Alpha decay of ^{186}Pb and ^{184}Hg: The influence of mixing of 0^+ states on α-decay transition probabilities

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Fine structure in the α decay of mass-separated ^{186}Pb and ^{184}Hg has been studied at the GSI on-line mass separator. Alpha singles spectra as well as α-x-t and α-e-t coincidence events were collected. The α decay of ^{186}Pb revealed feeding to a low-lying 0^+ state at 328(12) keV in ^{182}Hg. This state can be interpreted as being the bandhead of the deformed rotational band observed previously in in-beam studies. In the α decay of ^{184}Hg, feeding towards the first excited 2^+ state at 153 keV and the 0_2^+ state at 478 keV in ^{180}Pt was observed. The hindrance factor of the α decay towards the excited 0^+ state gives information about the particle-hole character of the states connected in the α decay. A two-level mixing calculation is introduced. From the mixing in Pt and the α-decay hindrance factors, small mixing is deduced for ground states of neutron-deficient Hg and Pb nuclei.

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I. INTRODUCTION

The coexistence of bands with different deformation in neutron-deficient even Hg and Pt nuclei has been known for some time from in-beam and laser studies as well as from α-decay, β^+, and electron capture decay studies (for a survey on the matter, see Ref. [1]). In the neutron-deficient even-even Hg isotopes, a deformed band has been found at low energies in $^{180-190}$Hg [1] with spin and parity ranging down to $I^\pi = 0^+$ for $^{184-190}$Hg and to $I^\pi = 4^+$ for ^{180,182}Hg. The excitation energy of the intruder 0^+ bandhead shows, as a function of the neutron number, a parabolic behavior with a minimum expected for ^{182}Hg, at N=102 (two neutrons below midshell). The low-spin states at low excitation energies can be studied in α decay, as α decay directly feeds into this part of the level scheme. Several examples of such studies can be found in Ref. [2]. Recently, we studied the α decay of ^{188}Pb, feeding the 0_2^+ state at 375 keV, and the 2_1^+ state at 367 keV [3]. The large hindrance factor (HF=21) of the α decay towards the 0_2^+ state relative to the α decay to the ground state indicates that the 0_2^+ state might be based on a π(2p-4h) (two-particle–four-hole) configuration, giving a strong retardation of the α decay of the Pb π(0p-0h) ground state towards this state, compared to the α decay towards the π(2h) ground state [2,3]. In the case of ^{182}Hg, the 0^+ bandhead and the 2^+ member of the intruder band are not known. In order to identify the 0^+ bandhead, we performed an α-decay study of ^{186}Pb to look for fine structure in the α-decay feeding excited states in ^{182}Hg.

In the neutron-deficient even Pt nuclei, it is believed that, for ^{188}Pt and lighter isotopes, the 0^+ bandhead of the strongly deformed rotational band mixes completely with the bandhead of the normal (weakly deformed) ground state band due to the decrease of its excitation energy with decreasing neutron number [4]. At the very neutron-deficient side, namely between ^{176}Pt and ^{178}Pt, the level systematics indicate that the strongly deformed band rises again in energy with decreasing neutron number [1]. From our α-decay studies of ^{180}Hg and ^{182}Hg, the variation of the hindrance factor for the α decay towards the excited 0^+ state (17 and 3.5, respectively) supports this configuration change between ^{176}Pt and ^{178}Pt [3]. Closer to midshell, at ^{180}Pt, the mixing in the ground state of the strongly deformed states with the normal states is believed to be even larger than for ^{178}Pt. This should reflect itself in the hindrance factor (HF). We studied the α decay of ^{184}Hg towards ^{180}Pt to observe the α feeding of the excited 0^+ state at 478 keV.

II. THE EXPERIMENT

The ^{186}Pb and ^{184}Hg nuclei were produced at the GSI on-line mass-separator facility at Darmstadt using the reactions (2.8 mg/cm^2) ^{144}Nd(^{46}Ti,4n)^{186}Pb and (2.8 mg/cm^2) ^{148}Nd(^{40}Ca,4n)^{184}Hg with a beam energy of 5 MeV/nucleon and an intensity of 20 particle nA, resulting in a production rate of 13 atoms/s for ^{186}Pb and 1100 atoms/s for ^{184}Hg after mass separation. The activity was implanted in 30 μg/cm^2 carbon foils mounted in the detection system. This detection setup is described in detail in Ref. [3]. It consisted of an implantation sta-

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tion where an α detector (PIPS type, 150 mm^2) and x-ray (LEGe) detector were mounted, and a decay station with an α detector (PIPS, 150 mm^2) and electron detector (plastic scintillator, 4 mm thick). Alpha singles spectra as well as α-e-t and α-x-t coincidence events were collected in a cycle adjusted to the half-life of the ^{186}Pb and ^{184}Hg, respectively, nuclei. The α-singles spectra were collected as α-TDC (time to digital converter) events in order to obtain precise half-lives. The energy calibration for the α detector was calculated using α lines emitted by isobaric isotopes and/or neighboring masses. For the ^{184}Hg experiment, the 4.490(15) MeV α line of ^{184}Pt, the 5.535(15) MeV α line of ^{184}Hg, and the 5.905(15) MeV α line of ^{183}Hg were used [5]. For the ^{186}Pb experiment, the 5.094(15) MeV α line of ^{186}Hg, the 5.975(5) MeV α line of ^{185}Tl, and the 6.335(10) MeV α line of ^{186}Pb were used [5,6]. In the following sections, the α-decay energies given with their uncertainties are experimental values from this work.

III. RESULTS

A. The α decay of ^{186}Pb

No fine structure in the α decay of ^{186}Pb was known until now. Figure 1 compares the α singles spectrum taken at mass 186 (a) with the α spectrum coincident with the LEGe detector (b). The α line at 6.335 MeV in the singles spectrum is the ground state to ground state α decay of ^{186}Pb [6]. A half-life of 4.83(3) s was obtained, in agreement with 4.7(1) s [6]. The 5.858(13) MeV α line belongs to the ground state to ground state α decay of the ^{182}Hg daughter nucleus, the 5.443(13) MeV α line belongs to the ^{178}Pt granddaughter nucleus, and the 5.76 MeV α line is due to the α decay of ^{186}Tl [5], the latter is also produced directly in the reaction. The 6.014(13) MeV α line could not be assigned to mass-contaminated activity or daughter activity. Its half-life was measured to be 5.2(8) s, similar to ^{186}Pb. The coincident α spectrum shows, apart from some random events of the 6.335 MeV α line from ^{186}Pb, an α line at 6.014(13) MeV and a bump of unresolved α lines between 5.6 and 5.8 MeV. The latter can be attributed to the α decay of ^{186}Tl. It was not possible to extract a decay scheme for ^{186}Tl because of the poor statistics and the fact that the α lines were not resolved. The α line at 6.014(13) MeV in Fig. 1(b) is promptly coincident with Hg K x rays [Fig. 1(c)] and with electrons that have an energy of ~250 keV [Fig. 1(d)], which would give a transition in Hg of about 330 keV, taking into account the K-electron binding energy. No γ ray with the appropriate energy could be observed in the α-LEGe coincidence data, yielding in a K-conversion coefficient of the transition of at least 2.5 ($\alpha_K[M3] = 2.4$). Combined with the prompt x-ray and electron coincidences, this means that the transition must have considerable $E0$ character. An α line feeding the 2_1^+ state in ^{182}Hg at 351 keV would have an energy of 5.991 MeV possibly forming a doublet with the 6.014 MeV α line. No coincidence with a 351 keV γ ray was observed. A lower limit of 45 was deduced for the hindrance factor of the 5.991 MeV α line (calculated with the formalism of Rasmussen [7]). From the half-life, from the Hg K x-ray and electron coincidences, and from the transition energy relations, we conclude that the 6.014 MeV α line belongs to the fine structure in the α decay of ^{186}Pb feeding a 0_2^+ level at 328(12) keV in ^{182}Hg. The reduced width of this α line is a factor of 21(4) lower than the reduced width of the α decay towards the ground state. Figure 2 shows the α-decay scheme of ^{186}Pb.

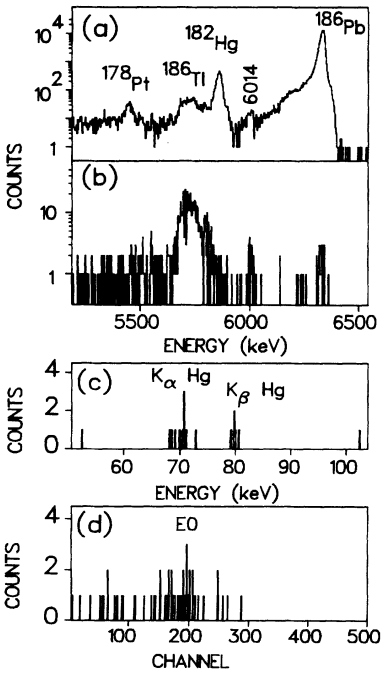

FIG. 1. Alpha, x-ray, and electron spectra taken at mass 186: singles α spectrum (a), α spectrum coincident with the LEGe detector (b), low-energy γ-ray spectrum (LEGe detector) (c), and electron spectrum (d), both coincident with the 6.014 MeV α line. Energies are denoted in keV.

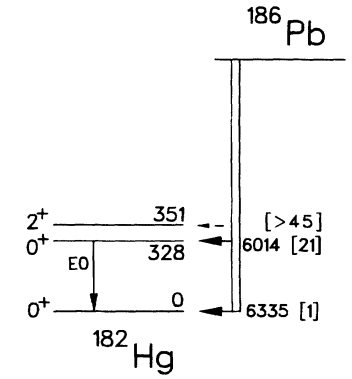

FIG. 2. The α-decay scheme of ^{186}Pb. Energies are denoted in keV and the number in square brackets are the hindrance factors of the α transitions relative to the ground state α decay.

B. The α decay of ^{184}Hg

The α-singles spectrum taken at mass 184 is shown in Fig. 3(a). The 5.535 MeV α line belongs to the ground state to ground state α decay of ^{184}Hg [5]. Its half-life was deduced from the TDC spectrum as 30.9(3) s, in agreement with literature [30.6(3) s [5]]. Some mass contamination is present in the α spectrum, assigned to ^{183}Hg and ^{185}Hg [see Fig. 3(a)]. The group of α lines with an energy between 4.96 and 5.20 MeV was assigned as belonging to the α decay of ^{184}Au [8]. The α line at 5.379 MeV was previously assigned to α decay of ^{184}Hg feeding the 2_1^+ state at 153 keV in ^{180}Pt by Hansen *et al.* [8]. The deduced hindrance factor [41(3)] is in agreement with the value of [8], namely 43(9). Figure 3(b) shows the α spectrum coincident with electrons, giving 4 lines [4.970(15)], 5.055(15), 5.104(15), and 5.379(15) MeV]. The 5.379(15) MeV α line is coincident with a γ ray of 153 keV and Pt K x rays and is assigned to α feeding of ^{184}Hg towards the 2_1^+ state in ^{180}Pt, confirming the results of Hansen *et al.* [8]. The 4.970(15) and 5.104(15) MeV α lines belong to the α decay of ^{184}Au based on their half-life [8]. The α line at 5.055(15) MeV, previously assigned to ^{184}Au α decay [8], shows a half-life of 28(9) s, compared to 53.0(14) s for ^{184}Au and 30.6(3) s for ^{184}Hg. The 5.055(15) MeV α line is coincident with high-energy electrons, with Pt K x rays and a γ ray of 153 keV. Therefore, taking into account the transition energy relations, we conclude that the 5.055(15) MeV α line belongs to the α decay of ^{184}Hg, feeding the 0_2^+ state at 478 keV in ^{180}Pt [9]. This state decays either by an $E0$ transition directly to the ground state or by an $E2$ cascade via the 2_1^+ state [$E0/(E0+E2)$ =20–54 %]. Due to the small efficiency of the LEGe detector for γ rays, the $0_2^+ \rightarrow 2_1^+$ transition (325 keV) was not observed. The hindrance factor for the α decay towards the 0_2^+ state is 2.4(2). Figure 4 shows the α-decay scheme of ^{184}Hg, together with the α-decay schemes of ^{180,182}Hg, taken from [3].

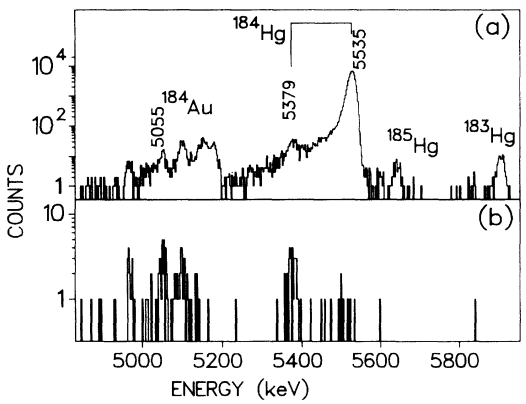

FIG. 3. The singles (a) and coincident (with the electron detector) (b) α spectrum taken at mass 184. Energies are denoted in keV.

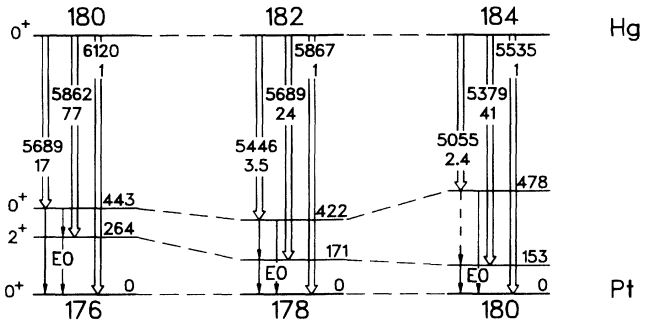

FIG. 4. The α-decay schemes of ^{180,182,184}Hg. The α-decay schemes of ^{180,182}Hg are taken from [3]. For each α line, the hindrance factors are given, relative to the ground state decay branch. Energies are denoted in keV.

IV. DISCUSSION

Coexisting shapes are present in the low-energy part of the even-even Pb, Hg, and Pt nuclei with neutron number between 98 and 114. Fingerprints for this phenomenon are band structures built on low-lying 0^+ states. In a number of nuclei, these excited 0^+ states can be fed in the α decay. The two cases of such fine structure in the α decay presented here together with the three cases presented in Ref. [3] make it now possible to discuss in a coherent way the large variation (from 2.4 to 21) in the hindrance factor of the α decay towards the excited state relative to the decay towards the ground state. Three states are connected in these decay studies: the ground state of the parent nucleus, the excited 0^+ state in the daughter nucleus, and the ground state in the daughter nucleus. Considerable mixing can occur between the coexisting structures and we will show that this mixing, as well in parent ground state as in the daughter states, can explain the large variation in hindrance factors.

In the next paragraph, we introduce a two-level mixing model, describing the variation of the α-decay hindrance factors as a function of the mixing between the 0^+ bandheads in the parent and in the daughter nucleus.

A. A two-level mixing model

Four states are involved in this problem and they are schematized in Fig. 5. It is now necessary to introduce four α-decay transition probabilities (T_1, T_2, T_3, and T_4) connecting the unmixed normal and intruder states of parent ($|u\rangle, |v\rangle$) with daughter ($|x\rangle, |y\rangle$) nuclei:

$$T_1 = \langle x|\tau|u\rangle \ , \quad T_2 = \langle y|\tau|u\rangle \ ,$$
$$T_3 = \langle x|\tau|v\rangle \ , \quad T_4 = \langle y|\tau|v\rangle \ , \qquad (1)$$

where τ represents the α-decay transition operator.

Introducing two-level mixing between the different bandheads, the parent ground and excited states and the daughter ground and excited states are given by

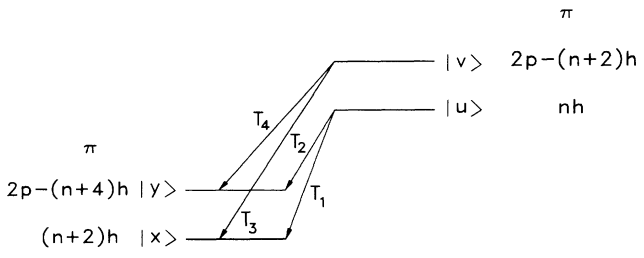

FIG. 5. Schematic drawing of the two-level system in parent and daughter nuclei and the possible α-decay branches.

$$|u\rangle_{\rm mix} = a|u\rangle + b|v\rangle \ ,$$
$$|v\rangle_{\rm mix} = -b|u\rangle + a|v\rangle \ ,$$

and (2)

$$|x\rangle_{\rm mix} = c|x\rangle + d|y\rangle \ ,$$
$$|y\rangle_{\rm mix} = -d|x\rangle + c|y\rangle \ ,$$

where normalization gives $a^2 + b^2 = 1$ and $c^2 + d^2 = 1$.

The hindrance factor, defined as the ratio of the reduced width of the ground-state–ground-state α decay to the ground-state–excited-state α decay, can then be written as

$$\mathrm{HF} = \frac{\delta^2_{\rm g.s.}}{\delta^2_{\rm exc}} = \frac{|acT_1 + adT_2 + bcT_3 + bdT_4|^2}{|-adT_1 + acT_2 - bdT_3 + bcT_4|^2} \ . \quad (3)$$

In Ref. [10] a survey is given of the reduced widths of the s-wave α decay between ground states of even-even nuclei in the lead region. The $\delta^2_{\rm g.s.}$ values of the even Pb and Hg nuclei under study here vary within a factor of 4. It is impossible to extract out of these values the α-decay transition probabilities (T_i). An oversimplification would be to assume that all T_i values are equal. This simplifies Eq. (3) to

$$\mathrm{HF} = \frac{|(a+b)(c+d)|^2}{|(a+b)(c-d)|^2} = \frac{|c+d|^2}{|c-d|^2} \ . \quad (4)$$

The hindrance factor becomes independent from the mixing in the parent nucleus but increases strongly with the increase of mixing in the daughter nucleus [see Fig. 6(a)]. This is contrary to our observation in the Hg to Pt decay: the hindrance factor drops from 17 for ^{180}Hg α decay to 2.4 for ^{184}Hg α decay, while it is believed that the mixing increases from 15% to 61% [4]. This led us to conclude that different α-decay strengths must be introduced. In order to obtain an estimate for the T_i values, we can use the description of the 0^+ intruder states as proton particle-hole excitations through the $Z = 82$ shell closure [1].

B. Description of the intruder 0^+ states as proton particle-hole excitations

In this frame, the normal states can be interpreted as $\pi(n\mathrm{h})$ hole states and the intruder 0^+ states as π(2p-

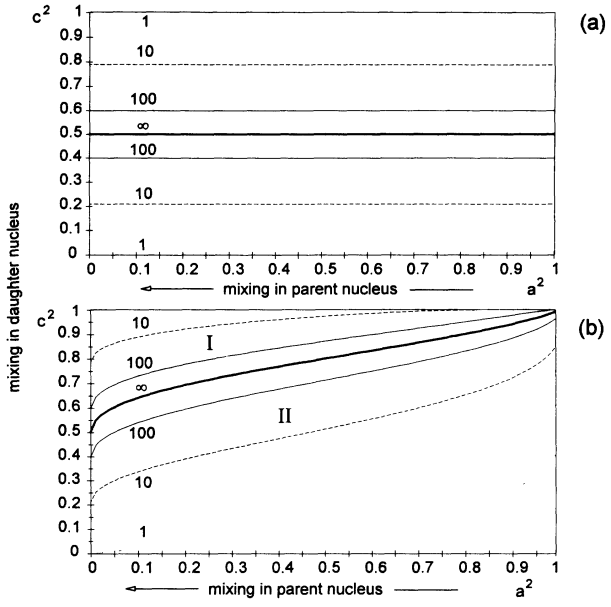

FIG. 6. The mixing of the daughter nucleus as a function of the mixing of the parent nucleus, for different hindrance factors, for two cases, namely $T_1 = T_2 = T_3 = T_4$ (a) and $T_1 = T_3 = T_4$ and $T_2 = 0$ (b).

$(n+2)$h) states (see Fig. 5) [2]. It is now possible to determine where the proton pair will be taken away in the different decay possibilities (T_i), we assume that the neutrons are only playing the role of spectator. The α-decay probabilities T_i then represent the following changes in proton configuration (see Fig. 5):

$$T_1: \ n\mathrm{h} \rightarrow (n+2)\mathrm{h} \ ,$$
$$T_2: \ n\mathrm{h} \rightarrow 2\mathrm{p} - (n+4)\mathrm{h} \ ,$$
$$T_3: \ 2\text{p-}(n+2)\mathrm{h} \rightarrow (n+2)\mathrm{h} \ ,$$
$$T_4: \ 2\text{p-}(n+2)\mathrm{h} \rightarrow 2\text{p-}(n+4)\mathrm{h} \ ,$$

and if we apply this for the Hg to Pt decay, T_1 is the ground-state–ground-state Hg decay, T_3 is the Po-like decay, and T_4 is the Pt-like decay. T_2 involves a two-step process and will be much slower than the other decay modes. We can now evaluate Eq. (3) by assuming $T_1 = T_3 = T_4$, and $T_2 = 0$. The systematics of the reduced widths of the ground state α decay of even-even nuclei suggests that this is a reasonable approximation [10]: the Pt, Hg, Pb, and Po reduced widths have comparable values within a factor of 4 in the region around $N = 100$. Equation (3) for the hindrance factor can then be written as

$$\mathrm{HF} = \frac{|(a+b)c + bd|^2}{|-(a+b)d + bc|^2} \ . \quad (5)$$

Figure 6(b) shows the influence of the mixing in the parent and daughter nucleus on the hindrance factors using Eq. (5). Two possible solutions arise from solving Eq. (5) resulting in two regions [see Fig. 6(b)], separated by the line connecting the data points with HF=∞. Region I

implies that a small variation in mixing of the daughter nucleus would result in large variations of the HF, namely orders of magnitude. This is contrary to our observations on the α decay of ^{180,182,184}Hg. Therefore, we will limit the discussion to region II.

The hindrance factors vary only slowly with the mixing in the parent nucleus, while the increase of mixing in the daughter nucleus decreases the hindrance factor more strongly. Figure 7(a) shows the solution of Eq. (5) for the three experimental cases in the α decay of even-even Hg: HF=17 (^{180}Hg$\rightarrow^{176}$Pt), HF=3.5 (^{182}Hg$\rightarrow^{178}$Pt), and HF=2.4 (^{184}Hg$\rightarrow^{180}$Pt). Also shown in Fig. 7 are the mixing values for ^{176,178,180}Pt from Dracoulis *et al.* [4], who extracted them from the extrapolation of the rotational band built on top of the 0^+ excited state: 15% for ^{176}Pt, 50% for ^{178}Pt, and 61% for ^{180}Pt. It is then possible to extract out of the experimental mixing values of Dracoulis *et al.* and our hindrance factors the mixing values for the ground states of Hg. This gives 3% mixing in ^{180}Hg, 16% for ^{182}Hg, and 18% for ^{184}Hg.

The same formalism can be applied to the α decay of ^{186,188}Pb to the 0^+ excited state in ^{182,184}Hg. The α decay of the π(0p-0h) Pb ground state towards the π(2p-4h) Hg excited state involves the same two-step process as in the Hg$\rightarrow$Pt case, and results in a large HF (=21) compared to the α decay to the π(2h) Hg ground state. Figure 7(b) shows the mixing in Pb as a function of the mixing in Hg, for HF=21. The mixing in Pb can be deduced from the mixing in Hg in the same way as for the Hg to Pt α decay. The small mixing in Hg, below 18%, limits the possible solutions to the region where the mixing in ^{186,188}Pb is small: $< 9\%$. It follows from these results that the ground state becomes less mixed when approaching the $Z = 82$ shell closure: from the strongly mixed Pt nuclei to the rather pure Pb ground states. This supports the persistence of the $Z = 82$ shell closure at the neutron-deficient Pb isotopes.

One can compare the results for Hg with the calculation of Ma *et al.* [11] for the position of the unmixed 0_2^+ state in ^{182}Hg deduced from a fit of the energies of the deformed band members from 6^+ to 12^+ in ^{182}Hg using the modified relation of a rigid rotor, $E = E_0 + AI(I+1) + BI^2(I+1)^2$. The resulting excitation energy, 338 keV, lies within the uncertainty on our experimental value [328(12) keV]. Taking into account an uncertainty of 20 keV on the estimated excitation energy of the deformed bandhead, one obtains a mixing probability of $< 4\%$ between the ground state and the 0_2^+ state of ^{182}Hg, similar to ^{184}Hg [3]: $< 3\%$. Lifetime measurements of the excited 0^+ state in ^{186,188}Hg have been performed at UNISOR [12]. From this the degree of mixing of the excited 0^+ state with the ground state can be deduced: 1% for ^{188}Hg and $> 4\%$ for ^{186}Hg. This small degree of mixing for the 0^+ states in the Hg isotopes is consistent with our findings described above.

The even smaller mixing in Pb is consistent with our half-life measurements of the excited 0^+ state in ^{190,192,194}Pb where only very small mixing is found between the excited 0^+ state and the 0^+ ground state in Pb [13]. Recently, Heese *et al.* observed yrast states in ^{186,188}Pb for the first time with a new recoil detection technique and found that these nuclei exhibit low-lying rotational bands very similar to their isotones ^{184,186}Hg [14] and concluded that the structure of the bands is different from the π(2p-2h) intruder states in $^{190-208}$Pb. In the case of ^{186}Pb, the level scheme was extended by Baxter *et al.* [15]. The occurrence of a strongly prolate deformed configuration and probably the weaker deformed oblate configuration gives a more complex structure at low excitation energy in the Pb isotopes for $A < 190$. Calculations, based both on extrapolations of rotational levels for the prolately deformed structure and on the heavier isotopes for the oblate deformed intruder configuration [14], indicate that both excited 0^+ states have similar excitation energies (500–700 keV). This probably gives rise to some mixing but leaves the 0^+ ground state relatively pure, in agreement with our findings.

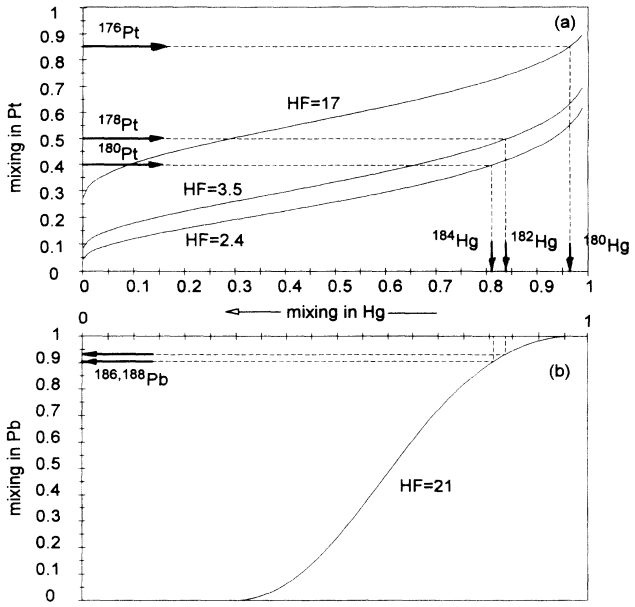

FIG. 7. The mixing of the daughter nucleus as a function of the mixing of the parent nucleus, parametrized with the hindrance factor for the Hg to Pt α decay (HG=17, 3.5, and 2.4) (a) and for the ^{186,188}Pb$\rightarrow^{182,184}$Hg α decay (HF=21) (b) (see text for further details).

V. CONCLUSION

The α decay of ^{186}Pb has been studied and fine structure has been observed for the first time, feeding a 0^+ state at 328(12) keV in ^{182}Hg. This state is interpreted as the bandhead of the deformed band of which only the $I \geq 4$ spin members were known before. The hindrance factor of the α feeding to the excited 0^+ state, 21, is the same as for the ^{188}Pb case [3]. The α decay of ^{184}Hg revealed feeding to the 0_2^+ and 2_1^+ states in ^{180}Pt. The decrease in hindrance factor of the α decay towards the 0_2^+ state from ^{180}Hg to ^{184}Hg further supports the idea of

the configuration change between ^{176}Pt and ^{178}Pt leading to even more mixing between the 0^+ states in ^{180}Pt.

A two-level mixing model has been introduced for the 0_2^+ excited and 0_1^+ ground states in parent and daughter nuclei connected by the α decay in the framework of $\pi(2\text{p-}n\text{h})$ configurations. The model shows a high sensitivity of the hindrance factor on the degree of mixing between intruder and normal state in the daughter nucleus, and only a weak dependence on the mixing in the parent nucleus. From the mixing calculations in Pt and our experimental hindrance factors, we can expect the mixing in Pb and Hg to be small, in qualitative agreement with experiment. Further refinement of the model has to be done concerning different α-decay strengths (T_i). Furthermore, the model will be applied to our α-decay studies above the $Z = 82$ shell gap. Also, other experimental data that give information about mixing, such as $E0$ transition probabilities and laser spectroscopic data, are necessary to complement the model.

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