High-spin states in the five-valence-particle nucleus ²¹³Po

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Excited states in ²¹³Po have been populated using the ¹⁸O + ²⁰⁸Pb reaction at 85 MeV beam energy and studied with the Euroball IV γ multidetector array. The level scheme has been built up to ∼2.0 MeV excitation energy and spin $I \sim 25/2\hbar$ from the triple γ coincidence data. Spin and parity values of several yrast states have been assigned from the γ angular properties. The configurations of the yrast states are discussed using results of empirical shell-model calculations and by analogy with the neighboring nuclei. The spin and parity values of several low-spin states of ²¹³Po previously identified from the β decay of ²¹³Bi are revised.

I. INTRODUCTION

²¹³Po is a five-particle nucleus with two protons and three neutrons outside the doubly magic core ²⁰⁸Pb. Thus one can expect its first excited states to come from a few spherical configurations mixed by the neutron-proton interactions. Some states issuing from pure π^2 configurations on the one hand and from pure ν^3 configurations on the other hand have been already identified in neighboring nuclei: (i) the first excited states of ²¹⁰Po are a textbook example of residual interaction in a two-proton configuration, and (ii) the properties of the three-neutron nucleus ²¹¹Pb are well accounted for using shell-model (SM) calculations [1].

It is worth pointing out that SM predictions for nuclei lying above ²⁰⁸Pb are not numerous. For instance, large-scale SM calculations have been performed for the $N = 126$ isotones, from $Z = 84$ to 94, in the full $Z = 82$–126 proton model space using the modified Kuo-Herling interaction [2] and the semiempirical shell model has been used to describe several nuclei close to ²⁰⁸Pb [3]. Moreover the ground-state configuration of three odd-odd nuclei, ²¹⁰Bi ($\pi^1\nu^1$), ²¹²Bi ($\pi^1\nu^3$), and ²¹²At ($\pi^3\nu^1$), have been recently predicted using effective interactions derived from the charge-dependent (CD) Bonn nucleon-nucleon potential [4], but there is no calculation dealing with many more valence nucleons. Indeed when a lot of protons and neutrons are added to the the doubly magic core ²⁰⁸Pb we reach the well-known region of octupole-deformed nuclei [5], which is outside the scope of SM calculations because of its too large valence space. In contrast, a study of the heavy Po nuclei with only two protons and many neutrons outside ²⁰⁸Pb allows us to investigate both the effective neutron-proton interactions and the configuration mixings, as these nuclei remain almost spherical.

In the present paper, we report on high-spin states in ²¹³Po, which are identified for the first time. The level scheme has been built up to ∼2.0 MeV excitation energy using high-fold γ coincidences and γ-ray anisotropies have been measured to assign the spin values. The yrast states of ²¹³Po are discussed using results of empirical shell-model calculations and by analogy with the neighboring nuclei.

II. EXPERIMENTAL METHODS AND DATA ANALYSIS

We have used the ¹⁸O + ²⁰⁸Pb reaction, the ¹⁸O beam with an energy of 85 MeV being provided by the Vivitron tandem

of IReS (Strasbourg). A 100 mg/cm² self-supporting target of ²⁰⁸Pb was employed, which was thick enough to stop the recoiling nuclei. Because of this large thickness, the ¹⁸O beam was stopped in the Pb target too, and the incident energy covered a large range of values, from 85 MeV down to the Coulomb barrier. The deexciting γ rays were recorded with the Euroball IV array consisting of 71 Compton-suppressed Ge detectors [6] (15 cluster germanium detectors placed in the backward hemisphere with respect to the beam, 26 clover germanium detectors located around 90°, and 30 tapered single-crystal germanium detectors located at forward angles). Each cluster detector is composed of seven closely packed large-volume Ge crystals [7] and each clover detector consists of four smaller Ge crystals [8].

Events were recorded on tape when at least three unsuppressed Ge detectors fired in prompt coincidence. In this way, a set of ∼4 × 10⁹ three- and higher-fold events were available for subsequent analysis. The main objective of the experiment was actually the study of the fusion-fission channel, which leads to the production of the high-spin states of ∼150 fragments, mainly located on the neutron-rich side of the valley of stability [9]. In addition, various transfer reactions have produced several Po isotopes. First, ²¹⁰,²¹¹,²¹²,²¹⁴Po have been identified from their known γ-ray yrast cascades [10]. Moreover, many new γ lines emitted by the two even-even ²¹²,²¹⁴Po isotopes have been found to be strong enough in our data set to be precisely analyzed [11–13]. Then we looked for the γ lines emitted by ²¹³Po.

Various procedures have been used for the offline analysis in order to fully characterize the excited levels of ²¹³Po (excitation energy and spin and parity values). Both multigated spectra and three-dimensional "cubes" have been built and analyzed with the RADWARE package [14], starting from the x rays of Po in order to identify the new transitions and to build the level scheme.

III. EXPERIMENTAL RESULTS

Prior to this work, the excited states of ²¹³Po were studied from the β decay of ²¹³Bi [15]. All the spin values assigned to these states are 7/2, 9/2, or 11/2, because of the properties of the ground state of ²¹³Bi ($I^\pi = 9/2^-$). These excited states are not expected to be populated by a reaction induced by
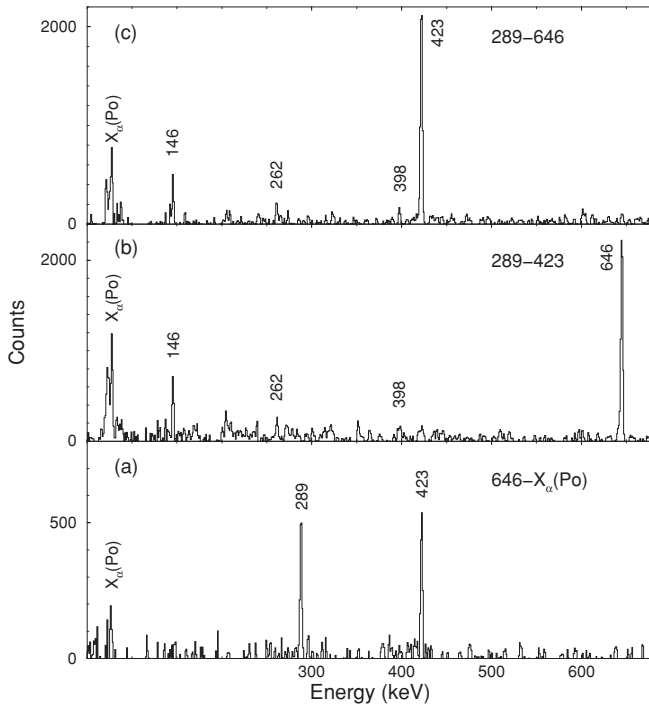
FIG. 1. Spectra of γ rays in double coincidence with (a) the first transition of ^{213}Po (646 keV) and the $K\alpha_1$ x ray of Po, (b) the 289 and 423 keV transitions, and (c) the 289 and 646 keV transitions.

FIG. 2. Level scheme of ^{213}Po determined in this work. The width of the arrows is representative of the relative intensity of the γ rays. The level at 1504 keV is likely a long-lived state (see Sec. IV).

heavy ions, since their spin values are very close to that of the ^{213}Po ground state ($I^\pi = 9/2^+$). The more recent study of the β decay of ^{213}Bi [16] has led to the identification of a new state, at 868.0 keV, which mainly deexcites toward the ground state. Its spin value, $I = 13/2$, was proposed on the basis of a comparison with results of semiempirical shell-model calculations. In that case, the 868.0 keV γ ray should be observed in the present work, as the first member of the yrast cascade.

In order to identify all the transitions depopulating the yrast states of ^{213}Po, we first examined spectra gated by the $K\alpha_1$ x ray[1] of Po. The spectrum of γ rays in coincidence with *two* $K\alpha_1$ x rays of Po displays, in addition to the transitions emitted by ^{212}Po [11,12], ^{214}Po [13], as well as ^{210,211}Po [10], three new transitions at 289, 423, and 646 keV. They are in mutual coincidence (see, for instance, the three spectra of Fig. 1), but they are not in coincidence with the transitions emitted by the other Po isotopes. Thus they must belong to the yrast structure of ^{213}Po, its population being expected in the reaction used in this work since all the neighboring isotopes are observed. Then all the double-gated spectra involving these three transitions, the $K\alpha_1$ x rays, as well as all the weaker lines like those observed in the spectra of Fig. 1 have been analyzed. The level

scheme built from all the observed coincidence relationships is shown in Fig. 2.

We have gathered in Table I the properties of the transitions assigned to ^{213}Po from this work. The R_{ADO} angular anisotropy with respect to the beam axis has been analyzed to determine the multipole order of the most intense γ rays, as was done for the γ rays of ^{212,214}Po obtained in the same experiment [11–13]. The results, given in Table I, allow us to determine the spin and parity values of the first yrast states. The I^π values of the 1504 and 1619 keV states, given in parentheses, will be discussed in the following section.

As regards the 289 keV transition, we extracted its internal conversion coefficient using its intensity imbalances measured in spectra in double coincidence with the 146 keV transition and either the 423 or the 646 keV transition. The obtained value, $\alpha_{tot} = 0.15(5)$, corroborates the $E2$ multipolarity for the 289 keV transition.

Last, we estimated the cross section of the production of ^{213}Po in this ^{18}O + ^{208}Pb reaction, $\sigma \sim 0.3$ mb. This is much lower than the value we obtained for ^{212}Po, $\sigma \sim 10$–20 mb [12], and about three times less than obtained for ^{214}Po, $\sigma \sim 0.5$–1 mb [13]. At bombarding energies around and lower than 85 MeV, the ^{18}O projectiles may break up into ^{14,12}C + He. Using the kinematics of the exit channel leading to ^{212}Po, we have shown [12] that the heavy partner of the breakup, ^{14}C, is emitted backward, implying that the production of ^{212}Po involves the fusion of the light partner, ^{4}He, and the ^{208}Pb

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[1]Low-energy transitions, such as the x rays of Po, are clearly observed in our work since we used a very low threshold for triggering the constant fraction discriminator of each Ge channel. This was allowed by the VXI electronic cards of the Euroball array. For that purpose, the lower thresholds of the 239 channels were carefully checked at the beginning of the data acquisition.
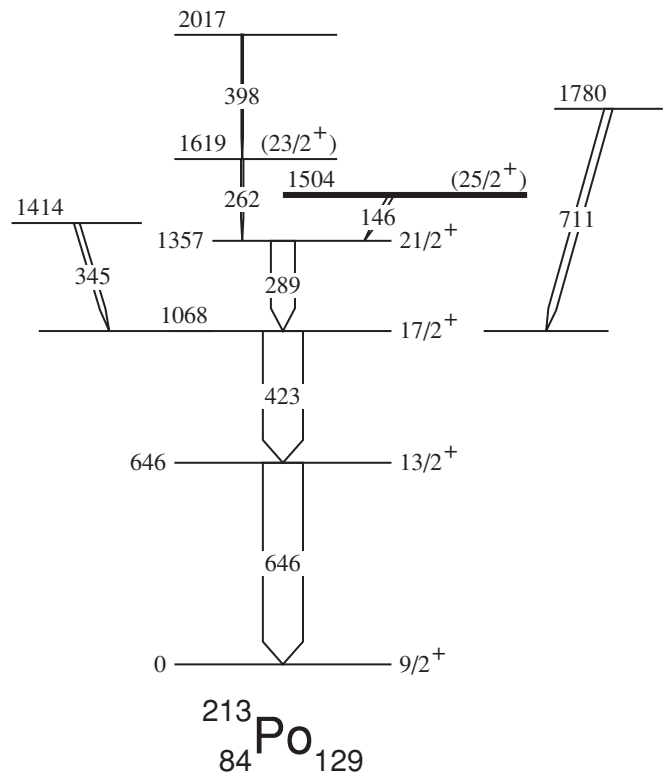
TABLE I. Properties of the γ transitions assigned to ^{213}Po from this work.

E_γ [a] (keV)	I_γ [b,c]	R_{ADO} [d]	E_i (keV)	E_f (keV)	I_i^π	I_f^π
146.2	8(2)		1504	1357	$(25/2^+)$	$21/2^+$
261.7	4.8(14)		1619	1357	$(23/2^+)$	$21/2^+$
289.0	60(10)	1.3(2)	1357	1068	$21/2^+$	$17/2^+$
344.5	15(5)		1413	1068		$17/2^+$
398.1	3.5(12)		2017	1619		$(23/2^+)$
422.8	100	1.18(10)	1068	646	$17/2^+$	$13/2^+$
645.6	–	1.25(10)	646	0	$13/2^+$	$9/2^+$
711.2	24(6)		1780	1068		$17/2^+$

[a]Uncertainties in transition energies are typically between 0.1 and 0.5 keV.

[b]Intensities measured in this experiment (i.e., with the requirement that a minimum of three unsuppressed Ge detectors fired in prompt coincidence) are normalized to the total intensity of the γ transitions populating the 1068 keV state.

[c]The number in parentheses is the error in the last digit.

[d]$R_{ADO} = I_\gamma(39.3°)/I_\gamma(76.6°)$.

target.[2] Thus we can infer that ^{214}Po is produced when the breakup leads to ^{12}C as the heavy fragment. In such a scenario, excited states of ^{213}Po are likely produced from the levels of ^{214}Po having the highest energies and decaying by neutron emission.

It is noteworthy that the above-mentioned transition at 868 keV has not been observed in our data set; it is correlated neither to the x rays of Po nor to the transitions newly assigned to ^{213}Po. Thus we do not confirm the previously proposed location of the $13/2^+$ yrast state at 868 keV [16]. A possible assignment of the 868 keV state observed in the β decay of ^{213}Bi will be discussed in the following section.

IV. DISCUSSION

^{213}Po is a five-particle nucleus with two protons and three neutrons outside the doubly magic core ^{208}Pb. Thus one can expect that its first excited states come from the $(\pi h_{9/2})^2 \otimes (\nu g_{9/2})^3$ shell-model configuration. The states issuing from elementary SM configurations such as $(\nu g_{9/2})^3$ and $(\pi h_{9/2})^2 \otimes (\nu g_{9/2})^1$ can be easily computed using the two-body empirical residual energies and the coefficients of fractional parentage corresponding to the case of three nucleons [18]. For that purpose, the residual energies are extracted from the energies of the $(\nu g_{9/2})^2$ multiplet (known in ^{210}Pb), the $(\pi h_{9/2})^2$ multiplet (known in ^{210}Po), and the $(\pi h_{9/2})^1 \otimes (\nu g_{9/2})^1$ multiplet (known in ^{210}Bi). The results of the two calculations are given in Figs. 3(a) and 3(b). The two groups of yrast states (drawn in green and blue) display similar features, those of the $(\nu g_{9/2})^3$ configuration being slightly more compressed in energy. Moreover, the

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[2]The fusion of the heavy partner,^{14}C, and the target was proposed to be the main mechanism leading to the production of Ra isotopes in the ^{18}O + ^{208}Pb reaction at 92 MeV [17].

$(\pi h_{9/2})^2 \otimes (\nu g_{9/2})^1$ configuration leads to the maximum spin, $25/2^+$; the corresponding level is expected to be isomeric as it is located closely above the $21/2^+$ state.

These predicted states compare very well with the results measured in two nuclei having these two elementary SM configurations, ^{211}Pb and ^{211}Po, respectively [see Figs. 3(c) and 3(d)]. ^{211}Pb exhibits two $11/2^+$ states close in energy; their wave functions are likely very mixed, one component from the $(\nu g_{9/2})^3$ configuration and the other from the $(\nu g_{9/2})^2 \otimes (\nu i_{11/2})^1$ component, the $\nu i_{11/2}$ orbital being located just above the $\nu g_{9/2}$ one. On the other hand, only one $11/2^+$ state was observed in ^{211}Po; its spectroscopic factor measured in the ^{211}Po(d,p) reaction indicates that this state mainly comes from the $(\pi h_{9/2})^2 \otimes (\nu i_{11/2})^1$ configuration [10], which means that another $11/2^+$ state remains to be identified. As regards the yrast states, those of ^{211}Pb are more compressed in energy than those of ^{211}Po. Moreover, the $25/2^+$ state of ^{211}Po is a long-lived isomeric state $[T_{1/2} = 25.2(6)$ s] deexciting through α decay [10], implying that the $21/2^+$ state is definitely higher in energy than the $25/2^+$ state in this nucleus.

At this point, we can surmise that the $(\pi h_{9/2})^2 \otimes (\nu g_{9/2})^3$ configuration of $^{213}_{84}$Po$_{129}$ would display the following features:

(i) the lowest excitation mainly comes from the $(\nu g_{9/2})^3$ configuration, which gives the $13/2_1^+$, $17/2_1^+$, and $21/2_1^+$ states;

(ii) the $25/2^+$ state due to the $(\pi h_{9/2})^2 \otimes (\nu i_{11/2})^1$ configuration is no longer a long-lived isomeric state decaying by α emission, as the $21/2_1^+$ state is located below it.

This is in good agreement with the experimental result (see Fig. 2), provided that the 146 keV transition is $E2$. It is worth recalling that we have got no direct information about its multipolarity; the only peculiar property of this γ ray is the fact that no transition could be placed above the 1504 keV state. That rules out the $M1$ case, as explained now. When the large value of the internal conversion coefficient $[\alpha_{tot}(146,M1) = 3.8]$ is taken into account, the total intensity of the 146 keV transition will amount to 40(10). Assuming that the intensity of a transition populating the 1504 keV state is only 50% of its total decay, such a transition would give a line having a height around 700 counts in the spectrum of γ rays in double coincidence with two yrast transitions, at variance with the observation (see the spectra in Fig. 1).

If the half-life of the 1504 keV state is much longer than the time window used to delimit a coincidence event (300 ns in our experiment), the nonobservation of the population of this state is obvious. Such a long half-life naturally occurs in case of an $E2$ transition with a low energy such as 146 keV, provided that the transition probability is slightly hindered: if $B(E2) = 0.1$ W.u., we obtain $T_{1/2}(146 \text{ keV}, E2) = 450$ ns. When the main configuration of the $21/2_1^+$ state of ^{213}Po is assumed to be not the same as that of the $25/2_1^+$ state $[(\nu g_{9/2})^3$ versus $(\pi h_{9/2})^2 \otimes (\nu i_{11/2})^1]$, we expect a very hindered $E2$ transition probability. For instance, the yrast-state configurations of $^{94}_{42}$Mo$_{52}$ are known to shift from proton to neutron excitations, which gives $B(E2; 8_1^+ \to 6_1^+) = 0.005$ W.u. [10]. In summary,
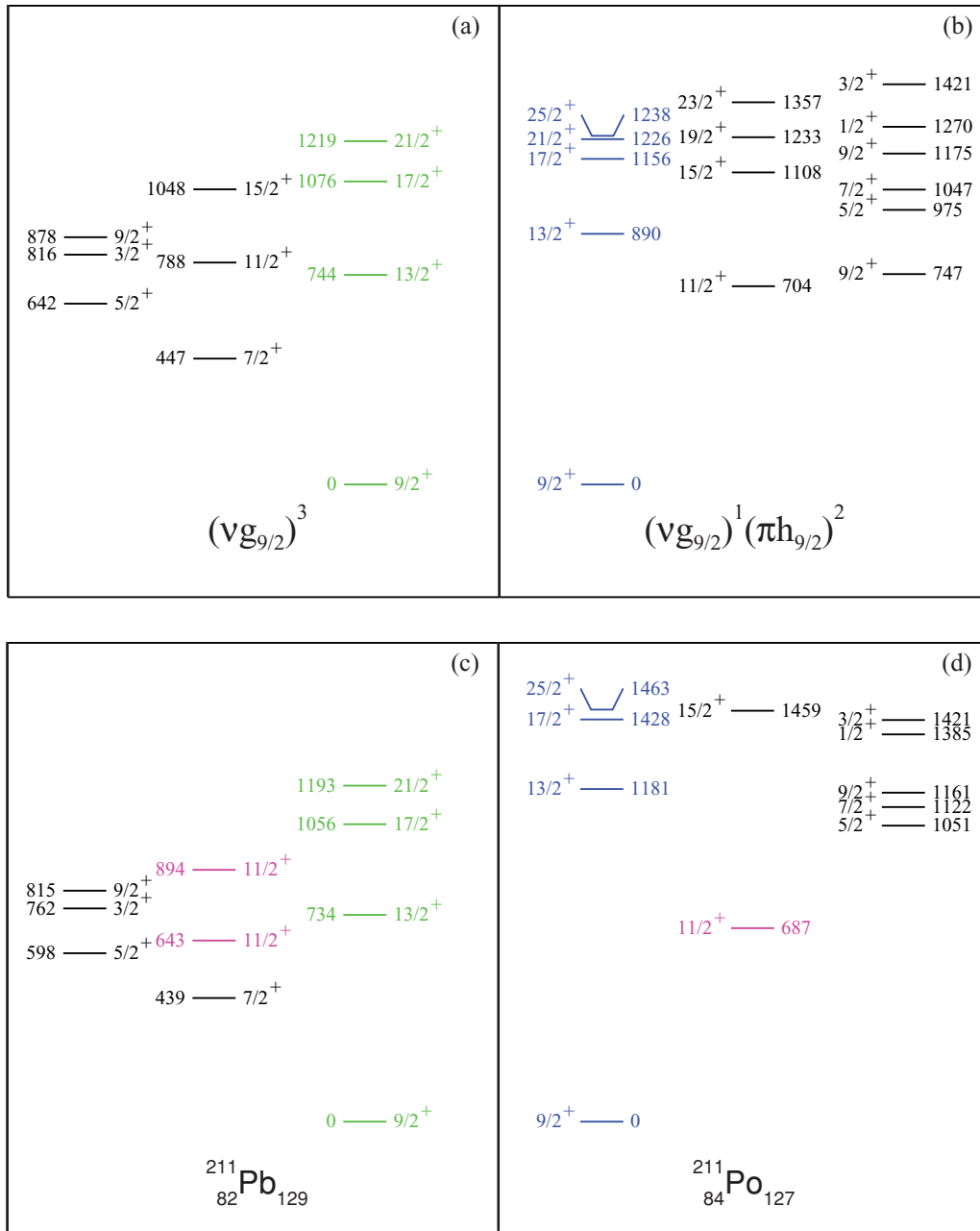
FIG. 3. (Color online) Top: Theoretical states belonging to the spherical $(\nu g_{9/2})^3$ configuration (a) and $(\pi h_{9/2})^2 \otimes (\nu g_{9/2})^1$ configuration (b), computed using empirical interactions extracted from the two-nucleon neighboring nuclei (^{210}Pb,^{210}Po,^{210}Bi). The *yrast* states of the two sets are drawn in green and blue, respectively. Bottom: First excited states measured in the three-neutron nucleus ^{211}Pb [1,19] (c), and in the two-proton one-neutron nucleus ^{211}Po [20,21] (d). The yrast states of the two nuclei are drawn in green and blue, respectively. The wave functions of the $11/2^+$ states (drawn in magenta) contain a large component of the $\nu i_{11/2}$ orbital located just above the $\nu g_{9/2}$ one.

the yrast states of ^{213}Po identified in the present work are drawn in the right part of Fig. 4 using the same color code as those of Fig. 3 (green and blue).

As displayed in Fig. 3(a), the $(\nu g_{9/2})^3$ configuration gives rise to several low-spin states which may be observed in the β decay of the $9/2^-$ ground state of $^{213}_{83}$Bi [16]. Moreover, as in ^{211}Pb, the $11/2^+$ state of the $(\nu g_{9/2})^3$ configuration can be strongly mixed with the state from the $\nu i_{11/2}$ orbital, leading to two $11/2^+$ states having similar properties. To suggest the new

spin values of the states measured in the β decay, which are drawn in the left part of Fig. 4, we made use of the following arguments:

(i) Three states are directly populated by the β decay, with similar log ft values ($\sim$6.2): the $9/2^+$ ground state and the excited states at 440 keV and 1100 keV [16].

(ii) The β decay of the $9/2^-$ ground state of $^{211}_{85}$At populates two states of ^{211}Po$_{127}$ with similar log ft values ($\sim$5.9):
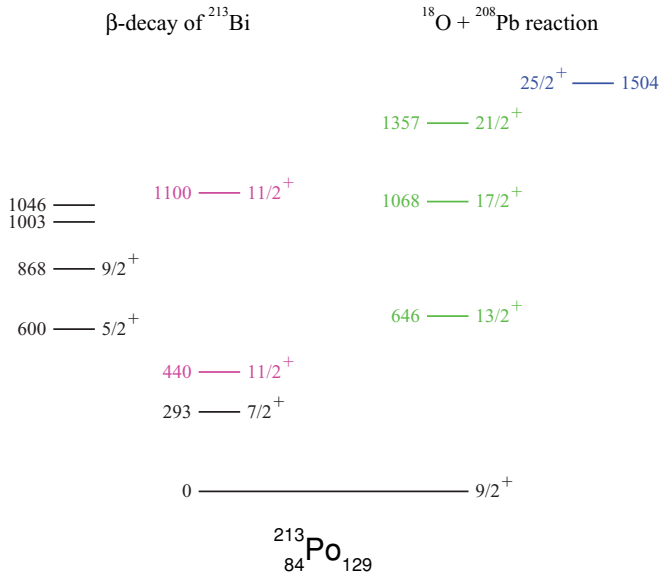
FIG. 4. (Color online) Right: High-spin levels of ^{213}Po identified in the present work. Left: Low-spin states measured in the β decay of the $9/2^-$ ground state of ^{213}Bi; the spin values (at variance with those assigned in Ref. [16]) are discussed in the text. The color code is the same as that of Fig. 3.

> the $\nu g_{9/2}$ ground state and the $\nu i_{11/2}$ excited state at 687 keV [10].

(iii) The 440 and 1100 keV states have similar decay schemes: one branch to the ground state and another to the first excited state at 293 keV. Moreover, the 1100 keV state decays to the 440 keV state.

(iv) The first excited state of the $(\nu g_{9/2})^3$ configuration is expected to have $I^\pi = 7/2^+$ [see Fig. 3(a)].

Thus, by combining results on the yrast states obtained in the present work and those on lower-spin states coming from the ^{213}Bi β decay [16], most of the states of the $(\nu g_{9/2})^3$ configuration can be identified. As said above, the two $11/2^+$ states display similar features, which occurs when two unperturbed states are very close in energy, giving a maximum mixing of the two states (here, $[(\nu g_{9/2})^3]_{11/2}$ and $[(\nu g_{9/2})^2(\nu i_{11/2})^1]_{11/2}$). Then we can assume that the energy of the $11/2^+$ states of the two *pure* configurations is around

half the sum of the two measured energies, i.e., 770 keV. This is in very good agreement with the predicted energy of the $11/2^+$ state of the $(\nu g_{9/2})^3$ configuration, 788 keV [see Fig. 3(a)]. As for the $\nu i_{11/2}$ orbital, it gives rise to many excited states having spin values in the range 1/2–27/2, from the breaking of either the neutron pair or the proton pair of the $(\pi h_{9/2})^2(\nu g_{9/2})^2(\nu i_{11/2})^1$ configuration. In any case, the yrast states lying above 1357 keV [the $21/2^+$ state from the $(\nu g_{9/2})^3$ configuration] likely involve the $\nu i_{11/2}$ orbital.

V. SUMMARY

The ^{18}O + ^{208}Pb reaction at 85 MeV beam energy was used to populate the high-spin states of ^{213}Po. Their γ decays were investigated using the Euroball IV array. The level scheme was built up to ~2.0 MeV excitation energy and spin $I \sim 25/2\,\hbar$ from the triple γ coincidence data. Spin and parity values of several yrast states were assigned from the angular properties of the γ-rays. Using results of empirical shell-model calculations and analogy with the neighboring nuclei, the main configurations of the yrast states are proposed. The first excitations come from the three-neutron configurations, particularly $(\nu g_{9/2})^3$. The spin and parity values of several states previously known from the β decay of ^{213}Bi were revised in order to account for the low-spin states expected in the $(\nu g_{9/2})^3$ configuration. Shell-model calculations using a realistic effective interaction derived from the CD-Bonn nucleon-nucleon potential have been recently performed in nuclei close to ^{208}Pb [4], giving results in very good agreement with experiments. It would be worth extending them to nuclei having more valence nucleons, such as the five-particle nucleus ^{213}Po.

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