LIFE TIME MEASUREMENTS OF 0+ INTRUDER STATES IN $^{190,192,194}$Pb

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The fine structure in the α-decay of mass-separated $^{194,196,198}$Po is studied. Feeding to the 0+ ground state and the first excited 0+ intruder state in $^{190,192,194}$Pb is observed. From α–e–t coincidences between the feeding α-ray and the E0 transition, the half life of the 0+ intruder state in $^{190,192,194}$Pb is measured. The mixing between intruder state and ground state is deduced.

In recent letters we reported on the excitation energies of shell-model intruder states in the neutron-deficient even-even lead (Pb) [1,2], odd-mass bismuth (Bi) and thallium (TI) [3] and odd-odd TI nuclei [4]. The typical behaviour of the excitation energy as a function of the neutron number, from $N=126$ down to $N=104$, is well reproduced in a spherical [5,6] and in a deformed shell-model framework [1,7]. The equivalence of the two approaches has recently been discussed by Heyde et al. [8].

So far only energy systematics have been discussed, as there is little experimental information on transition probabilities. A direct measure of the mixing of coexisting shapes in even–even nuclei is the E0 transition strength between the intruder state and the ground state [9]. But in the Pb, mercury (Hg) and platinum (Pt) nuclei, notorious examples of shape coexistence, there exists no systematic information on excited 0+ half lives. In this letter we report on precise life time measurements of the first excited 0+ intruder states in $^{190,192,194}$Pb by measuring in the α-decay of $^{194,196,198}$Po respectively, the coincidence time spectrum between the α-ray feeding the 0+ state and the E0 deexcitation towards the ground state. The deduced monopole strength is then used to obtain the mixing between the deformed intruder state and the spherical ground state. Such mixing has recently been suggested to explain the deviation of the change in the mean square radius $\langle r^2 \rangle$ of the even-$A$ Pb nuclei from the droplet model [10].

The neutron-deficient isotopes $^{198}$Po (1.76 min), $^{196}$Po (5.5 s) and $^{194}$Po (0.41 s) were produced in the reaction of 240 MeV $^{20}$Ne on $^{182}$W (Ta foils were used to degrade the beam to optimal energy). A stack of three enriched $^{182}$W foils (total thickness 2.1 mg/cm$^2$, made at GSI-Darmstadt by H. Folger) was mounted inside our FEBIAD ion source. More details on the LISOL set-up can be found in ref. [11]. The mass-separated polonium (Po) beam was implanted in a 30 lag/cm$^2$ C foil. For the study of $^{198}$Po and $^{196}$Po, this foil was mounted in a wheel that periodically moved the activity to a decay position in between an α detector (150 mm$^2$ PIPS, 15 keV resolution) and an e$^-$ detector (5 mm thick NE104 plastic). An α–e coincidence efficiency of 4% was obtained. For the study of 0.41 s $^{194}$Po the C foil was surrounded at the implantation station by the α and e$^-$ detector. The FWHM resolution of the fast timing set-up was about 840 ps.

Fig. 1 shows the α-singles spectrum at mass 196 together with three projections out of the α–e–t coincidence matrix of mass 196. The high selectivity of the α–e coincidence for the α-branch to the intruder at 769 keV in $^{192}$Pb is evident by comparing fig. 1a and 1b. The TAC spectrum of fig. 1d was gated by the α line of 5769 keV in the decay of $^{198}$Po to the 0+ intruder in $^{192}$Pb and by the E0 (769 keV) electrons (see fig. 1c). Although there are only 460 counts in the TAC spectrum, a precise half-life value for the intruder state in $^{192}$Pb of (750 ± 100) ps can be obtained as the TAC spectrum is completely free of random coincidence. Similar results are obtained for the decay of $^{198,194}$Po to respectively $^{194}$Pb and $^{190}$Pb but
for $^{190}$Pb only an upper limit can be set on the half life. Table 1 summarizes our results.

It is possible to extract out of the E0 half-lives the monopole strength. The absolute nuclear electric-monopole transition probability $W(E0)$ is here:

$$W(E0) = \frac{\ln 2}{T_{1/2}(0^+)} = \rho^2(E0) \sum \Omega_j(Z, k),$$

(1)

with $\rho^2(E0)$ being the strength parameter containing the nuclear matrix element, and $\Omega_j(Z, k)$ being the so-called electronic factors ($j$ represents the electronic shells $K$, $L_1$, $L_{11}$,...). The electronic factors $\Omega_l$, $\Omega_{l_1}$, and $\Omega_{l_{11}}$ electronic factors are calculated with the method of Kantele [12]. The electronic factor $\Omega_{l_{11}}$ is calculated from the $\Omega_{l_1}$ value by using experimental K/M E0 ratios [13]. The strength parameter $\rho^2(E0)$ can be compared with the E0 single-particle unit proposed by Bohr and Mottelson [14],

$$\rho_{sp,n}^2 = 0.5 A^{-2/3}.$$  
(2)

The ratio between $\rho_{sp,n}^2$ and $\rho_{exp}^2$ gives the hindrance of the E0 transition (see table 1). This E0 single-particle unit is based on a 50% mixing of two shell-model states. The hindrance factors drop by almost one order of magnitude when going from $^{194}$Pb to $^{190}$Pb. But in the case of the Pb nuclei, where the intruder state is deformed while the ground state is spherical (see e.g. ref. [1]), the E0 transition rate is strongly dependent on the difference in deformation of the initial and final state. The mixing of the spherical and deformed state is then obtained in the following way (see refs. [9,15]):

$$|0^+_{\text{int}}\rangle = +b|\text{sph}\rangle - a|\text{def}\rangle,$$

(3)

$$|0^+_g\rangle = a|\text{sph}\rangle + b|\text{def}\rangle,$$

(4)

and

$$\rho_{\text{int-gs}}^2 = a^2 b^2 \left( \frac{3Z^2}{4\pi} \right)^2 \langle \beta^2 \rangle_{\text{def}}^2.$$  
(5)

Eq. (5) can be used to obtain the mixing between intruder state and ground state, provided the deformation parameter $\langle \beta^2 \rangle_{\text{def}}$ of the $0^+$ intruder state is known. In refs. [5,16] we emphasized the strong resemblance between the bandstructure built upon the intruder state in Pb (a 2p–2h proton state) and the ground state band in the Pt nuclei (a 4h proton state). The Pt isotopes with neutron number greater than 110

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**Fig. 1.** Mass 196 spectra: (a) $\alpha$-singles spectrum, (b) “prompt” projection of the $\alpha$ detector from the $\alpha$–$e$–$t$ coincidence matrix, (c) electron spectrum gated by the 5769 keV $\alpha$ line. (d) TAC spectrum gated by the 5769 keV $\alpha$ line and the 769 keV E0 electron line. The result of the half-life convolution fit is given as a full line. The energy value of the $^{196}$Po $\alpha$ lines are given in keV.
Out of the measured half-life values \( T_{1/2}(0^+ \) ) the experimental monopole strength \( \rho_{\text{exp}}(E0) \) is determined. By comparing this value with the E0 single-particle unit \( \rho_{\text{sp}}(E0) \), the hindrance factor of the E0 transition can be obtained. The mixing of the intruder state and ground state is calculated with eq. (5). The mixing matrix elements \( \langle V \rangle \) are deduced from a two-level mixing calculation.

<table>
<thead>
<tr>
<th>( E(0^+) ) keV</th>
<th>( T_{1/2}(0^+) ) ps</th>
<th>( \rho_{\text{exp}}(E0) \times 10^3 )</th>
<th>( \rho_{\text{sp}}(E0) \times 10^3 )</th>
<th>Hindrance factor</th>
<th>( \beta )</th>
<th>( a^2 )</th>
<th>( b^2 )</th>
<th>( \langle V \rangle ) keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{194}\text{Pb} )</td>
<td>930.6(9)</td>
<td>1100±200</td>
<td>1.0±0.2</td>
<td>14.6</td>
<td>14.6</td>
<td>0.17</td>
<td>0.997</td>
<td>0.003</td>
</tr>
<tr>
<td>(^{192}\text{Pb} )</td>
<td>768.5(17)</td>
<td>750±100</td>
<td>1.7±0.2</td>
<td>14.7</td>
<td>8.6</td>
<td>0.175</td>
<td>0.995</td>
<td>0.005</td>
</tr>
<tr>
<td>(^{190}\text{Pb} )</td>
<td>658(4)</td>
<td>≤220</td>
<td>≥6</td>
<td>14.8</td>
<td>≤2.5</td>
<td>0.18</td>
<td>≤0.98</td>
<td>≥0.02</td>
</tr>
</tbody>
</table>

The effect of the mixing of intruder state and ground state on the mean square radius of \(^{194},^{192}\text{Pb} \) relative to the spherical value is, taking the results from the deformed approach in table 1, \( 3 \times 10^{-3} \% \) and \( 6 \times 10^{-3} \% \), respectively. The observed deviation of \( \langle r^2 \rangle \) from the spherical droplet model is for \(^{192}\text{Pb} \) roughly of the order of 0.3\% [10] and thus cannot be explained by the mixing of the deformed intruder state into the spherical ground state.

We studied the fine structure of the \( \alpha \)-decay of \(^{198},^{196},^{194}\text{Po} \) by measuring \( \alpha-e^{-} \) coincidences on mass-separated sources. A summary of our results is given in fig. 2. Feeding to the first excited \( 0^+ \) intruder state has been observed. The half life of this intruder state in \(^{194},^{192},^{190}\text{Po} \) has been measured and by comparing the transition rate with theoretical estimates it has been possible to deduce the mixing between intruder state and ground state. Although the mixing increases as a function of decreasing neutron number and decreasing excitation energy of the intruder state,
the obtained mixing amplitudes cannot explain the deviations of the mean square radii of the involved Pb ground states from the droplet-model estimates.

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References

[13] P. Van Duppen et al., to be published.