Isomer γ spectroscopy of the ^{217}Bi isotope

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The structure of the heavy neutron-rich bismuth isotope ^{217}Bi has been studied for the first time, exploiting the fragmentation of a primary uranium beam at the FRS-RISING setup at GSI and performing γ-decay spectroscopy, since μs isomeric states were expected in this nucleus. Gamma-rays following the decay of a $t_{1/2} = 3\mu s$ isomer were indeed found, allowing one to establish the low-lying structure of ^{217}Bi. Level energies are compared to large-scale shell-model calculations.

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I. INTRODUCTION

The study of nuclei far from stability has been a major research field in modern nuclear physics, a field that has grown up substantially with the advent of radioactive beams. Various regions of the nuclide chart have been explored with stable beams using mainly fusion-evaporation, deep-inelastic or fission reactions. However, the neutron-rich isotopes nearby lead have always been difficult to populate with the aforementioned reactions. In the last fifteen years their study has been made gradually possible by the use of fragmentation reactions combined with in-flight mass separators and advanced setups for decay-spectroscopy. For example the fragmentation of a uranium beam was used to produce ^{212}Pb and ^{211}Bi and measure their isomeric decay [1]. Similarly, the adjacent elements beyond N=126 and below Z=82, such as thallium and mercury [2, 3] have been studied. For the elements beyond N=126 but well above Z=82 the situation is very different as they can be populated, with large cross sections, with spallation or fragmentation reactions on uranium. The α-decay from these heavy isotopes can also populate lighter nuclei towards the lead region, enabling their spectroscopic study. However, the bismuth isotopes, one proton above lead, are not all reachable via decay of easy-to-produce heavy nuclei. The ^{211}Bi isotope has been studied via transfer and fragmentation reactions [1, 4, 5], and via the β and α decay of ^{211}Pb and ^{215}At, respectively [6, 7], leading to the discovery of two isomeric states in the same decay sequence. The ^{213}Bi nucleus has also been studied by α decay of ^{215}At [8], and

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its first excited state $13/2^-$ was observed. Besides ^{211}Bi, the only other known isomeric state in the neutron-rich odd-even bismuth isotopes is in ^{215}Bi, six neutrons above N=126, which was populated with a spallation reaction at ISOLDE [9]. Such reactions at ISOLDE were also successfully employed for the production of ^{215}Pb [10] and ^{218}Bi [11].

Recent improvements in the experimental devices and beam intensities now allow exploring more extensively the exotic neutron-rich nuclei in this region, via fragmentation reactions from a ^{238}U beam [12]. For example, the neutron-rich lead isotopes were studied, taking advantage of long-lived (μs range) 8^+ seniority isomers, predicted by theory and indeed found up to ^{216}Pb [12]. Nearby isotopes were also effectively populated for the first time, up to mass number 219 for the bismuth nuclei and to mass 210 for the mercury isotopes [13–15].

In this mass region neutrons are filling the $g_{9/2}$ shell beyond the N=126 shell closure, giving origin in the even-even lead isotopes to a low-lying level structure which agrees with the predictions of the seniority scheme [12]. A very basic expectation is that the level structure of $^{211-217}$Bi follows the same pattern, since the unpaired proton outside the Z=82 shell should couple with the excited levels of the corresponding even-even lead core. The situation can be complicated by the fact that the coupling gives origin to a multiplet of states with different spins, which can make the decay of the seniority isomer to proceed through several branchings. It is also possible that the high-spin members of a multiplet lowers in energy, thus creating spin traps with long lifetimes (τ >ms). Experimentally, the two known nuclei ^{211,215}Bi have basically the same low-spin structure [4, 9], apart from a level inversion at high spin that forms the measured yrast trap in ^{215}Bi [9]. The knowledge of the ^{217}Bi nucleus, which is the object of the present study, is limited to its ground state that decays β^- to excited states of ^{217}Po with an half-life of 92 (3) s [16]. Spin and parity of the the ground state are not known but from systematics one can safely assume that it is $9/2^-$, due to the occupation by the 83rd proton of the $h_{9/2}$ single-particle state.

The present paper, that reports the first spectroscopic study of the exotic neutron-rich nucleus ^{217}Bi, is organized as follows. In the first section the experimental setup is described in detail. In the second one the results from ion mass identification and γ spectroscopy are presented and discussed. The final section deals with the theoretical interpretation of the observed level scheme, in the framework provided by the shell-model calculation taking into account the recent results on effective three-body forces in lead nuclei [12].

II. EXPERIMENTAL SETUP

The results of this work have been obtained by exploiting the advanced features of the state-of-the-art FRS-RISING setup [17–20] and the UNILAC-SIS accelerator facilities at GSI by using a 1 GeV A ^{238}U beam with an intensity of around 1.5×10^9 ions/spill. The $\sim$ 1 s spills were separated by a $\sim$ 2 s period without beam. The uranium ions were fragmented on a 2.5 g/cm^2 Be target (followed by a 223 mg/cm^2 Nb stripper) and the reaction products were separated and identified in mass and atomic number with the double-stage magnetic spectrometer FRS [17]. This is a mass spectrometer suitable for discriminating the different magnetic rigidities of relativistic beams, from light to heavy ions. The information gathered from its detectors (see later) allows one to unambiguously identify masses in the heavy region of interest (A $\sim$ 210-220). The first detectors along the spectrometer were located at the second focal plane, where charge states from the primary beam as well as other heavy ions can arrive, being their magnetic rigidity similar to the one of the isotopes of interest. These detectors cannot sustain the resulting high counting rate ($\sim 10^8$ Hz) coming from the aforementioned contaminations, and therefore an homogenous 2 g/cm^2 Al degrader was placed after the first dipole in order to exclude from the acceptance of the FRS the heavy fragments. The wedge-shaped Al degrader at the intermediate focal plane was set with a thickness of 758 mg/cm^2, while its angle was the appropriate one to produce a monochromatic beam.

The identification in magnetic rigidity ($B\rho$) is achieved through focal-plane position measurements with respect to the position of a beam with a well-known $B\rho$. The plastic scintillators at the intermediate and final focal planes allow extracting the time of flight (TOF). The mass over charge ratio (A/q) of the fragments is calculated from the TOF and the $B\rho$, measured on an event-by-event basis. The atomic number of the fragments is obtained from two ionization chambers placed in the final focal plane. Finally, the comparison of the $B\rho$ before and after the Al wedge-shaped degrader allows one to discriminate a possible change in the ion charge state. These measurements are sufficient to provide a complete identification of the isotopes event by event. Figure 1 shows a typical identification plot obtained. The different isotopes are clearly separated in both Z and A/q ratio (or better A/Z, since only the fully-stripped ions were selected).

At the final focal plane, the ions were slowed down in a thick Al degrader in order to reduce the energy of the fragments of interest before being implanted in a composite double-sided silicon-strip (DSSSD) detector system comprising 3 layers, each with three DSSSD pads [20, 21]. The monochromatic beam ensures that the implantation depth in the active stopper is the same for all the fragments of a certain A/q and Z. The DSSSD detector system was surrounded by the RISING γ spectrometer [18, 19], consisting of 105 germanium crystals arranged in 15 clusters with 7 crystals each. The full-energy γ-ray peak detection efficiency of the array was measured to be 15% [18] at 662 keV. In the present ex-

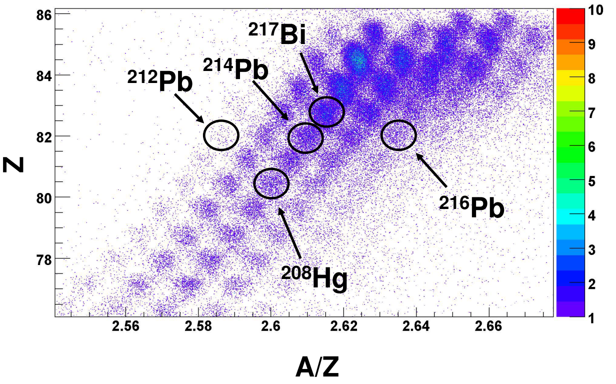

FIG. 1. (Colour online) Ion identification plot at the final focal plane of the FRS. The ^{217}Bi products have been circled, as well as some neighbouring nuclei to provide a reference.

periment, due to the presence of the active stopper with its metal casing, the absolute efficiency of the array was measured to be ∼13% at 662 keV. The time correlation between the γ rays and the ions detected with the active stopper allowed one to perform at the same time isomer spectroscopy and β-delayed γ-ray spectroscopy [13].

III. EXPERIMENTAL RESULTS

Figure 2 shows the γ spectrum following the isomeric decay of ^{217}Bi. Four transitions are clearly visible and their intensities are reported in Table I. The peak at 77 keV corresponds to the K$_\alpha$ X rays from bismuth.

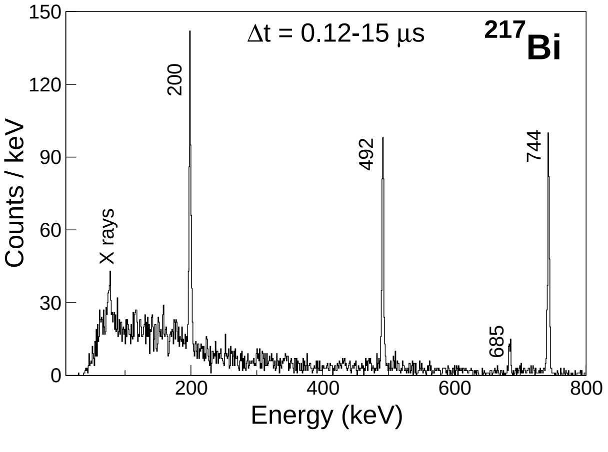

FIG. 2. Gamma-ray spectrum from the decay of the isomeric state in ^{217}Bi. The spectrum has been obtained by gating on the time window 0.12 - 15 μs.

Figure 3 presents the results of $\gamma\gamma$ coincidences. The γ rays at 744, 492 and 200 keV are in mutual coincidence, and a coincidence relationship is also evident between the 744- and the 685-keV lines. As anticipated above, one can expect that the structure of bismuth nuclei is determined by the coupling of the single proton outside the Z=82 shell closure to the excited levels in ^{216}Pb. Since the lowest single-proton orbital above Z=82 is $h_{9/2}$, one expects that the low-lying levels in ^{217}Bi have the configuration: $\pi h_{9/2} \otimes \nu g^2_{9/2}{}^{(0^+ \ldots 8^+)}$. The isomeric state should have a spin-parity $25/2^-$, with a $\pi h_{9/2} \otimes (\nu 2g_{9/2})^{8^+}$ configuration, corresponding to the 8^+ isomer of lead nuclei. Therefore, following the systematics from lighter odd-even bismuth isotopes, the 200-, 492- and 744-keV γ rays are tentatively assigned to the cascade $21/2^- \rightarrow 17/2^- \rightarrow 13/2^- \rightarrow 9/2^-$. The $25/2^- \rightarrow 21/2^-$ transition is expected to have a low energy (in ^{211}Bi it is only 30 keV) which makes it highly converted and unfeasible to measure. This is similar to the case of the even-even lead isotopes [12]. The 685-keV γ ray is in coincidence only with the 744-keV one, see Fig. 3, and it is hence assigned to a decay from a state located 685 keV above the $13/2^-$ level and 7 keV lower than the $21/2^-$ state. Figure 4 shows the exponential fit to the decay curves of the four transitions. Within errors, the four fits give the same decay constant, which suggests that the four transitions are following the decay of the same isomer, namely the expected $25/2^-$ state. Since anyway one cannot exclude completely that the 685-keV γ ray follows the decay of a second isomer (with a very similar half-life) we have preferred to extract the half-life of the $25/2^-$ isomer from the error-weighted average of

TABLE I. Areas, intensities corrected for efficiency and internal conversion and decay constant t$_{1/2}$ for transitions identified in ^{217}Bi.

E$_\gamma$ (keV)	Area	Intensity (%)	t$_{1/2}$ (μs)
200	401 (38)	92 (9)	3.1(2)
492	331 (32)	87 (8)	2.9(2)
685	45 (13)	14 (4)	3.3(7)
744	307 (35)	100 (11)	2.8(1)

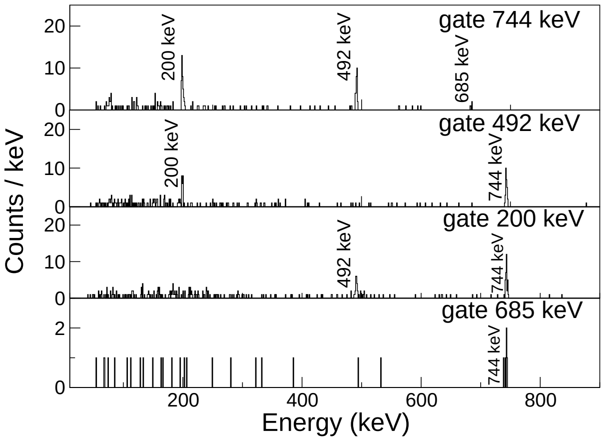

FIG. 3. Gamma-ray prompt coincidence spectra for the decay from the isomeric state in ^{217}Bi, with gates on the four transitions following the isomer.

the decay constants of the 200- and 492-keV transitions. The isomer half-life deduced in this way is 3.0(2) μs.

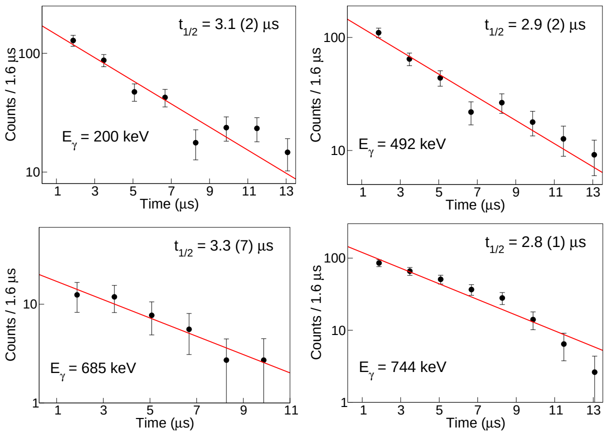

FIG. 4. (Colour online) Time distributions and exponential fits, in red, for the 200-, 492-, 685- and 744-keV transitions assigned to the ^{217}Bi nucleus.

The characteristic K_α X rays from bismuth at 77 keV are observed with an intensity compatible with the internal conversion of the other four γ rays. Considering that the binding energy of the K electrons in bismuth is 90.5 keV, this means that the transition directly depopulating the isomer must be below $\sim$90 keV. From systematics in bismuth, lead and mercury isotopes [2, 12], we assume a lower limit of 20 keV for this transition. Although the energy of the $25/2^- \rightarrow 21/2^-$ transition is not known, the fact that it has to be between 20 and 90 keV implies that it is highly converted, and consequently the energy dependence of the E2 transition rate is compensated by the opposite energy dependence of the total E2 conversion coefficient. As a result, the B(E2) value from the isomeric state is only weakly dependent on the transition energy, making it possible to have an estimate of the B(E2) strength that ranges from 6.2 ± 0.3 e^{2}fm^4 for 20 keV to 4.4 ± 0.2 e^{2}fm^4 for 90 keV.

For the state decaying via the 685-keV γ ray to the $13/2^-$ level in ^{217}Bi, the most straightforward assumption from the measured decay constant is that it belongs to a second decay branch of the same isomer feeding the other states. The γ rays connecting the isomer to this level may not be observed due to their low energy. Considering that the X rays observed are compatible with the internal conversion of the four transitions, the energy of these connecting transitions has to be below 90 keV. The most probable scenario is that the 685-keV transition has an M1 or E2 multipolarity leading to a $15/2^-$ or $17/2^-$ assignment for the new state at 1429 keV. Such assignment would imply at least two (or three if the spin is $15/2^-$) transitions connecting the $25/2^-$ isomer to the 1429-keV state. All such transitions will be well below 90 keV, of E2 (M1) character, and thus almost completely converted. The new state (states) then formed will be isomeric, and the combination of the $25/2^-$ isomer half-life with that (those) of this (these) intermediate state (states) should lead to the measured half-life of the 1429-keV level. This is compatible only with half-lives of the order of 100 ns for the intermediate state (states), which are inside the range expected from systematics in the decay sequence of a seniority isomer of this region [5]. If the 1429-keV state is fed by the $25/2^-$ seniority isomer, this branching ratio must be considered when estimating the B(E2; $25/2^- \rightarrow 21/2^-$), resulting in a value which ranges from 5.6 ± 0.3 e^{2}fm^4 to 3.6 ± 0.2 e^{2}fm^4.

As mentioned before, one cannot exclude that a second isomer exists in ^{217}Bi and one possibility could be that the 1429-keV state itself is isomeric. An isomeric transition of 685 keV would be well compatible with the measured half-life only if it has an E3 multipolarity, thus giving a $19/2^+$ isomeric nature for the 1429-keV state. In view of systematics, it is highly unlikely that this state is isomeric and located at such low energy.

Figure 5 shows the level scheme of ^{217}Bi proposed from the present work.

IV. THEORETICAL DISCUSSION

The new states observed in ^{217}Bi should be formed by coupling a valence proton in the $h_{9/2}$ orbital to the core-excited states in ^{216}Pb. Being the excited states up to 8^+ in ^{216}Pb understood within the seniority scheme $(2g_{9/2})^2$, the same structure is expected in ^{217}Bi with the yrast states forming the sequence $9/2^-$, $13/2^-$, $17/2^-$, $21/2^-$ and $25/2^-$. Figure 6 shows, for the $^{211-217}$Bi nuclei, the results of shell-model calculations with the Kuo-Herling (KH) interaction compared with the experimentally known level schemes. The valence space to describe these nuclei is constituted by the neutron shells $(g_{9/2}i_{11/2}d_{3/2}d_{5/2}g_{7/2}s_{1/2}j_{15/2})^8$ and by the proton shells $(h_{9/2}f_{7/2}i_{13/2}f_{5/2}p_{3/2}p_{1/2})^1$. A full calculation in this space is feasible, using state-of-the-art large-scale shell-

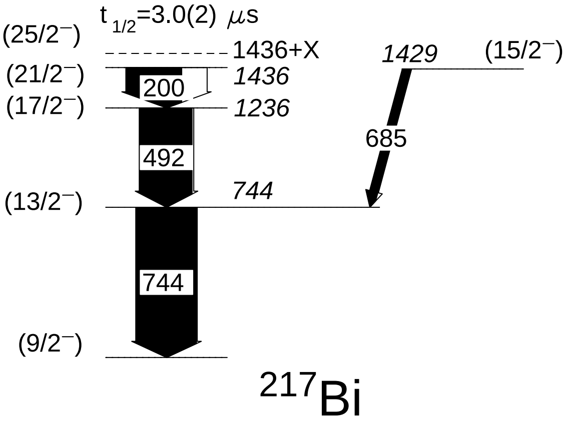

FIG. 5. Level scheme of ^{217}Bi deduced from the present data.

model codes like ANTOINE or NATHAN, only up to ^{213}Bi. For ^{215,217}Bi a reduction in the model space is needed. The calculations for these two nuclei were performed by restricting the proton valence space to $h_{9/2}f_{7/2}$ and by allowing up to six neutrons in the $i_{11/2}$ shell and up to four neutrons in the $j_{15/2}$ shell, while no restriction is given to the occupancy of the other neutron orbitals $g_{9/2}, d_{3/2}, d_{5/2}, g_{7/2}, s_{1/2}$. The fact that the energy of the first excited state $13/2^-$ is well reproduced shows that, even with this truncation, the pair scattering from the $\nu g_{9/2}$ orbital to the shells above is properly described.

The agreement between the calculated and experimental level energies is very satisfactory, being of the order of 100 keV (see Fig. 6). The analysis of the nuclear wave function confirms the above-mentioned simple scheme where the single proton in the $h_{9/2}$ orbital couples to the excited, seniority-two, neutron states of the corresponding even-even Pb isotopes.

Concerning the 1429-keV level in ^{217}Bi, for which we propose a $15/2^-$ or $17/2^-$ assignment, the shell-model calculations predict a $15/2^-$ state close by in energy.

A sensitive test of the nuclear wave function is given by the B(E2) values of the transitions depopulating the isomeric states. The half lives of the $25/2^-$ levels in ^{211}Bi and ^{217}Bi are 1.4(3) μs [1] and 3.0(2) μs (this work) that yield a reduced transition probability B(E2) of 8(2) e^{2}fm^4 for ^{211}Bi, and from 6.2 ± 0.3 e^{2}fm^4 to 4.4 ± 0.2 e^{2}fm^4 for ^{217}Bi, as discussed before. The $25/2^-$ seniority isomer is not known in ^{213}Bi, while in ^{215}Bi the presence of the $27/2^-$ spin-trap does not allow a seniority isomer. It is worth to notice that the spin inversion in ^{215}Bi between $25/2^-$ and $27/2^-$ is well reproduced by shell-model calculations. We have calculated the B(E2)s using the same valence space and interaction already employed for the level energies and adopting the standard effective charges for this region: $e_\pi = 1.5e$ and $e_\nu = 0.8e$. The results are 92 e^{2}fm^4 and 1.0 e^{2}fm^4 for ^{211}Bi and ^{217}Bi, respectively. The discrepancy with the experimental results is large. What is most disturbing is that, while the experimental B(E2)s are close to each other, as it happens for the corresponding B(E2)s in the core nuclei ^{210}Pb and ^{216}Pb, the theoretical B(E2)s, which for the lead cores were comparable, differ here by a factor 100. As mentioned above, for the ^{217}Bi calculations a restricted shell model space had to be used and this is the most probable cause of the large difference in the calculated B(E2)s. With the intent to further understand this peculiar behaviour, we have applied to the Bi isotopes the same approach successfully adopted in Ref. [12], where effective three-body forces have been included. In the bismuth case, however, since there is a proton in the valence space, it is difficult to perform a diagonalization in a space which includes all the neutron (and proton) shells as in Ref. [12]. On the other hand, it was shown that the relevant renormalization for the quadrupole operator is provided by particle-hole excitations across the $\Delta J = 2$, $0\hbar\omega$ shells $\nu i_{13/2} - \nu g_{9/2}$ and $\pi h_{11/2} - \pi f_{7/2}$, partners in the quasi-SU(3) scheme [12]. They are responsible for quadrupole coherence [22] and their inclusion allows one to evaluate the possible effect of three-body forces.

For the bismuth isotopes we have then performed the calculations including only these relevant shells, plus the $\pi h_{9/2}$ orbital occupied by the unpaired proton. As discussed in Ref. [12] the Kahana Lee Scott (KLS) interaction and the effective charges $e_\pi \sim 1.5e$ and $e_\nu \sim 0.5e$ have been used. In a first stage, the diagonalization of the Hamiltonian is performed in the $(\nu g_{9/2})^n$ space, with the addition of the $\pi h_{9/2}$ occupied by the unpaired proton. The results obtained for the B(E2) values from the $25/2^-$ states of ^{211,217}Bi are 27 and 21 e^{2}fm^4, respectively. When particle-hole excitations from the core are allowed, these strengths increase to 38 and 28 e^{2}fm^4, respectively. The disagreement between the measured and the calculated B(E2)s remains large for both ^{211}Bi and ^{217}Bi but the inclusion of effective three-body forces makes now also the calculated B(E2)s similar among them. The fact that the ratio between the ^{211}Bi and ^{217}Bi B(E2)s is reproduced is significant since it shows that the inclusion of core excitations, equivalent to consider effective three-body forces, is improving the agreement with the experimental measurements. What remains to be understood is the discrepancy of the absolute value, which in both nuclei is experimentally lower by a factor 4-5. Explanations for this behaviour are not straightforward and may be found when more refined shell-model calculations in such large spaces will be possible.

V. CONCLUSIONS

The present paper reports first results on the excited states in the neutron-rich nucleus ^{217}Bi. The study of this exotic isotope was made possible by the presence of isomeric states, which allowed one to perform decay γ spectroscopy using a radioactive beam from uranium fragmentation. Four transitions were assigned to the decay from an isomeric state with a half life of 3(2) μs. The expected decay branch from the seniority isomer was observed, but there is evidence for another decay branch most probably from the same isomer. The derived level scheme was compared with systematics from lighter isotopes, as well as state-of-the-art shell-model calculations. Whereas the level energies of ^{217}Bi as well as of the other lighter odd-even Bi isotopes are well reproduced, the same calculations fail completely to predict the experimental B(E2) from the $25/2^-$ seniority isomers in ^{211}Bi and ^{217}Bi. When effective three-body forces are included, the correct ratio between the experimental B(E2) is reproduced but not the absolute value. These experiments on heavy exotic nuclei are still at the limits in terms of statistics and sensitivity and may gain a lot from the expected improvements of experimental setups and beam intensities. Finally, from the theoretical point in view, in order to overcome the present difficulties, developments of codes able to perform a diagonalization in the full valence space are mandatory.

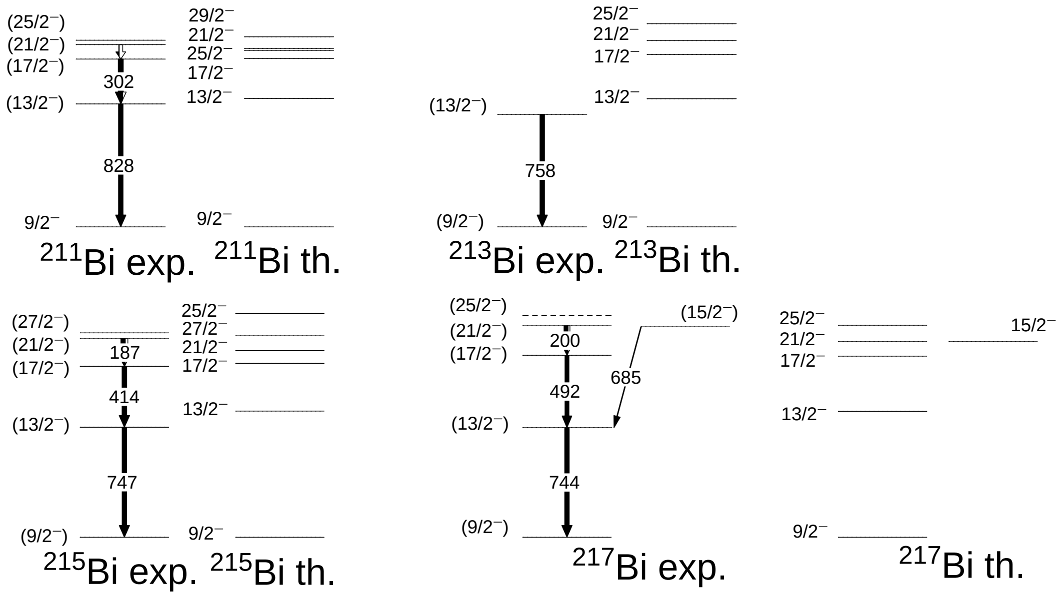

FIG. 6. Experimental and calculated partial level schemes for the odd-even bismuth isotopes. The calculations were performed using the KH interaction. The ^{217}Bi level scheme results from the present work. The experimental spectra are taken from Refs. [4, 8, 9]

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[1] M. Pfützner *et al.*, Phys. Lett. **B444**, 32 (1998).
[2] N. Al-Dahan *et al.*, Phys. Rev. **C80**, 061302(R) (2009).
[3] S. J. Steer *et al.*, Phys. Rev. **C78**, 061302(R) (2008).
[4] G. J. Lane *et al.*, Nucl. Phys. **A682**, 71c (2013).
[5] K. H. Maier *et al.*, Z. Phys. **A332**, 263 (1989).
[6] M. M. Hindi *et al.*, Phys. Rev. **C38**, 1370 (1988).
[7] J.D.Bowman *et al.*, Phys. Rev. **C25**, 941 (1982).
[8] V. G.Chumin *et al.*, Z.Phys. **A358**, 33 (1997).
[9] J. Kurpeta *et al.*, Eur. Phys. J. **A18**, 31 (2003).
[10] H. DeWitte *et al.*, Phys. Rev. **C87**, 067303 (2013).
[11] H. DeWitte *et al.*, Phys. Rev. **C69**, 044305 (2004).
[12] A. Gottardo *et al.*, Phys. Rev. Lett. **109**, 162502 (2012).
[13] G. Benzoni *et al.*, Phys. Lett. **B715**, 293 (2012).
[14] A. I. Morales *et al.*, Phys. Rev. **C89**, 014324 (2014).
[15] A. Gottardo *et al.*, Phys. Lett. **B725**, 292 (2013).
[16] K.Rykaczewsk *et al.*, Proc.Conf on Exotic Nuclei and Atomic Masses **AIP Conf.Proc. 455**, 581 (1998).
[17] H. Geissel *et al.*, Nucl. Instr. Meth. **B70**, 286 (1992).
[18] S. Pietri *et al.*, Nucl. Instr. Meth. **B261**, 1079 (2007).
[19] P. H. Regan *et al.*, Nucl. Phys. **A787**, 491c (2007).
[20] R. Kumar *et al.*, Nucl. Instr. Meth. **A598**, 754 (2009).
[21] P. H. Regan *et al.*, Int. J. Mod. Phys. **E17**, 8 (2008).
[22] E. Caurier *et al.*, Rev. Mod Phys. **77**, 427 (2005).
[23] M. Dufour and A. P. Zuker, Phys. Rev. **C54**, 1641 (1996).