Direct Observation of Competing $M1$ and $M3$ Transitions in ^{10}B

A. Kuşoğlu,[1,2,*] D. L. Balabanski,[1] R. Z. Hu,[3] S. Q. Fan,[3] F. R. Xu,[3] P. Constantin,[1] P.-A. Söderström,[1] M. Cuciuc,[1] S. Aogaki,[1] R. S. Ban,[1] R. Borcea,[4] A. Coman,[4] R. Corbu,[1] C. Costache,[4] A. Covali,[1] I. Dinescu,[4] N. M. Florea,[4] V. Iancu,[1] A. Ionescu,[4] N. M. Mărginean,[4] C. Mihai,[4] R. E. Mihai,[4,5] C. V. Nedelcu,[1,6] T. Petruse,[1,6] H. Pai,[1] A. Pappalardo,[1] O. A. Sirbu,[1] C. O. Sotty,[4] L. Stan,[4] A. N. State,[1] D. A. Testov,[1] T. Tozar,[1] A. Turturica,[4] G. Turturica,[1] S. Ujeniuc,[4] C. A. Ur,[1] V. Vasilca,[1] and F. Zhu[1]

[1]*Extreme Light Infrastructure-Nuclear Physics (ELI-NP), Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului Street, 077125 Bucharest-Măgurele, Romania*
[2]*Department of Physics, Faculty of Science, Istanbul University, Vezneciler/Fatih, 34134 Istanbul, Turkey*
[3]*School of Physics, and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[4]*Department of Nuclear Physics, Horia Hulubei National Institute for Physics and Nuclear Engineering, 30 Reactorului Street, Bucharest-Măgurele 077125, Romania*
[5]*Institute of Experimental and Applied Physics, Czech Technical University in Prague, Husova 5, Prague, Czech Republic*
[6]*Doctoral School in Engineering and Applications of Laser and Accelerators, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania*

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Excited states in ^{10}B were populated with the $^{10}\mathrm{B}(p,p'\gamma)^{10}\mathrm{B}^*$ reaction at 8.5 MeV and their γ decay was investigated via coincidence γ-ray spectroscopy. The emitted γ rays were measured using large-volume $\mathrm{LaBr_3:Ce}$ and $\mathrm{CeBr_3}$ detectors placed in anti-Compton shields. This allowed the observation of weak γ-ray transitions, such as the $M3$ transition between the $J^\pi, T = 0^+, 1$ isobaric analog state (IAS) and the $J^\pi, T = 3^+, 0$ ground state and the $E2$ transition between the $J^\pi, T = 2^+_1, 0$ state and the IAS, i.e., performing measurements of branching ratios at the level of $\lambda \geq 10^{-4}$. For the first time in ^{10}B, the competing $M1$ and $M3$ transitions from the decay of the IAS have been observed in a γ spectroscopy experiment. The experimental results are compared with *ab initio* no-core shell model calculation using the newest version of the local position-space chiral N^{3}LO nucleon-nucleon interaction. The calculations reproduce correctly the ordering of the bound states in ^{10}B, and are in reasonable agreement with the observed branching ratios and reduced transition probabilities.

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Introduction—Structural effects in the lightest stable nuclei were the first to be studied experimentally. Early research focused on isospin mixing, properties of isospin multiplets and α clustering. Recently, the existing experimental data for the γ decay of the stable $N = Z$ doubly odd nuclei and the β decay of the corresponding isospin multiplets were reviewed [1]. Nowadays, with the advances in *ab initio* many-body theories, there is renewed interest in the structure of these nuclei. The reason is that most of the data were obtained in the second half of the last century and, in some cases, lack the needed precision to meet these advances. Thus, many subtle structural effects remained unexplored. Here, we report a γ-ray spectroscopic study of ^{10}B, which was carried out with an extension of the ROSPHERE array [2], for measurements of high-energy γ rays [3]. This allowed the identification of extremely weak transitions via coincidence γ-ray spectroscopy using the $^{10}\mathrm{B}(p,p'\gamma)^{10}\mathrm{B}^*$ reaction to measure γ-ray branching ratios on the level of $\lambda \geq 10^{-4}$. The first results of these studies were reported in a conference proceeding [4].

Electron [5–8] and pion [9] scattering experiments, suggested an $M3$ transition between the $J^\pi = 0^+$, $T = 1$ $(0^+, 1)$ isobaric analog state (IAS) in ^{10}B with an excitation energy of 1740 keV and the $J^\pi = 3^+$, $T = 0$ $(3^+, 0)$ ground state (gs), where T indicates the isospin quantum number. This transition was not observed in the γ-ray spectra obtained in those experiments, and it would compete with an $M1$ transition between the IAS and the first excited $J^\pi = 1^+$, $T = 0$ $(1^+, 0)$ state in ^{10}B at 718 keV. In the present experiment, we have unambiguously identified this $M3$ transition using coincidence γ-ray spectroscopy.

Furthermore, the correct description of the level ordering in ^{10}B has been an on-going challenge for *ab initio* models for a long time. Early studies with a no-core shell model (NCSM) and Green's function Monte Carlo calculations using different nucleon-nucleon (NN) potentials [10–13] failed to predict the 3^+, 0 state as the gs. Reference [10]

*Contact author: asli.kusoglu@eli-np.ro, kusoglu@istanbul.edu.tr

commented that a possible reason might be that alpha clustering effects were not correctly taken into account. The next step was to involve three-nucleon ($3N$) forces for the description of ^{10}B. It is shown that the correct ordering is reproduced using the AV8′ NN potential with $3N$ Illinois [10,11] or Tuscon-Melbourne TM′(99) [14] forces, but when using Urbana IX [10,11] $3N$ force, the problem persists.

NCSM studies using NN potentials up to the fourth order of the chiral perturbation theory (χPT) in basic spaces ($N_{\max}$) up to 10 $\hbar\omega$ were applied to calculate the spectrum of ^{10}B [15–17]. By including the $3N$ interaction, the 3^+, 0 gs was reproduced correctly [16,17]. Other NCSM studies employing the N^{2}LO$_{\rm opt}$ interaction report a 1^+, 0 gs [18]. Further NCSM calculations were reported for the $^{10-14}$B isotopes using several different interactions [19], i.e., INOY [20], N^{3}LO [21], CDB2k [22], and N^{2}LO$_{\rm opt}$ [18]. For ^{10}B the basic space is $N_{\max} = 10\ \hbar\omega$. These results are compared with shell model calculations obtained in Ref. [19] with the YSOX interaction [23]. The INOY, a nonlocal interaction, reproduces the ordering of ^{10}B(gs, $3^+, T = 0$), ^{10}B*(718 keV, $1^+, T = 0$), and ^{10}B*(IAS, $0^+, T = 1$). The other NCSM interactions fail to reproduce the level ordering, while the shell model calculation reproduces the 3^+, 0 gs.

Shell model calculations for p-shell nuclei using a N^{3}LO $NN +$ N^{2}LO $3N$ potential are consistent with NCSM calculations with the same interaction and correctly reproduce the level ordering [24]. The Daejeon16 and JISP16 NN potentials were applied to p-shell nuclei [25]. These calculations correctly place the 3^+, 0 gs and the 1^+, 0 excited state, without using $3N$ forces. In recent works, the spectra of p-shell nuclei were studied using semilocal momentum-space (SMS) regularized NN LO, NLO, and N^{2}LO potentials in combination with $3N$ forces at N^{2}LO regularized as the SMS potentials [26], as well as interactions beyond N^{2}LO, e.g., N^{3}LO, N^{4}LO, and N^{4}LO$^+$ [27]. The results for ^{10}B demonstrate the migration of the 1^+, 0 depending on the potential used.

A lot of effort has been concentrated on resolving the problem with the 3^+, 0 gs. However, the correct calculation of the excitation spectrum of ^{10}B still remains a problem. Very few calculations reproduce the placement of the 0^+, 1 IAS [19,23,24]. In this Letter, we report a NCSM calculation, using a N^{3}LO potential which correctly describes the excitation spectrum of ^{10}B. We compare the experimental transition probabilities and branching ratios with the results from the calculation.

Experimental details—Excited states in ^{10}B were populated via the ^{10}B$(p, p'\gamma)^{10}$B* inelastic proton scattering reaction. The proton beam was accelerated to 8.5 MeV with an average intensity of 0.8 nA and was delivered by the 9-MV Tandem accelerator at IFIN-HH. An 99.24% enriched 30-mg/cm^2-thick self-supporting ^{10}B target was used. The thickness of the target was determined by measuring the weight of the metal boron powder and dividing it by the disc surface area which has a 1 cm diameter. The full array consisting of 23 ELI-NP large volume ($3'' \times 3''$) LaBr$_3$:Ce and CeBr$_3$ detectors [28], and two ROSPHERE HPGe detectors with anti-Compton shields [2] was used [3]. The former detectors were mounted at 37°, 70°, 90°, 110°, and 143° with respect to the beam. The two HPGe detectors were placed at 90° to identify the reaction channels and the contaminants in the target. Conical heavy metal collimators were mounted in front of the BGO shields to reduce the total count rate to shield the BGOs from a direct hit. Thus, the total photopeak efficiency of the array varied between 4.8% and 1.6% at $E_\gamma = 718$ and 4444 keV with an energy resolution of 29.7 and 89.2 keV, respectively. This assembly enables measurements of well-resolved weak transitions in the MeV energy range.

The experimental data were read out, stored, and processed with a dedicated in-house software framework digital data acquisition system DELILA [29]. Signals from the scintillation and HPGe detectors were recorded using V1730 CAEN digitizers with DPP-PSD firmware [28] and V1725 with DPP-PHA firmware [30], respectively. The V1730 and V1725 digitizers have 16 channels, 14-bit resolution, and a sampling rate of 500 and 250 MS/s, respectively. No external trigger was set. By using digital electronics, an average total trigger rate of 900 kHz was reached. The data were sorted on an event-by-event mode using the ROOT framework [31]. The energy calibration of the detectors was done by fitting second order polynomials to the spectra of ^{60}Co, ^{152}Eu, ^{56}Co, and composite PuBeNi sources [32]. The calibration was further fine-tuned to in-beam conditions using the known intense γ transitions of ^{10}B [33].

A partial level scheme of ^{10}B, revealing the γ decay of the bound states, is shown in Fig. 1. The relative intensities of the transitions obtained from singles γ-ray spectra were reported in Ref. [4]. Contaminating γ rays from the ^{10}B$(p, \alpha\gamma)^7$Be*, ^{10}B$(p, \gamma)^{11}$C* reactions, the β -delayed γ rays from decay of ^{11}C, ^{12}C, and single- (SE) and double-escape (DE) peaks were observed in the single spectra.

An example of a coincidence γ-ray spectrum obtained by gating on the 414-keV transition of ^{10}B is displayed in Fig. 2. The 718 and 1022-keV γ-ray transitions from the decay of the 1740-keV state and the crossover 1740-keV transition are clearly visible. The 1433 and 3009-keV γ rays feeding the 2154-keV state, and the 1577-keV transition feeding the 3587-keV state are also observed in the spectra. Few γ rays originating from resonance states and SE peaks were observed, too.

The γ-decay branching ratios for the bound states in ^{10}B were obtained from the $\gamma\gamma$ coincidence spectra by gating on the 414, 3009, and 1577-keV transitions, respectively. They are listed in Table I. The arrow widths of the transitions

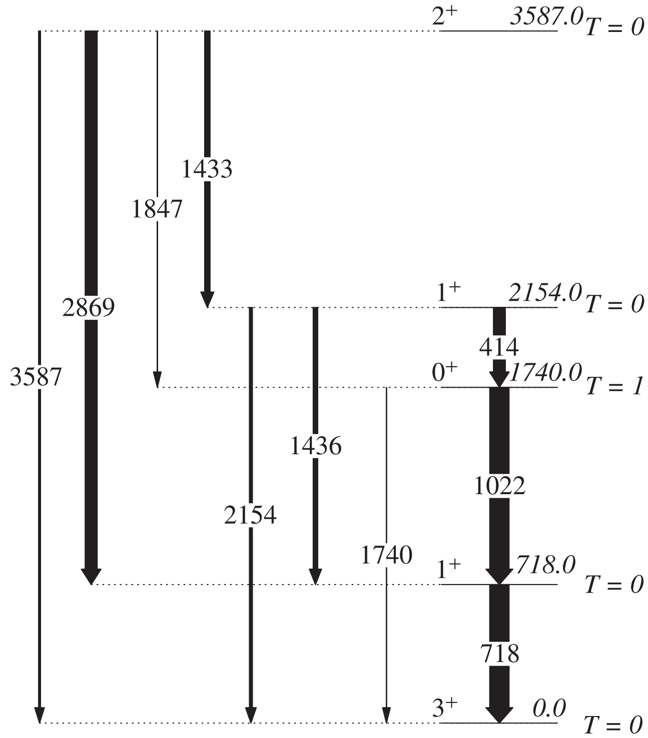

FIG. 1. A partial level scheme of the bound states of ^{10}B. Arrow widths are proportional to the branching ratios (in %) observed in the present experiment. Spin, isospin, and parities have been taken from Ref. [33].

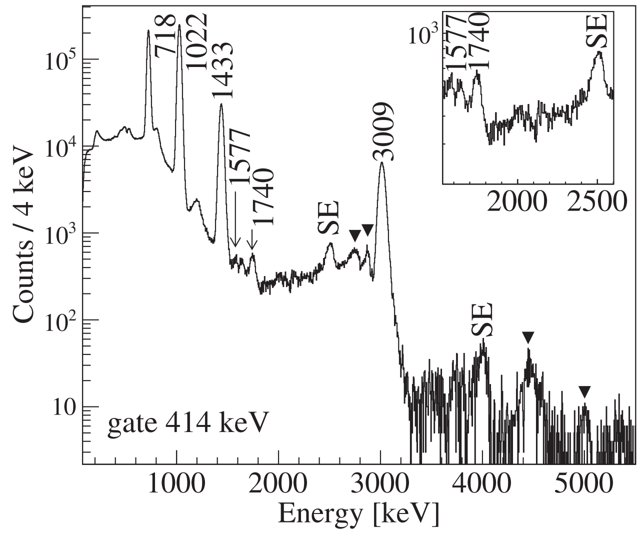

FIG. 2. The γ-ray spectrum observed in coincidence with the 414 keV γ-ray transition of ^{10}B. The ^{10}B γ rays are labeled with their energies. The peaks marked with the triangles indicate contamination.

in Fig. 1 reflect the obtained γ-ray branching ratios. The 1847-keV transition, shown in Fig. 3, was observed only in coincidence with the 718-keV transition. The intensity of the 1847-keV transition was taken into consideration when deducing the branching ratios of the 3587-keV level. The

TABLE I. The initial (E_i) and γ-ray energies (E_γ) of ^{10}B are from the present experiment and rounded to the nearest integer. The spin parity assignments of initial (J_i^π) and final (J_f^π) states, and multipolarity of the γ-ray transitions ($\sigma\lambda$) are taken from Ref. [34] unless specified differently. Calculated and experimental reduced electromagnetic transition probabilities and branching ratios of the bound states in ^{10}B are presented. Branching ratios obtained in this work are compared with NNDC evaluated data [34] and NCSM calculations.

					$B(E\lambda/M\lambda)(\mathrm{e}^2\,\mathrm{fm}^{2\lambda}/\mu_N^2\,\mathrm{fm}^{2\lambda-2})$		Branching ratios		
E_i (keV)	E_γ (keV)	J_i^π	J_f^π	$\sigma\lambda$	NCSM	Ref. [34]	NCSM	Ref. [34]	This work
718	718	1_1^+	3^+	$E2$	4.150	4.147(21)	100.0	100.0	100.0
1740	1022	0^+	1_1^+	$M1$	13.43	7.5(22)	100.0	100.0	99.75(8)
	1740	0^+	3^+	$M3$[a]	2.780×10^3	$< 9.281(3978) \times 10^8$[b]	3.342×10^{-7}	< 0.2	0.25(3)
2154	414	1_2^+	0^+	$M1$	0.0094	0.192(20)	1.45	51.6(16)	61.32(19)
	1436	1_2^+	1_1^+	$M1$	0.0141	0.00016(5)	90.73	27.3(9)	23.30(15)
				$E2$	0.0221	15.6(17)			
	2154	1_2^+	3^+	$E2$	1.120	1.7(2)	7.82	21.1(16)	15.38(14)
3587	1433	2^+	1_2^+	$M1$	0.0287	0.0152(27)	67.36	14(2)	27.8(9)
				$E2$	0.5647	15.2(69)			
	1847	2^+	0^+	$E2$[a]	0.0338	< 0.7748(532)[b]	0.04	< 0.3	0.12(3)
	2869	2^+	1_1^+	$M1$	0.0008	< 0.0009	16.36	67(3)	62.1(7)
				$E2$	0.1241	17.8(18)			
	3587	2^+	3^+	$M1$	0.0004	0.00047(27)	16.24	19(3)	9.98(34)
				$E2$	0.0476	1.15(36)			

[a]The multipolarity of these transitions was suggested in Refs. [5] and [35], respectively, for 1740 and 1847 keV transitions and unambiguously determined in this work.

[b]Calculated by assuming experimental branching ratio from NNDC and total half-life as 102(7) and 4.9(21) fs, respectively, for 1740 and 3587 keV levels.

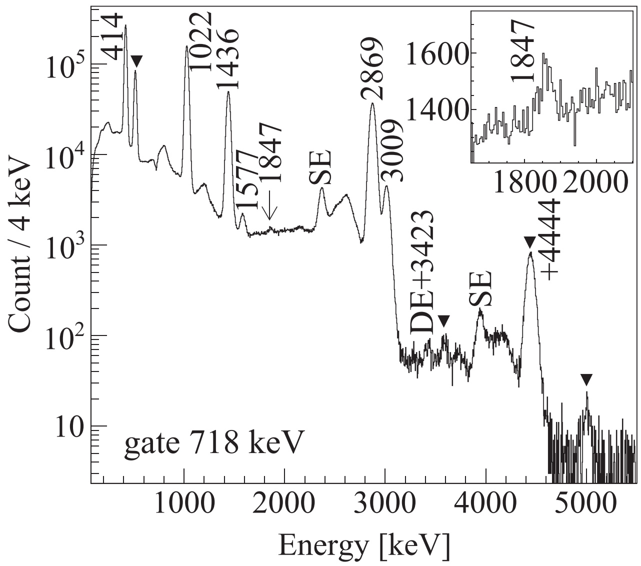

FIG. 3. The γ-ray spectrum observed in coincidence with the 718 keV γ-ray transition of ^{10}B. The notations are the same as indicated in Fig. 2.

area of each photopeak was corrected by scaling the simulated absolute efficiency of the detector setup [3] to the experimental absolute efficiency.

Discussion—So far, several experiments report the γ decay branching ratios of bound [35–41] and unbound [41–47] states in ^{10}B. Only upper limits were reported for the weak 1740 and 1847-keV transitions [35,39–41]. The present measurement unambiguously confirms the existence of these transitions from coincidence γ-ray spectroscopy.

We performed an *ab initio* calculation using the no-core shell model (NCSM) [48] with the newest version of the chiral N^{3}LO *NN* interaction with a regulator cutoff of $R_\pi = 1.2$ fm [49]. This is a local position-space chiral interaction with a weak tensor force component, which would require only a moderate 3*N* force [49]. A harmonic oscillator (HO) frequency of $\hbar\Omega = 20$ MeV was used in the numerical calculation, which minimizes the calculated binding energy of the nucleus. We took the maximum many-body HO excitation energy of $N_{\max} = 8$ which defines the model space. It is shown that $N_{\max} = 8$ can reasonably reproduce the converged calculations of $A \sim 10$ nuclei [12]. To expedite the convergence of numerical calculations, the chiral *NN* interaction was evolved to a low momentum scale $\lambda = 2.2$ fm^{-1} using the similarity renormalization group [50].

The experimental and calculated bound excited states of ^{10}B are plotted in Fig. 4. Here, we should mention that previous calculations using the earlier versions of the N^{3}LO *NN* force without the inclusion of the 3*N* force cannot reproduce the correct 3^+, 0 ground state and the correct order of the levels in ^{10}B [12,15–19,51].

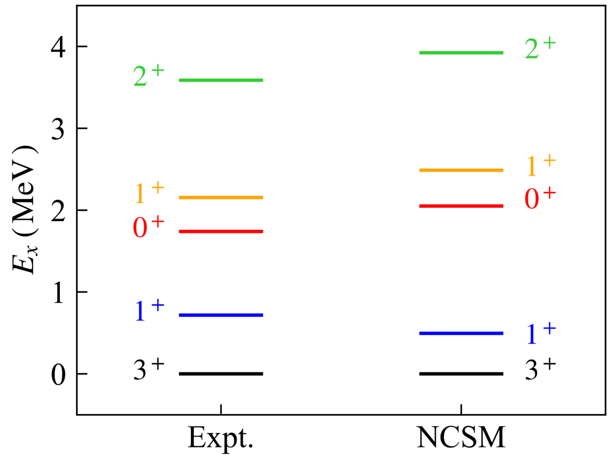

FIG. 4. Experimental bound excited states of ^{10}B compared with the NCSM calculation with the newest version of the local position-space chiral N^{3}LO *NN* force [49].

We also calculated the reduced electromagnetic transition probabilities between the initial (i) and final (f) states, defined as

$$B(\sigma\lambda; \xi_i J_i \to \xi_f J_f) \equiv \frac{1}{2J_i + 1} |\langle \xi_f J_f \| O_{\sigma\lambda} \| \xi_i J_i \rangle|^2, \quad (1)$$

where J_i (J_f) indicates the spin of the initial (final) state, while ξ_i (ξ_f) represents all other quantum numbers relevant to the states. $\langle \xi_f J_f \| O_{\sigma\lambda} \| \xi_i J_i \rangle$ is the reduced matrix element of the electromagnetic multipole operator $O_{\sigma\lambda}$, calculated by the NCSM wave functions obtained. Table I gives the transition calculations compared with experimental data from [34] and those obtained in the present experiment. We see that reasonable agreements are obtained among calculations and data, except the *M*3 transition from the 0^+, 1 to 3^+, 0 state. As shown in Table I, the branching ratios of the transitions can be obtained with the transition probabilities, also showing reasonable agreements among calculations and data, except the ratios from the second 1^+, 0 excited state, which may be due to the sensitivity of this state to the detail of the interaction as commented in Ref. [17].

While NCSM calculations manage to reproduce the ordering of the bound states in ^{10}B, the magnitude of the competing *M*3 transition connecting the 0^+, 1 IAS and the 3^+, 0 gs remains a puzzle. Usually, *M*3 transitions are strongly hindered and the corresponding excited states are spin-trap isomers. However, in the case of ^{10}B, the decay of the IAS goes to the gs and to the 1_1^+, 0 state.

The structure of the low-lying states in ^{10}B can be understood by investigation of three body picture of a core nucleus with two valence nucleons at the nuclear surface. Based on this picture, the 3^+, 0 and 1_1^+, 0 states have $T = 0$, $S = 1$ *pn* pair in the *D* and *S* waves, respectively around the 2α core. The level inversion is suggested to be due to the attractive spin-orbit interaction for the $S = 1$ *pn* pair from the core in the D wave and the $3^+, 0$ state comes down to the gs [52,53].

Experimental studies related to clustering aspects of the structure of $A = 10$ nuclei were reported for both, ^{10}Be where four molecular bands have been reported [54–60], one of them being built on the $0^+, 1$ gs [55,56], and ^{10}B [54,55]. In ^{10}B, the $2^+_4, 1$ state at 8895 keV was reported to have a molecular structure [61]. In ^{10}Be, a $\alpha{:}2n{:}\alpha$ molecular band, built on the $0^+_2, 1$ state at 6179 keV, is discussed. Kuchera *et al.* point at a similar analog band in ^{10}B built on the $0^+_2, 1$ state at 7560 keV, and the $2^+_4, 1$ state at 8895 keV being the first member of this band, which corresponds to the $2^+, 1$ state at 7542 keV in ^{10}Be [61]. A possible candidate for a $4^+, 1$ member of the molecular band in ^{10}B was also reported [62].

A recent experiment reports gs molecular structure in ^{10}Be [63]. Similarly, some clustering might occur for the $0^+, 1$ IAS at 1740 keV. Von Oertzen pointed out the similarity in the excitation of the $2^+_1, 1$ state in ^{10}Be and the $2^+_3, 1$ state in ^{10}B, which may reflect the fact that they belong to molecular bands [55]. Thus, the occurrence of a competing $M3$ transition in the decay of $0^+, 1$ IAS in ^{10}B might be due to clustering effects.

Conclusion—The γ decay of the bound states of ^{10}B was measured with an array of 23 Compton-suppressed $3'' \times 3''$ $LaBr_3{:}Ce$ and $CeBr_3$ detectors using the $^{10}B(p, p'\gamma)^{10}B^*$ reaction. This made possible the identification of weak transitions. Thus, the existence of competing $M1$ and $M3$ transitions which deexcite the $J^\pi, T = 0^+, 1$ IAS was confirmed unambiguously, and their branching ratio was found to be $\lambda = I_\gamma(M3)/I_\gamma(M1) = 2.5(1) \times 10^{-4}$, where I_γ denotes the intensity of the corresponding transition. Clustering effects in both the $3^+, 0$ gs and the $0^+, 1$ IAS are suggested to enhance the $M3$ transition.

The experimental results were compared with *ab initio* NCSM calculations using the newest version of the local position-space chiral N^3LO NN interaction, which correctly describes the level ordering of the bound states in ^{10}B. The branching ratios and the reduced transition probabilities were calculated as well. Apart from the results for the $M3$ transition, they were found to be within a reasonable agreement with experimental data.

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