Fine Structure in the Alpha Decay of Even-Even Nuclei as an Experimental Proof for the Stability of the $Z = 82$ Magic Shell at the Very Neutron-Deficient Side

J. Wauters, N. Bijnens, P. Dendooven,* M. Huyse, Han Yull Hwang,† G. Reusen, and J. von Schwarzenberg
LISOL, Instituut voor Kern- en Stralingsfysica, K. U. Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium

P. Van Duppen‡ and ISOLDE Collaboration
CERN, CH-1211 Genève 23, Switzerland

R. Kirchner and E. Roeckl
Gesellschaft für Schwerionenforschung Darmstadt, Postfach 110541, 6100 Darmstadt, Germany
(Received 29 November 1993)

Fine structure has been observed in the α decay of ^{202}Rn, ^{194,196,198}Po, ^{186,188}Pb, and ^{180,182,184}Hg and has led to the identification of low-lying 0^+ states in ^{198}Po, ^{190,192,194}Pb, ^{182,184}Hg, and ^{176,178,180}Pt. The large variation in the hindrance factors of the α decay to the excited 0^+ state is a proof for the persistence of the $Z = 82$ shell closure at the neutron-deficient side. Comparing the reduced widths of the α decays to the ground and excited states offers a unique way to probe the proton particle-hole character of the 0^+ states in this region.

PACS numbers: 23.60.+e, 21.60.Cs, 27.70.+q, 27.80.+w

Alpha decay, although one of the oldest study objects in nuclear physics, remains an intriguing decay mode. The explanation of the striking relation between the α-decay half-life and the α-decay energy, known as the Geiger-Nuttall law, was one of the prominent successes of quantum mechanics [1,2]. Later on, Rasmussen [3] proposed to extract from the partial α-decay half-lives and the α-decay energies, the reduced α widths (δ^2), a quantity containing most of the nuclear structure information. Reproducing the α-decay widths has been a challenge for theory over many years; a recent calculation on the absolute α-decay width of ^{212}Po can be found in Ref. [4]. Meanwhile, extended systematics on reduced widths for s-wave transitions of α decay between ground states of doubly even nuclei have been collected and interpreted. An anomalous behavior of these widths was reported for the light lead nuclei by Hornshøj, Hansen, and Jonson [5]. From further studies of this phenomenon, Toth *et al.* [6] concluded that either shape changes have a strong influence on the α-decay rate or that $Z = 82$ is no longer a magic number for the light lead isotopes. In a recent study we measured the α-decay rate in the $^{191}\mathrm{Bi}^{m,g} \rightarrow {}^{187}\mathrm{Tl} \rightarrow {}^{183}\mathrm{Au}$ chain, where the α decay not only links spherical with deformed states but also oblate shapes with prolate shapes [7]. The reduced widths of all these α decays are in the same range, quite similar to the decay of the even-even neighbors. Clearly, as was already stated in 1974 by Hornshøj *et al.* [8], shape changes are not strongly influencing the α-decay rate. Furthermore, we remeasured the α branching ratios of ^{188,190,192}Pb [9] and studied the α-decay properties of the neutron-deficient polonium and radon nuclei [10]. No evidence for the disappearance of the $Z = 82$ magic shell could be found.

Buck, Merchant, and Perez presented recently a new approach to α decay of heavy nuclei [11]. In a simple cluster model, without taking into account effects of deformation, they were able to reproduce the α-decay half-lives of the heavy even-even nuclei within a factor of approximately 2. Their conclusion is that most of the physics in α-decay half-lives is embedded in preformed alpha clusters moving in orbits with a large value of a global quantum number and with an appropriately chosen radius capable of fitting the Q value. The model of Buck, Merchant, and Perez reproduces also the α-decay half-lives of heavy odd-mass nuclei [12,13]. This yields strong support for the cluster description. In contrast to the $N = 126$ shell closure which is explicitly accounted for in the model by an increase of the global quantum number, the proton shell closure at $Z = 82$ seems to be relatively unimportant. Brown also analyzed partial α-decay half-lives and one of his conclusions is that perhaps $Z = 82$ is not a good magic number for the very light lead isotopes [14].

These important conclusions are mainly based on the partial α-decay half-lives, i.e., on the total half-life and the α branching ratio, of s-wave ground-state-to-ground-state α decay of even-even nuclei. The large experimental uncertainties on the alpha-decay observables, together with the model-dependent interpretation over a wide range of Z and N values, weaken these conclusions. The comparison of different s-wave alpha-decay branches from the same nucleus could offer an alternative approach. In the region around the $Z = 82$ shell closure with neutron number midshell between $N = 82$ and 126, shape coexistence occurs at low excitation energy. In the even-even nuclei this phenomenon is characterized by low-lying 0^+ states. A recent review on shape coexistence and shell-model intruder states can be found in Ref. [15]. These 0^+ states are at such low energy that in

0031-9007/94/72(9)/1329(4)$06.00

some cases they even become the first excited state. This has the interesting consequence that they become accessible to α decay. We report in this Letter on an experimental study of the α decay to excited 0^+ states in ^{198}Po, ^{190,192,194}Pb, ^{182,184}Hg, and ^{176,178,180}Pt. The most striking result is that the so-called hindrance factor, i.e, the ratio between the reduced α width of the ground-state-to-ground-state transition and the reduced α width of the decay to the excited 0^+ state, varies in these nuclei from 1.1 to 21. We shall show that these strong variations are due to the existence of the $Z=82$ shell gap and to proton pair particle-hole (p-h) excitations through this shell closure.

Alpha singles as well as alpha-electron, alpha-x, and alpha-gamma coincidence experiments have been performed on mass-separated samples of ^{202}Rn (at the ISOLDE separator), ^{194,196,198}Po (at the LISOL separator), and ^{186,188}Pb, ^{180,182,184}Hg (at the GSI separator). This has led to the identification of 0^+ intruder states in ^{198}Po [16], ^{190}Pb [17], ^{182}Hg [18], and ^{176,178}Pt [19] and to the study of the α feeding towards the first excited 0^+ and/or 2^+ states in ^{198}Po, ^{190,192,194}Pb, ^{180,182,184}Hg, ^{176,178,180}Pt, and ^{172,174,176}Os. More details on the experimental procedure can be found in Refs. [16–19]. Table I summarizes the experimental results. Figure 1 gives an overview of the fine structure in the α decay of these nuclei, only the α decay to the first excited 0^+ and 2^+ states is given. The hindrance factors of the transitions to the 2^+ states are calculated by assuming a $l=2$ centrifugal barrier.

Nine cases of α decay to the first excited 0^+ state have been measured. A dramatic variation in the hindrance factor is observed: In ^{194}Po the α decay to the excited 0^+ state has the same reduced width as the α decay to the ground state of ^{190}Pb while in ^{188}Pb the decay to the excited 0^+ state is as much hindered as the decay to the 2^+ state in ^{184}Hg (a factor of 21 and 24, respectively). Another interesting observation is that the large scattering in the observed partial half-lives for the α decay to the excited 0^+ states cannot be reproduced by the model of Buck, Merchant, and Perez [11]. The ratio between the theoretical and experimental partial α-decay half-life of the feeding to the excited 0^+ state, given in Table I, ranges from 10^{-2} to 0.77 whereas the corresponding ratio for the ground-state-to-ground-state α decays varies only from 0.58 to 1.9. Both on a relative scale (hindrance factors) as on an absolute scale (α-decay half-lives) the feeding towards excited 0^+ states exhibits a remarkable behavior. For our further discussion we will only use the relative scale. The explanation of the peculiar behavior of

TABLE I. Fine structure in the $l=0$ α decay. The energy of the involved levels (E_x) is given in keV [16–19]. The excited 0^+ states that have been identified by the α-decay study are given in italic characters. The energies (E_α), α branching ratios (I_α), and partial half-lives [$T_{1/2\alpha}$(exp)] from the α decay to the ground state are taken from Ref. [10]. The absolute intensity of the α decay to the excited 0^+ state (I_α) reflects the uncertainty on the α branching ratio of the ground state. The hindrance factor (HF) is calculated using the method of Rasmussen [3] and the theoretical α-decay half-lives [$T_{1/2\alpha}$(th)] using the method of Buck, Merchant, and Perez [11].

	E_x (keV)	E_α (MeV)	I_α (%)	HF	$T_{1/2\alpha}$(th)/$T_{1/2\alpha}$(exp)
$^{202}\mathrm{Rn} \xrightarrow{\alpha} {}^{198}\mathrm{Po}$	0	6.641	80–100	1	1.5–1.9
	816	5.841	$(1.4–1.8)\times10^{-3}$	19(6)	$(7.5\times9.4)\times10^{-2}$
$^{198}\mathrm{Po} \xrightarrow{\alpha} {}^{194}\mathrm{Pb}$	0	6.180	57	1	0.85
	931	5.273	7.6×10^{-4}	2.8(5)	0.27
$^{196}\mathrm{Po} \xrightarrow{\alpha} {}^{192}\mathrm{Pb}$	0	6.521	94	1	1.17
	769	5.769	2.1×10^{-2}	2.5(1)	0.39
$^{194}\mathrm{Po} \xrightarrow{\alpha} {}^{190}\mathrm{Pb}$	0	6.842	93	1	0.98
	658	6.194	0.22	1.1(1)	0.77
$^{188}\mathrm{Pb} \xrightarrow{\alpha} {}^{184}\mathrm{Hg}$	0	5.980	3–10	1	0.24–0.81
	375	5.614	$(2.9–9.5)\times10^{-2}$	21(3)	$(1.1–3.6)\times10^{-2}$
$^{186}\mathrm{Pb} \xrightarrow{\alpha} {}^{182}\mathrm{Hg}$	0	6.335	<100	1	<1.46
	328	6.014	<0.20	21(4)	$<6.6\times10^{-2}$
$^{184}\mathrm{Hg} \xrightarrow{\alpha} {}^{180}\mathrm{Pt}$	0	5.535	1.25	1	0.98
	478	5.067	2.0×10^{-3}	2.4(4)	0.39
$^{182}\mathrm{Hg} \xrightarrow{\alpha} {}^{178}\mathrm{Pt}$	0	5.865	8.6	1	0.58
	422	5.446	2.9×10^{-2}	3.5(6)	0.17
$^{180}\mathrm{Hg} \xrightarrow{\alpha} {}^{176}\mathrm{Pt}$	0	6.118	33	1	0.79
	443	5.689	2.6×10^{-2}	17(5)	4.3×10^{-2}

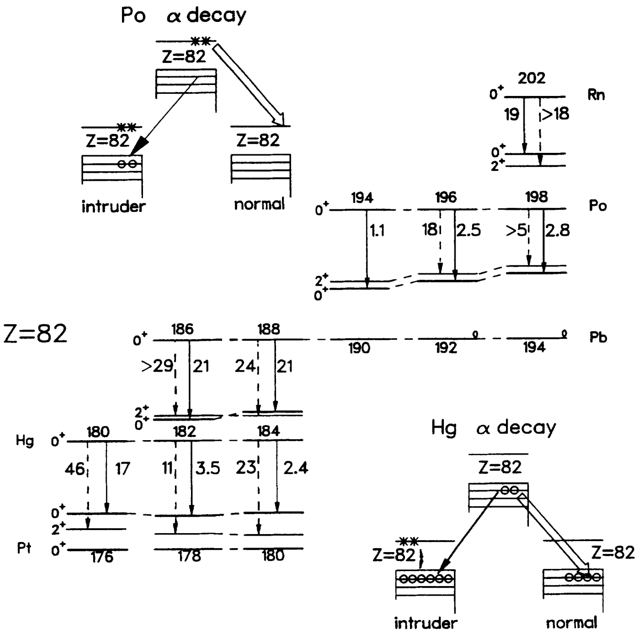

FIG. 1. A survey of the observed α-decay fine structure. The hindrance factors for the $l=0$ to the excited 0^+ state and $l=2$ to the excited 2^+ state, relative to the ground-state decay, calculated using the method of Rasmussen [3], are given next to the transitions. A solid line stands for the 0^+ to 0^+ transition, the broken line for a 0^+ to 2^+ transition. A schematic representation of the α decay above and below the $Z=82$ shell gap is shown in the insets.

the hindrance factors must be found in the difference between the structures of the ground state and the excited 0^+ state in the daughter nucleus in relation to the ground state of the parent nucleus. All observed 0^+ states in this study can be described within the framework of shape coexistence [15]. In this context two main theoretical approaches have been used. The first one is the shell model with excitation of pairs of protons through the $Z=82$ shell. The second one is the deformed mean-field approach. But as discussed in [15], a unified view is emerging. We will use the first approach because a description in terms of proton pair excitations seems closer to the α-decay process itself representing the emission of a joint proton and neutron pair. Although these shell-model intruder states come down to low energies in the polonium, lead, and mercury isotopes (in ^{190,192,194}Pb and ^{182}Hg they even become the first excited state), their mixing with the normal states is limited. In ^{198}Po, the first excited 0^+ state is less than 6% mixed with the ground state configuration [16,20]. Using lifetime measurements of the E0 transition to the ground state [17], the mixing in the lead nuclei of normal with intruder states is deduced to be 0.3% in ^{194}Pb, 0.5% in ^{192}Pb, and > 2% in ^{190}Pb. By fitting the energies of the 6^+ and 12^+ band members to a rotor, Simon *et al.* [21] deduce the position of the unmixed 0^+ bandhead of the intruder band in ^{182,184}Hg. By comparing this position with the experimental one, the mixing can be deduced. In both cases it is less than 3% [18,19]. The situation is more complex in the platinum isotopes. As discussed in Ref. [15], it is believed that the strongly deformed intruder configuration ($\beta_2 \approx 0.25$, in the shell-model language a 2p-6h state) becomes the ground state in $^{178-186}$Pt. A shape change towards a weakly deformed ground state ($\beta_2 \approx -0.15$, in the shell-model language a 4h state) occurs between ^{188}Pt and ^{186}Pt and between ^{178}Pt and ^{176}Pt. However, considerable mixing between the prolate and oblate states obscures this picture. Dracoulis *et al.* [22] calculate the mixing with a two-band analysis using experimental excitation energies from in-beam studies. The ground and excited 0^+ states in ^{180}Pt and ^{178}Pt have maximum mixing (50%), while the excited 0^+ state in ^{176}Pt has 85% intruder and 15% normal character.

The insets in Fig. 1 indicate the possible proton configurations that are involved in the α decay above and below the $Z=82$ closure, assuming a normal ground-state configuration. As can be seen in, e.g., the reduced-width plot in Fig. 3(a) of Ref. [10], the ground-state-to-ground-state α decay of neutron-deficient polonium isotopes is 3 to 4 times faster than that of the corresponding lead isotopes. This would imply that in the α decay of polonium isotopes, the removal of two protons from *above* the $Z=82$ gap, populating the corresponding *ground state* in Pb, is 3 to 4 times faster than the removal of two protons from *below* the gap, populating the corresponding 2p-2h *intruder state* in Pb. Such a situation can be found in ^{198}Po, where the decay to the intruder state is 2.8 times slower than the decay to the ground state. In ^{194}Po the decay to the intruder is as fast as the decay to the ground state: This can only be explained if the ground state of ^{194}Po is a mixture of normal and intruder states. Indeed, based on an extrapolation of the energy position of the intruder states in ^{196}Po [15], ^{198}Po [15], and ^{200}Po [23], we expect the 0^+ state in ^{194}Po to lie around 350 keV, leading to considerable mixing. The α decay from ^{202}Rn to the intruder state in ^{198}Po is 19 times retarded which can be understood as being the difference between radonlike decay (the removal of one of the two proton pairs above the shell gap) and leadlike decay (the removal of a proton pair below the shell gap). This is again based on the reduced widths of the ground-state-to-ground-state α decay in this region [see Fig. 3(a) of Ref. [10]]. The situation is completely different below the $Z=82$ shell closure: if the ground state of the parent nucleus has a normal configuration, the α decay to the intruder state must be strongly retarded. The reason is that the α decay to the intruder state is a two-step process involving the removal of a proton pair *and* the promotion of a pair of protons across the shell closure (see inset in Fig. 1). The decay of both lead isotopes studied here (^{186}Pb and ^{188}Pb) to the 0^+ intruder state has a hindrance factor of more than 20.

This retardation is a strong indication for the 2p-4h character of the intruder state in Hg and for the closed-shell character of the ground state in ^{188}Pb and ^{186}Pb. The hindrance factor for the $l=0$ α decay towards the excited 0^+ state in the Pt isotopes changes from ≈ 3 for ^{178}Pt and ^{180}Pt to 17 for ^{176}Pt. This confirms the proposed shape change in the ground state from a strong mixture of oblate and prolate deformation in ^{178,180}Pt to a more pure oblate configuration in ^{176}Pt. The α decay to the prolate excited 0^+ state (2p-6h) in ^{176}Pt is indeed strongly retarded.

The observation of large variations in the hindrance factors of $l=0$ α decay to the excited 0^+ states in even-even polonium, lead, mercury, and platinum nuclei is an experimental proof for the persistence of the $Z=82$ shell gap at the neutron-deficient side, even at $N=104$, halfway between $N=82$ and $N=126$. Furthermore fine-structure studies provide an excellent tool to probe the particle-hole character of low-lying 0^+ states and obtain new information on the variety of shapes found in this region. The present study confirms the coexistence picture described in Ref. [15].

(i) A shape change from a weakly deformed to a strongly mixed ground state does occur in the even platinum nuclei between $A=176$ and 178.

(ii) The ground state of the even mercury isotopes has a 2h character while the first excited 0^+ state has a 2p-4h character; there is little mixing between these two states.

(iii) The ground state of the even lead isotopes has a closed proton configuration while the first excited 0^+ state has a 2p-2h character; there is little mixing between these two states.

(iv) The character of the neutron-deficient polonium ground states is changing from a 2p configuration (^{198}Po) to a mixture of 2p and 4p-2h configurations (^{194}Po).

This qualitative picture should be consolidated by a more quantitative analysis. The nine cases studied here form an excellent basis for further theoretical studies. It will be a challenge for the present α-decay models to reproduce the effect of the $Z=82$ shell closure and the influence of shell-model intruder states on the $l=0$ α decay to the different 0^+ states.

Recently Heese *et al.* [24] observed yrast states in ^{188}Pb and ^{186}Pb which are an indication for a different structure than in the heavier lead nuclei. Nazarewicz [25] has interpreted this as evidence for well-deformed prolate states of 4p-4h character, predicted to intrude to low energies from $N \leq 108$ on. The question arises where the oblately deformed 2p-2h state lies and how strongly the three different configurations (0p-0h, 2p-2h, and 4p-4h) interact. The study of fine structure in the α decay of neutron-deficient polonium isotopes might provide a unique opportunity to clarify this question.

---

[*] Present address: Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550.

[†] On leave from Mokwon University, 24. Mok-Dong, Chung-Ku, Taejon, 301-729, Korea.

[‡] On leave from Instituut voor Kern- en Stralingsfysica, K. U. Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium.

[1] G. Gamow, Z. Phys. **51**, 204 (1928).
[2] E. U. Condon and R. W. Guerney, Nature (London) **122**, 439 (1928).
[3] J. O. Rasmussen, Phys. Rev. **113**, 1593 (1959).
[4] K. Varga, R. G. Lovas, and R. J. Liotta, Phys. Rev. Lett. **69**, 37 (1992).
[5] P. Hornshøj, P. G. Hansen, and B. Jonson, Nucl. Phys. **A230**, 365 (1974).
[6] K. Toth, Y. A. Ellis-Akovali, C. R. Bingham, D. M. Moltz, D. C. Sousa, H. K. Carter, R. L. Mlekodaj, and E. H. Spejewski, Phys. Rev. Lett. **53**, 1623 (1984).
[7] J. Wauters, P. Decrock, P. Dendooven, M. Huyse, G. Reusen, and P. Van Duppen, Z. Phys. A **339**, 533 (1991).
[8] P. Hornshøj, P. G. Hansen, B. Jonson, H. L. Ravn, L. Westgaard, and O. B. Nielsen, Nucl. Phys. **A230**, 365 (1974).
[9] J. Wauters, P. Dendooven, P. Decrock, M. Huyse, R. Kirchner, O. Klepper, G. Reusen, E. Roeckl, and P. Van Duppen, Z. Phys. A **342**, 277 (1992).
[10] J. Wauters, P. Dendooven, M. Huyse, G. Reusen, P. Van Duppen, and P. Lievens, Phys. Rev. C **47**, 1447 (1993).
[11] B. Buck, A. C. Merchant, and S. M. Perez, Phys. Rev. Lett. **65**, 2975 (1990).
[12] B. Buck, A. C. Merchant, and S. M. Perez, J. Phys. G **18**, 143 (1992).
[13] B. Buck, A. C. Merchant, and S. M. Perez, Phys. Rev. C **45**, 2247 (1992).
[14] B. A. Brown, Phys. Rev. C **46**, 811 (1992).
[15] J. L. Wood, K. Heyde, W. Nazarewicz, M. Huyse, and P. Van Duppen, Phys. Rep. **215**, 101 (1992).
[16] J. Wauters, P. Dendooven, M. Huyse, G. Reusen, P. Lievens, and P. Van Duppen, Z. Phys. A **344**, 29 (1992).
[17] P. Dendooven, P. Decrock, M. Huyse, G. Reusen, P. Van Duppen, and J. Wauters, Phys. Lett. B **226**, 27 (1992).
[18] N. Bijnens, M. Huyse, Han Yull Hwang, J. von Schwarzenberg, P. Van Duppen, J. Wauters, H. Folger, and R. Kirchner (to be published).
[19] J. Wauters, P. Dendooven, M. Huyse, G. Reusen, P. Van Duppen, R. Kirchner, O. Klepper, and E. Roeckl, Z. Phys. A **345**, 21 (1993).
[20] J. Wauters, Ph.D. thesis, K. U. Leuven, 1992 (unpublished).
[21] R. S. Simon, K.-H. Schmidt, F. P. Hessberger, S. Hlavac, M. Honusek, G. Münzenberg, H.-G. Clerc, U. Gollerthan, and W. Schwab, Z. Phys. A **325**, 197 (1986).
[22] G. D. Dracoulis, A. E. Stuchbery, A. P. Byrne, A. R. Poletti, S. J. Poletti, J. Gerl, and R. A. Bark, J. Phys. G **12**, L97 (1986).
[23] N. Bijnens, M. Huyse, Han Yull Hwang, J. Schwarzenberg, P. Van Duppen, and J. Wauters (to be published).
[24] J. Heese, K. H. Maier, H. Grawe, J. Grebosz, H. Kluge, W. Meczynski, M. Schramm, R. Schulbart, K. Spohr, and J. Styczen, Phys. Lett. B **302**, 390 (1993).
[25] W. Nazarewicz, Phys. Lett. B **305**, 195 (1993).