Lett. **34**, 7 (1996). 10.1209/epl/i1996-00407-y

[8] N. Curtis, D.D. Caussyn, N.R. Fletcher, F. Maréchal, N. Fay, D. Robson, Decay angular correlations and spectroscopy for ^{10}Be$^*\rightarrow^4$He+^{6}He, Phys. Rev. C **64**, 044604 (2001). 10.1103/PhysRevC.64.044604

[9] M. Milin, M. Zadro, S. Cherubini, T. Davinson, A. Di Pietro, P. Figuera, D. Miljanić, A. Musumarra, A. Ninane, A.N. Ostrowski et al., Sequential decay reactions induced by a 18 MeV ^{6}He beam

on ^{6}Li and ^{7}Li, Nucl. Phys. A **753**, 263 (2005). https://doi.org/10.1016/j.nuclphysa.2005.02.154

[10] M. Freer, E. Casarejos, L. Achouri, C. Angulo, N.I. Ashwood, N. Curtis, P. Demaret, C. Harlin, B. Laurent, M. Milin et al., α:2n:α Molecular Band in ^{10}Be, Phys. Rev. Lett. **96**, 042501 (2006). 10.1103/PhysRevLett.96.042501

[11] N. Itagaki, S. Aoyama, S. Okabe, K. Ikeda, Cluster-shell competition in light nuclei, Phys. Rev. C **70**, 054307 (2004). 10.1103/PhysRevC.70.054307

[12] P. Choudhary, P.C. Srivastava, P. Navrátil, *Ab initio* no-core shell model study of $^{10-14}$B isotopes with realistic *NN* interactions, Phys. Rev. C **102**, 044309 (2020). 10.1103/PhysRevC.102.044309

[13] A. Kuşoğlu, D.L. Balabanski, R.Z. Hu, S.Q. Fan, F.R. Xu, P. Constantin, P.A. Söderström, M. Cuciuc, S. Aogaki, R.S. Ban et al., Direct Observation of Competing $M1$ and $M3$ Transitions in ^{10}B, Phys. Rev. Lett. **133**, 072502 (2024). 10.1103/PhysRevLett.133.072502

[14] A. Kuşoğlu, The amazing world of the light nuclei, Sci. Bull. **21** (2024). 10.1016/j.scib.2024.08.040

[15] P.A. Söderström, E. Açıksöz, D.L. Balabanski, F. Camera, L. Capponi, G. Ciocan, M. Cuciuc, D.M. Filipescu, I. Gheorghe, T. Glodariu et al., ELIGANT-GN — ELI Gamma Above Neutron Threshold: The Gamma-Neutron setup, Nucl. Instrum. Methods Phys. Res. Sect. A **1027**, 166171 (2022). https://doi.org/10.1016/j.nima.2021.166171

[16] D. Bucurescu, I. Căta-Danil, G. Ciocan, C. Costache, D. Deleanu, R. Dima, D. Filipescu, N. Florea, D.G. Ghiţă, T. Glodariu et al., The ROSPHERE γ-ray spectroscopy array, Nucl. Instrum. Methods Phys. Res. Sect. A **837**, 1 (2016). https://doi.org/10.1016/j.nima.2016.08.052

[17] S. Aogaki, D.L. Balabanski, R. Borcea, P. Constantin, C. Costache, M. Cuciuc, A. Kuşoğlu, C. Mihai, R.E. Mihai, L. Stan et al., A setup for high-energy γ-ray spectroscopy with the ELI-NP large-volume $LaBr_3$:Ce and $CeBr_3$ detectors at the 9 MV Tandem accelerator at IFIN-HH, Nucl. Instrum. Methods Phys. Res. Sect. A **1056**, 168628 (2023). https://doi.org/10.1016/j.nima.2023.168628

[18] L. Capponi, A. Kuşoğlu, P.A. Söderström, D.L. Balabanski, G.V. Turturică, G. Bocchi, S. Chesnevskaya, A. Dhal, D. Dinescu, N. Djourelov et al., First in-beam experiment with the ELIADE detectors: a spectroscopic study of ^{130}La, J. Instrum. **16**, T12001 (2021). 10.1088/1748-0221/16/12/T12001

[19] S. Aogaki, DELILA: Digital Extreme Light Infrastructure List-mode Acquisition - project status report, in: K.M. Spohr (Ed.) ELI-NP Annual Report p. 213 (2022).

[20] A. Kuşoğlu, P. Constantin, P.A. Söderström, D.L. Balabanski, M. Cuciuc, S. Aogaki, R.S. Ban, R. Borcea, R. Corbu, C. Costache et al., Groundbreaking developments in ^{10}B with inelastic proton scattering, Nuovo Cimento C **47**, 47 (2024). 10.1393/ncc/i2024-24047-6

[21] D.R. Tilley, J.H. Kelley, J.L. Godwin, D.J. Millener, J.E. Purcell, C.G. Sheu, H.R. Weller, Energy levels of light nuclei A = 8,9,10, Nucl. Phys. A **745**, 155 (2004). https://doi.org/10.1016/j.nuclphysa.2004.09.059

[22] A. Kuşoğlu, D.L. Balabanski, R.Z. Hu, S.Q. Fan, F.R. Xu, P. Constantin, P.A. Söderström, M. Cuciuc, S. Aogaki, R.S. Ban et al., Phys. Rev. C (in preparation) (2024).

[23] P.J. Li, D. Beaumel, J. Lee, M. Assié, S. Chen, S. Franchoo, J. Gibelin, F. Hammache, T. Harada, Y. Kanada-En'yo et al., Validation of the ^{10}Be Ground-State Molecular Structure Using ^{10}Be(p, $p\alpha$)^{6}He Triple Differential Reaction Cross-Section Measurements, Phys. Rev. Lett. **131**, 212501 (2023). 10.1103/PhysRevLett.131.212501

[24] A.N. Kuchera, G.V. Rogachev, V.Z. Goldberg, E.D. Johnson, S. Cherubini, M. Gulino, M. La Cognata, L. Lamia, S. Romano, L.E. Miller et al., Molecular structures in T = 1 states of ^{10}B, Phys. Rev. C **84**, 054615 (2011). 10.1103/PhysRevC.84.054615

[25] A. Doté, H. Horiuchi, Y. Kanada-En'yo, Antisymmetrized molecular dynamics plus Hartree-Fock model and its application to Be isotopes, Phys. Rev. C **56**, 1844 (1997). 10.1103/PhysRevC.56.1844

[26] S.K. Saha, D.R. Entem, R. Machleidt, Y. Nosyk, Local position-space two-nucleon potentials from leading to fourth order of chiral effective field theory, Phys. Rev. C **107**, 034002 (2023). 10.1103/PhysRevC.107.034002

[27] B.R. Barrett, P. Navrátil, J.P. Vary, *Ab initio* no core shell model, Prog. Part. Nucl. Phys. **69**, 131 (2013). https://doi.org/10.1016/j.ppnp.2012.10.003

[28] P. Navrátil, W.E. Ormand, *Ab Initio* Shell Model Calculations with Three-Body Effective Interactions for p-Shell Nuclei, Phys. Rev. Lett. **88**, 152502 (2002). 10.1103/PhysRevLett.88.152502

[29] C.W. Johnson, W.E. Ormand, P.G. Krastev, Factorization in large-scale many-body calculations, Comput. Phys. Commun. **184**, 2761 (2013). https://doi.org/10.1016/j.cpc.2013.07.022