



Novel Manifestation of α -Clustering Structures: New “ $\alpha + {}^{208}\text{Pb}$ ” States in ${}^{212}\text{Po}$ Revealed by Their Enhanced $E1$ Decays

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Excited states in ${}^{212}\text{Po}$ were populated by α transfer using the ${}^{208}\text{Pb}({}^{18}\text{O}, {}^{14}\text{C})$ reaction, and their deexcitation γ rays were studied with the Euroball array. Several levels were found to decay by a unique $E1$ transition ($E_\gamma < 1$ MeV) populating the yrast state with the same spin value. Their lifetimes were measured by the Doppler-shift attenuation method. The values, found in the range 0.1–1.4 ps, lead to very enhanced transitions, $B(E1) = 2 \times 10^{-2} - 1 \times 10^{-3}$ W.u. These results are discussed in terms of an α -cluster structure which gives rise to states with non-natural-parity values, provided that the composite system cannot rotate collectively, as expected in the “ $\alpha + {}^{208}\text{Pb}$ ” case. Such states due to the oscillatory motion of the α -core distance are observed for the first time.

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In the early days of the development of nuclear theory, the α particle was considered as the basic building block of any nucleus, providing a simple explanation for the emission of α s by heavy nuclei or the fact that all of the light nuclei with $A = 4n$ have higher binding energies per particle than any of their neighbors. But many arguments [1] were rapidly developed against this picture, which was almost completely abandoned to the benefit of single-particle description of nuclei based on the hypothesis of a common mean field for all nucleons.

A strong revival of the α -cluster model occurred in the 1960s when both experimental and theoretical studies revealed that the concept of α clustering is essential for the understanding of the structure of light nuclei. The states based on α particles (and other bound substructures) are not so much found in the ground states but rather observed as excited states close to the decay thresholds into clusters, as suggested by Ikeda [2]. In particular, the Hoyle state, i.e., the 0_2^+ state at 7.65 MeV in ${}^{12}\text{C}$ which has recently been interpreted as an α -particle condensate [3], and other similar states in heavier $n\alpha$ nuclei, have attracted much renewed attention (see, e.g., [4]). Also, so-called nuclear molecules, such as the α -core system rotating about its center of mass, have lately been studied intensely and with great success (for a review, see [5]).

The persistence of α clustering in heavy nuclei is much less documented. This is even the case of ${}^{212}\text{Po}$, a typical nucleus with two protons and two neutrons outside the doubly magic core, ${}^{208}\text{Pb}$. Up to now, there was no clear-cut evidence of its cluster structure. Shell model (SM) configurations involving a few orbits account reasonably well for the excitation energies of its low-lying yrast states [6]. Nevertheless, the α width of its ground state is predicted more than 1 order of magnitude smaller than the

experimental value. This has called for a hybrid model comprising both shell and cluster configurations [7]. Then the α -decay energy and the half-life are well reproduced and a large amount of α clustering is found (30%). Such a result suggests that the low-lying yrast spectrum of ${}^{212}\text{Po}$ could also be explained in terms of an $\alpha - {}^{208}\text{Pb}$ cluster model, which was explored in some theoretical works (see, e.g., [8–10]).

This Letter reports on the evidence of α clustering in ${}^{212}\text{Po}$ by means of several very enhanced $E1$ transitions which link excited states with non-natural parity to the yrast states having the same spin values. While such results are not expected from SM configurations, they can be explained in terms of “ $\alpha + {}^{208}\text{Pb}$ ” structure. This represents a novel manifestation of α clustering, very different from that observed in light nuclei where the α -core system can rotate collectively about its center of mass.

Excited states in ${}^{212}\text{Po}$ were populated by α transfer using the ${}^{208}\text{Pb}({}^{18}\text{O}, {}^{14}\text{C})$ reaction. The ${}^{18}\text{O}$ beam of 85 MeV energy was provided by the Vivitron tandem at IReS (Strasbourg). The target of 100 mg/cm² ${}^{208}\text{Pb}$ was thick enough to stop the recoiling nuclei as well as the ${}^{18}\text{O}$ beam. The γ rays were detected by the 71 Ge detectors of the Euroball IV array [11], i.e., 15 cluster detectors placed in the backward hemisphere with respect to the beam, 26 clover detectors located around 90°, and 30 tapered single-crystal detectors located at forward angles. The 239 Ge crystals of the Euroball array could be grouped into 13 rings (three forward, four close to 90°, and six backward) or into two groups at 39.3° and 76.6°. Events were recorded on tape when at least three detectors fired in prompt coincidence; this led to a set of $\sim 4 \times 10^9$ three- and higher-fold events. Various procedures have been used for the offline analysis in order to fully characterize the

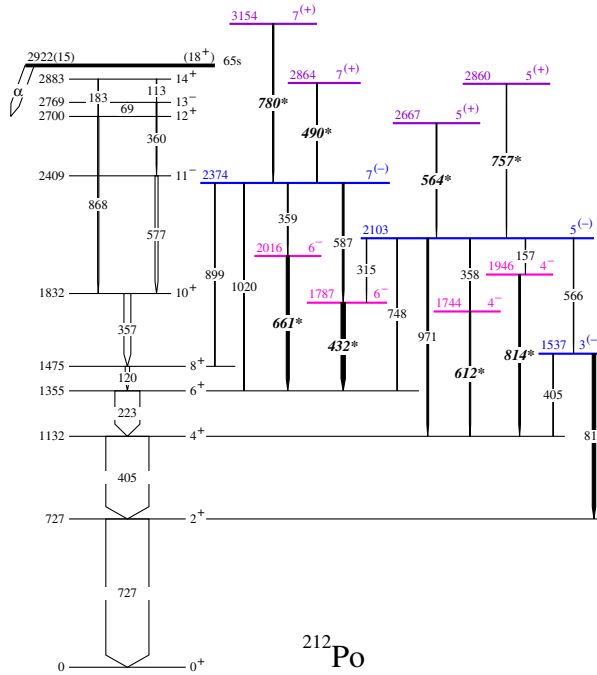


FIG. 1 (color online). Part of the level scheme of $^{212}_{84}\text{Po}_{128}$ obtained in this work. The long-lived isomeric state at 2922(15) keV excitation energy, a pure α emitter not observed in the present work, is drawn for the sake of completeness. The width of the arrows is representative of the intensity of the γ rays. The transitions marked with an asterisk are emitted by states with $\tau < 1.4$ ps (see Table I). The colored states are also displayed in the bottom part of Fig. 3.

excited levels of ^{212}Po (excitation energy, spin and parity, decay modes, and lifetime).

Both multigated spectra and three-dimensional “cubes” have been built and analyzed with the RADWARE package [12] in order to establish the level scheme. By gating on the known transitions [6,13], we have assigned about 50 new γ rays to ^{212}Po , deexciting 35 new excited states. About ten of them are located above 2.92 MeV, the energy of the (18^+) long-lived state. A partial level scheme, showing the γ decay of the yrast states and some of the levels which are the object of this Letter, is displayed in Fig. 1. The complete level scheme will be published and discussed elsewhere [14].

The stopping time of ^{212}Po in the lead target is about 1 ps; thus, it would have been expected that all of the

transitions lying in the low-energy part of the level scheme are emitted at rest. Nevertheless, we have found several γ rays with $E_\gamma < 1$ MeV which exhibit shifts and broadenings in energy due to the Doppler effect (some of them are marked by an asterisk in Fig. 1), meaning that they are emitted during the slowing-down; thus, the corresponding excited states do have lifetimes $\lesssim 1$ ps. The 780 keV transition, located in the high-energy part of the level scheme, displays only shifted components. The value of its energy, measured as a function of the detector angle, is symmetric around 90° (see the left part of Fig. 2), showing that the ^{212}Po nuclei recoil along the beam axis, the best fit giving $\frac{v}{c} = 1\%$. The modulus of the ^{212}Po velocity proves that the ^{14}C ejectiles are also emitted along the beam axis, but in the backward direction (in perfect agreement with previous results [15,16]). Thus, the α particle is transferred almost at rest.

The lifetimes of seven excited levels were determined using the Doppler-shift attenuation method, which is based on the time correlation between the slowing-down of the recoiling ion and the decay of the nuclear level of interest (cf. e.g., Ref. [17]). The data analysis was performed using a standard procedure (cf. e.g., Ref. [18]). For the description of the slowing-down process via Monte Carlo methods, we used a modified version of the program DESASTOP [19,20]. The line shapes of the transitions to be analyzed were obtained using the coincidence matrices by setting gates on fully stopped γ -ray peaks belonging to transitions which depopulate levels lying below the level of interest. Examples of line-shape analysis are displayed in the right part of Fig. 2; all of the results are summarized in Table I.

The spin and parity values of the excited states have been assigned with the help of the analysis of the γ -ray angular distributions measured for the 13 rings of the Euroball IV array. For transitions having too weak intensity to be analyzed in that way, their anisotropies have been determined using the intensities measured at two angles relative to the beam axis, $R_{\text{ADO}} = I_\gamma(39.3^\circ)/I_\gamma(76.6^\circ)$. For instance, the angular properties of the 810-, 971-, and 1020-keV transitions, as well as of the 587- and 359-keV transitions, indicate that they are dipole transitions linking states with $\Delta I = 1$, such as the 577-keV yrast transition. Then the states at 1537, 2103, and 2374 keV have odd spin values, while the 2016- and 1787-keV states have even spin values. The a_2 angular coefficients of the

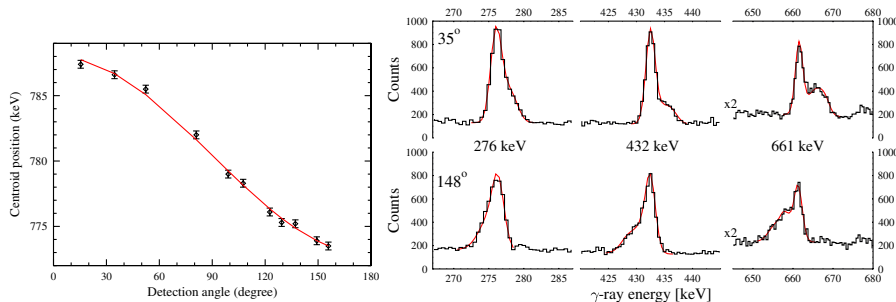


FIG. 2 (color online). Left: energy of the Doppler-shifted line around 780 keV as a function of the detection angle. The curve is the best fit obtained for a relative velocity $\frac{v}{c} = 1\%$ and a transition energy of 780.4 keV. Right: examples of line-shape analysis at forward (35°) and backward (148°) angles.

TABLE I. Lifetimes derived in the present work.

Level		Decay		Level		Decay	
E_i (keV)	I_i^π	E_γ (keV)	τ^a (ps)	E_i (keV)	I_i^π	E_γ (keV)	τ^a (ps)
1744	4^-	612.3	0.48(15)	2667	$5^{(+)}$	563.8	≤ 1.4
1751	8^-	276.1	0.48(20)	2860	$5^{(+)}$	757.2	≤ 1.4
1787	6^-	432.3	0.45(8)	2864	$7^{(+)}$	490.2	≤ 0.55
1946	4^-	813.6	0.47(15)	2867	$9^{(+)}$	397.7	≤ 1.4
2016	6^-	661.3	0.49(16)	3155	$7^{(+)}$	780.4	0.12(6)
2465	10^-	633.0	0.61(16)	3210	$9^{(+)}$	740.2	≤ 1.4

^aThe number in parentheses is the error in the last digit.

432- and 661-keV transitions (marked with an asterisk in Fig. 1) are positive. Since they cannot be quadrupole transitions linking states with $\Delta I = 2$ because of the other decay paths of states located above them, they are assigned as dipole $\Delta I = 0$ transitions. Thus, the spin value of the 1787- and 2016-keV states is $6\hbar$. These states cannot have positive parity because their decays towards the 4^+ yrast state are not observed, whereas they should be favored by the energy factors. Then the multiplicities of the 432- and 661-keV transitions are assigned as $E1$. In summary, the spin and parity values of all of the states of ^{212}Po observed in the present work have been determined using similar arguments, both from the properties of the populating and decaying transitions. As a result, all of the transitions given in Table I are assigned to be $E1$, $\Delta I = 0$. Their short lifetimes lead to very enhanced transitions, with values of the $B(E1)$ reduced transition probabilities in the range $[2 \times 10^{-2} - 1 \times 10^{-3}]$ W.u. [typical $B(E1)$ values are $< 10^{-5}$ W.u.].

The bottom part of Fig. 3 displays most of the ^{212}Po states observed in this work, grouped as a function of their underlying structure. As noted in the introduction, low-lying SM configurations account reasonably well for the excitation energies of the positive-parity yrast states [drawn with filled squares in Fig. 3(a)]. However, they fail to reproduce the large $B(E2)$ transition strengths, while a better description is achieved using the cluster model [8,9]. As for the negative-parity states drawn in Fig. 3(b), they involve the coupling of the low-lying 3^- octupole vibration to the excitation of the valence nucleons. Such a coupling is well known in the region of $^{146}_{64}\text{Gd}_{82}$, where the octupole excitation also plays an important role. It is worth pointing out that the negative-parity states shown in Fig. 3(b) have the same behavior (relative energies of even- and odd- I states and deexcitation modes) as those identified in ^{148}Gd [21].

On the other hand, the two groups of even- I negative-parity states, as well as the two groups of odd- I positive-parity states [see the filled circles in Figs. 3(a) and 3(b), respectively] cannot be explained by low-lying SM configurations. They are the fingerprints of the $\alpha + ^{208}\text{Pb}$ structure, which we will now explain.

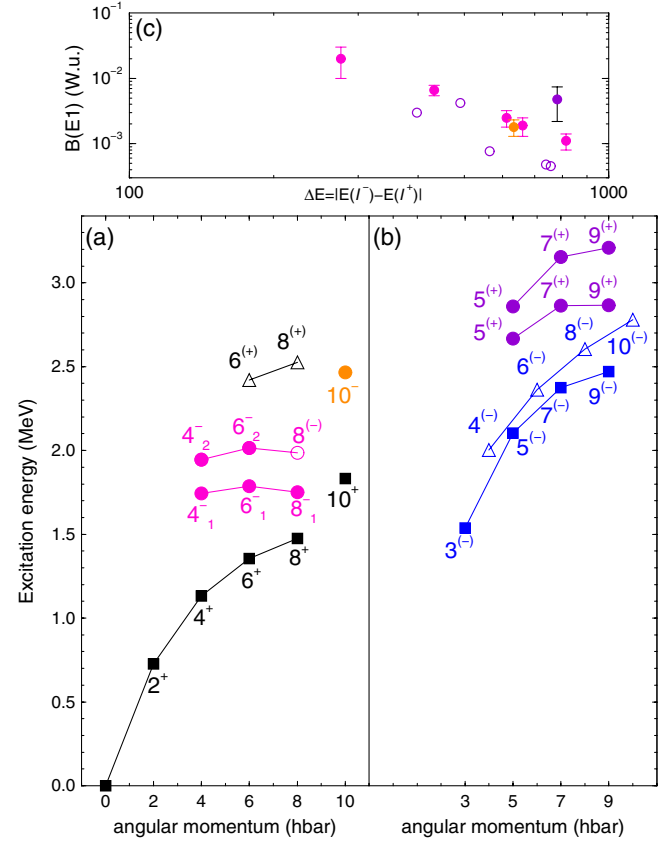


FIG. 3 (color online). (a), (b) Excitation energy of the ^{212}Po states as a function of angular momentum. Each state drawn with a filled circle decays by an enhanced $E1$ transition towards the yrast state having the same I value (drawn with a filled square). (c) Experimental $B(E1)$ values (in W.u.) versus the energy difference (in keV) between $I^\pm$ levels (log-log plot). The empty circles are lowest limits of $B(E1)$ calculated from the limit values of the lifetimes given in the right-hand portion of Table I.

First of all, strongly enhanced $B(E1)$ values are commonly found in nuclei exhibiting an electric dipole moment, such as light nuclei described in terms of a bimolecular system rotating about its center of mass or heavy nuclei displaying octupole deformation [22]. More generally, when a nucleus clusterizes into fragments with different charge to mass ratios, its center of mass does not coincide any more with its center of charge, and a sizeable static $E1$ moment may arise in the intrinsic frame [23]. For instance, the dipole moment of the $\alpha + ^{208}\text{Pb}$ system, computed using Eq. (1) of Ref. [23], is as large as 3.7 efm, which would lead to very enhanced $E1$ transitions. It is worth noting that the $E1$ rates measured in the present work [see Fig. 3(c)] are close to the ones measured in some heavy nuclei [24].

Following the ansatz of Ref. [7] dealing with the ground state of ^{212}Po , we assume that the wave function of every excited state can be written as the sum of two parts: $\Psi^{\text{tot}}(I^\pi) = a\Psi^{\text{SM}}(I^\pi) + b\Psi^{\text{cluster}}(I^\pi)$.

Let us discuss the $\alpha + ^{208}\text{Pb}$ system. Its Hamiltonian has the following form: $H_{\text{cluster}} = H_\alpha(r) + H_{\text{dipole}}(d)$. $H_\alpha(r)$ is

a central potential in which the α particle moves (see, e.g., [8,9]); its eigenfunctions $\chi_\alpha^\pi(I)$ have the natural parity, $\pi = (-1)^I$. $H_{\text{dipole}}(d)$ is a one-dimensional double-well potential where the “collective” coordinate is the dipole moment. This double well accounts for the fact that in the intrinsic frame, the α particle can either sit on one side or the other of the core. This picture is very similar to the octupole case described in Ref. [25]; however, here it is with zero deformation as the core is spherical. In each well we have a ground state (no node, $v = 0$) and one excited state (one node, $v = 1$). They may be viewed as states where the α particle vibrates against the Pb core. Neither right (R) nor left (L) states *per se* have good parity. The projection on good parity gives the four states, $\varphi_{0,1}^\pm = \frac{1}{\sqrt{2}}[\varphi_{0,1}^R \pm \varphi_{0,1}^L]$.

Thus, the cluster wave functions are given by

$$\Psi_{0,1}^{\text{cluster}}(I\pi) = \chi_\alpha^{\pi'}(I) \otimes \varphi_{0,1}^\pm \quad (1)$$

with $\pi = \pm\pi'$, meaning that for each I value, we get two states with $\pi = +$ and two states with $\pi = -$.

Such a scenario accounts well for the experimental findings. The non-natural-parity states ($4^-, 6^-, \dots, 5^+, 7^+, \dots$) are likely pure cluster states ($a \sim 0$). On the other hand, the wave functions of the natural-parity states should be strongly admixed [cf. the mixing predicted for the ground state of ^{212}Po in the calculation of Ref. [7], $(b/a)^2 \sim 0.3$] since, as mentioned above, the low-lying SM configurations give rise to states with even I and positive parity, as well as states with odd I and negative parity (when coupled to octupole vibration). This situation may explain why the four states of same spin but alternating parity do not follow the usual $+, -, +, -$ sequence in a 1D double-well potential. The two states of positive parity are spread by this coupling to SM configurations so that the final sequence will be $+, -, -, +$. One has to also invoke the mixings in order to understand the downward trend of the $B(E1)$ values, as seen in Fig. 3(c). This calls for more detailed theoretical studies combining both shell and cluster configurations.

In summary, we have used the transfer of an α particle induced by a heavy-ion beam at very low energy to populate excited states of ^{212}Po . This has revealed two sets of levels with non-natural parity: a first one with even- I values around 2 MeV excitation energy and a second one with odd- I values around 3 MeV. These levels only decay to the yrast states having the same I value by very enhanced $E1$ transitions [$B(E1) \sim 2 \times 10^{-2} - 1 \times 10^{-3}$ W.u.]. They are the fingerprints of the $\alpha + ^{208}\text{Pb}$ structure. The oscillatory motion of the α -core distance around the equilibrium position is observed for the first time.

One may speculate that adding more α s to the ^{208}Pb core, like, e.g., two α s to give ^{216}Rn , may exhibit similar physics. For example, the two α s may move coherently as a ^8Be and then the present scenario may repeat itself

partially or the two α s move independently and then more complex structures can be expected.

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