

A novel manifestation of α clustering in ^{212}Po : Pure α - ^{208}Pb states revealed by their enhanced E1 decays

A. Astier¹, P. Petkov^{1,2}, M.-G. Porquet¹, D.S. Delion^{3,4}, P. Schuck⁵

¹ Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS and Université Paris-Sud, 91405 Orsay, France,

² INRNE, Bulgarian Academy of Science, 1784 Sofia, Bulgaria,

³ Horia Hulubei National Institute of Physics and Nuclear Engineering 407 Atomistilor, 077125 Bucharest, Romania,

⁴ Academy of Romanian Scientists, 54 Splaiul Independentei 050094 Bucharest, Romania,

⁵ Institut de Physique Nucléaire, IN2P3-CNRS and Université Paris-Sud, 91406 Orsay, France.

E-mail: Alain.Astier@csnsm.in2p3.fr

Abstract. Excited states in ^{212}Po have been populated by α transfer using the $^{208}\text{Pb}(^{18}\text{O}, ^{14}\text{C})$ reaction and studied with the Euroball γ multidetector array. The level scheme of ^{212}Po has been extended up to ~ 3.2 MeV excitation energy. Spin and parity values have been assigned thanks to the measurements of γ angular distributions and γ - γ angular correlations. Several γ lines have been found to be shifted by the Doppler effect, allowing for the measurements of the associated lifetimes by the DSAM method. The values, found in the [0.1-1.4] ps range, lead to very enhanced E1 transitions. The emitting states, which have non-natural parity values, are the fingerprints of the “ α - ^{208}Pb ” structure present in ^{212}Po . They are in the same excitation-energy range as the states issued from shell-model configurations.

1. Introduction

When a nucleus clusterizes into fragments with different charge to mass ratios, its center of mass does not coincide anymore with its center of charge, and a sizeable static E1 moment may arise in the intrinsic frame [1] leading to large values of the $B(\text{E1})$ transition probabilities. This feature is well documented in deformed systems, such as light nuclei described in terms of a “ α -core” system rotating around its center of mass, or heavy nuclei displaying octupole deformation [2, 3]. In the ^{212}Po case, the “ α - ^{208}Pb ” composite system cannot rotate collectively as its center of mass is too close to the spherical-core center, and up to now there was no clear-cut experimental evidence of such a cluster structure. In this paper we present the discovery of “pure” α -cluster states in ^{212}Po , which have been revealed by their enhanced E1 decays [4, 5].

2. Experimental Details and Results

Excited states in ^{212}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 which was composed of 239 Ge crystals. The oxygen beam was delivered by the Vivitron tandem of IReS (Strasbourg, France) at 85 MeV incident energy and 30 nA intensity in the 6^+ charge state. A thick lead target (100 mg/cm²) was used, in order to stop all reaction products. Indeed, the experiment was devoted to the study of the high spin states of the neutron-rich isotopes produced in the fusion-fission

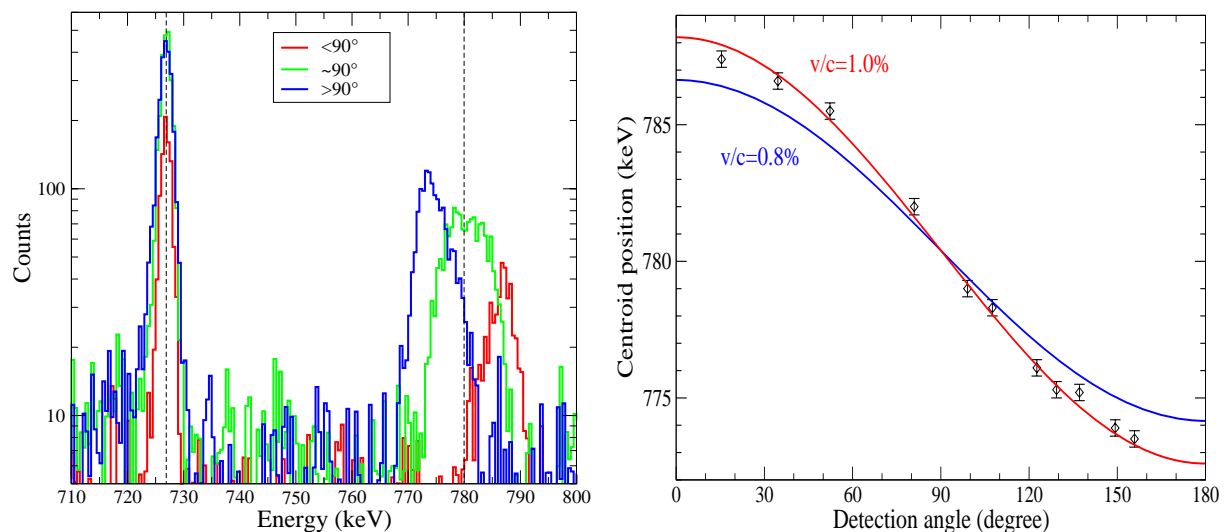


Figure 1. Left: Part of a triple-gated spectrum emphasizing the Doppler shift and broadening of the 780 keV transition, whereas the energy and the width of the 727 keV line ($2^+ \rightarrow 0^+$) do not depend on the detection angle. Each of the three lines is the part of the statistics registered at backward angles, around 90° angles, and at forward angles, respectively. The two dashed lines indicate the 727.1 keV and 780.4 keV (rest) energies. Right: Energy of the Doppler-shifted line around 780 keV as a function of the detection angle. The red curve is the best fit obtained for a relative velocity $\frac{v}{c} = 1\%$ and a transition energy of 780.4 keV, and the blue curve corresponds to the velocity of the ^{226}Th compound nucleus, $\frac{v}{c} = 0.8\%$.

exit channel of the reaction, and the fission fragments emit therefore their low-lying γ -rays at rest in the target. However, the relatively high production of ^{212}Po in the reaction allowed us to perform a detailed study of this nucleus as well. We have estimated that the cross section of the exit channel leading to the production of ^{212}Po is $\sim 10 - 20$ mb. About 50 new γ rays and 35 new states have been established in this work in the ^{212}Po level scheme, which has been extended up to spin 15 and 3.2 MeV excitation energy, mainly from the analysis of γ^3 coincidences.

The stopping time of ^{212}Po in the lead target is about 1 ps; thus it would have been expected that all the transitions lying in the low-energy part of the level scheme are emitted at rest, as it happens for the fission fragments. And actually this is the case for all the transitions deexciting the yrast levels. However, we have also found a dozen of gamma rays which behave differently: these gamma rays are emitted during the slowing down of ^{212}Po in the target. This behaviour is revealed by the observation of Doppler shifts and broadenings of these transitions. It is thus the first indication that several states in ^{212}Po have unexpectedly very short lifetimes, as illustrated in the left part of Fig. 1. In this triple-gated spectrum it is clearly seen that, whereas the $2^+ \rightarrow 0^+$ transition (727 keV) is emitted at rest, the 780 keV transition is entirely emitted in-flight. The analysis of the Doppler shifts of the 780 keV line, displayed in the right part of Fig. 1, allows us to know more about the reaction mechanism itself: i) The symmetry around 90° implies that the ^{212}Po nuclei recoil along the beam axis; ii) the best fit of the ^{212}Po velocity is $v/c=1\%$, whereas the velocity of the fusion exit-channel (*i.e.* the ^{226}Th compound nucleus) is only $v/c=0.8\%$; iii) the direction and the modulus of this velocity indicate that the ^{14}C ejectiles are also emitted along the beam axis, but in the backward direction. Thus the α particle is transferred almost at rest. The reaction leading to the population of the state decaying via the 780 keV transition is then the ($^{18}\text{O}, ^{14}\text{C}$) transfer reaction.

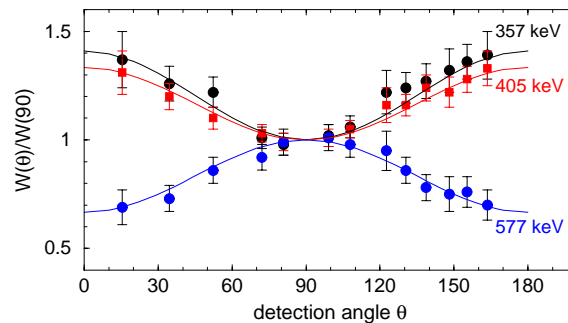


Figure 2. Angular distribution of three yrast transitions in the ^{212}Po measured in this work. Solid lines are the fits using the standard Legendre polynomials.

The spin and parity values of most of the excited states of ^{212}Po have been assigned from the analysis of the γ -ray angular distributions and γ - γ angular correlations. Typical examples of angular distributions are shown in Fig. 2 for three yrast transitions for which the multiplicities were already established: the 357- and 405-keV lines are quadrupole E2 transitions, and the 577-keV line is a stretched dipole E1 transition. The measurements clearly show that the spins are aligned in a plane perpendicular to the beam axis, with an attenuation coefficient $\alpha_2 \sim 0.7$. Among the new results, we have established that all levels of interest discussed here have the same behavior: they decay by a unique E1 transition ($E_\gamma < 1$ MeV) populating the yrast state with the same spin value (therefore with $\Delta I = 0$, which is obtained by the angular distribution results and consistent with every decay paths established in the level scheme). These E1 transitions are detected with Doppler shifts and broadenings. Two groups of levels ($I^\pi = 4^-, 6^-, 8^-$ and $I^\pi = 5^+, 7^+, 9^+$) have thus been identified at ~ 2 MeV and ~ 3 MeV excitation energy, respectively. Their lifetimes have been measured by the Doppler Shift Attenuation Method (DSAM). The values, found in the range $[0.1-1.4]$ ps, lead to very-enhanced E1 transitions, $B(E1) = 2 \times 10^{-2} - 1 \times 10^{-3}$ W.u. (i.e. up to 1000 times more than typical $B(E1)$ values).

3. Discussion

At first glance, it would seem natural to describe the whole low-lying structure of ^{212}Po by a shell-model approach as it was performed, with rather good success, for the yrast states [6]. However such calculations cannot lead to non-natural parity states ($4^-, 6^-, 8^-$) at such a low excitation energy (~ 2 MeV).

A major result of the present work is the observation of many strongly enhanced E1 transitions connecting several excited states to the yrast ones, having the same spin values. 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. Some typical values are shown in Fig. 3 using filled symbols (Sm isotopes with $N \sim 90$, ^{225}Ra and ^{225}Ac , cluster states of ^{18}O). They are one order of magnitude greater than those of transitions measured in octupole-vibrational nuclei (displayed with empty symbols) and three orders of magnitude greater than those of single-particle transitions in Bi isotopes. The E1 rates measured in the present work in ^{212}Po are definitely located in the top part of the figure, which evidences the “ α - ^{208}Pb ” structure of the emitting states. Thus, the new levels discovered in ^{212}Po are the fingerprints of the “ α - ^{208}Pb ” structure.

In ref. [5] we present a possible model in order to understand the whole ^{212}Po experimental knowledge. The starting hypothesis is that *every* excited state of ^{212}Po can be written as the

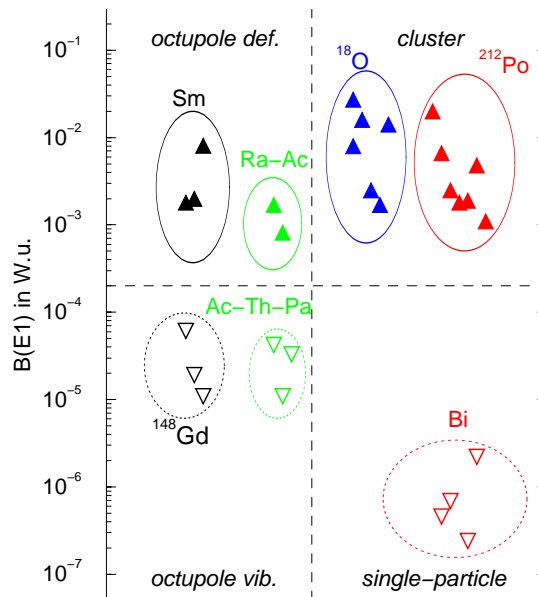


Figure 3. Values of $B(E1)$ transition rates (in Weisskopf units) for four typical cases: Transitions in octupole-deformed nuclei (Sm isotopes with $N \sim 90$, ^{225}Ra and ^{225}Ac), transitions in octupole-vibrational nuclei (^{148}Gd , ^{225}Ac , ^{231}Th , ^{231}Pa), transitions between single-particle states in Bi nuclei, and transitions involving cluster states. The ^{212}Po data have been extracted in this work. The abscissa of the figure is meaningless, the horizontal position of each point is chosen only for clarity purpose.

sum of two parts:

$$\Psi^{tot}(I^\pi) = a \Psi^{SM}(I^\pi) + b \Psi^{cluster}(I^\pi) \quad (1)$$

where Ψ^{SM} stands for the pure shell-model piece and $\Psi^{cluster}$ takes account of the α clustering. In the treatment of the cluster part of the wave function, the relative motion of the two clusters can be expressed as a double-well potential for the α particle sitting on the right or the left hand side of the ^{208}Pb core. Taking into account the two first states in each potential well and the tunnelling which lifts the left-right degeneracy, we obtain four different states with alternating parities, for each spin value. Then, only natural-parity states will mix with the shell-model configurations, whereas the non-natural parity states will remain “pure” cluster states.

Fig. 4 summarizes most of the ^{212}Po states observed in the present work and the interpretation of their underlying structure:

- The yrast positive-parity states (in black) can mainly be understood in terms of two-particle excitation, as their excitation energy as a function of angular momentum follows the typical curve expected in case of pair breaking. However the “ α - ^{208}Pb ” content of these states explains the large $B(E2)$ ’s which were previously measured for the 6^+ and 8^+ yrast states.
- The negative-parity states (in blue) involve mainly the coupling of the low-lying 3^- octupole vibration to the excitation of the valence neutrons.
- The non-natural parity states (even spins, negative parity in magenta, and odd spins, positive parity in violet) are the fingerprints of the “ α - ^{208}Pb ” structure.

The abovementioned scenario explains relatively well the order of our experimental findings. However it must be refined by a fully microscopic treatment. Some years ago, the theoretical description of the α width of the ^{212}Po ground state by means of a hybrid model led to a

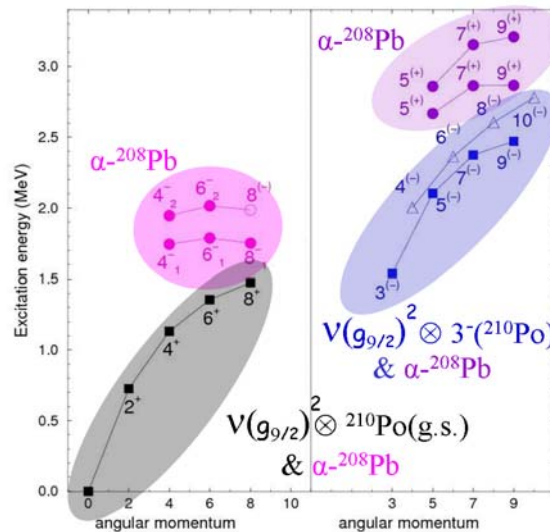


Figure 4. Excitation energy as a function of angular momentum of most of the ^{212}Po states observed in this work. Each state drawn with a filled circle (magenta and violet) decays by an enhanced E1 transition towards the state with the same angular momentum. The assigned configurations are indicated for each group of states (see text). The excitation energy of the first 3^- state in ^{210}Po is ~ 2.4 MeV.

large amount (30%) of α clustering [7]. Our results strengthen this picture, by adding a novel manifestation of α clustering [4, 5].

4. Conclusion

We have discovered that the ^{212}Po nucleus presents the “ α -core” structure. Pure “ α - ^{208}Pb ” states, with non natural parity, have been revealed by their enhanced E1 decays. However, in contrary to the case of light nuclei where the rotation of the di-nuclear system can occur and is well observed, the manifestation of the α clustering is different in ^{212}Po , as it would come from the oscillation motion of the α -core distance around its equilibrium position. Microscopic studies devoted to the ^{212}Po description are planned for the future.

Acknowledgments

The Euroball project was a collaboration among France, the United Kingdom, Germany, Italy, Denmark and Sweden. A.A., P.P. and M.-G.P. are very indebted to their colleagues involved in the EB-02/17 experiment, which was devoted to the fission fragments, and in which the present data on ^{212}Po were recorded. This work was partially supported by the collaboration agreement Bulgarian Academy of Sciences and CNRS, under contract No 16946, and by Contract IDEI-119 of the Romanian Ministry of Education and Research.

References

- [1] Iachello F 1985 *Phys. Lett.* **160B** 1
- [2] Ahmad I and Butler P 1993 *Annu. Rev. Nucl. Part. Sci.* **43** 71
- [3] Butler P and Nazarewicz W 1996 *Rev. Mod. Phys.* **68** 349
- [4] Astier A *et al.* 2010 *Phys. Rev. Lett.* **104** 042701
- [5] Astier A *et al.* 2010 *Eur. Phys. J.* **A46** 135
- [6] Poletti A R *et al.* 1987 *Nucl. Phys.* **A473** 595
- [7] Varga K, Lovas R G and Liotta R J 1992 *Phys. Rev. Lett.* **69** 37