$E3$ strength of the 11^- to 8^+ isomeric decays in ^{194}Pb and ^{196}Pb and oblate deformation

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(Received 19 July 2005; published 22 December 2005)

The $E3$ decays of the 11^- isomers in the isotopes ^{194}Pb and ^{196}Pb have been studied experimentally and evaluated in terms of configuration mixing due to the development of oblate deformation. New results include a remeasurement of the lifetime of the 11^- isomer in ^{194}Pb and clarification of the intensities of its main decay branches including the known 496 keV $E3$ branch. Its intensity is an order of magnitude weaker than previously reported, leading to an $E3$ transition strength of 29(4) W.u. Limits are placed on possible $E3$ decays of the 11^- isomer in ^{196}Pb to a previously assigned 8^+ two-proton state. Neither the branch, nor the state is observed. An alternative 562 keV transition to a new state at 2630 keV is proposed, with an $E3$ strength of 26(2) W.u. The approximately constant $E3$ strength for the range of even-even isotopes $^{190-196}$Pb is consistent with an oblate deformation for the 11^- state of similar magnitude. This is supported by K-constrained potential-energy-surface calculations for the 11^- and 8^+ configurations.

DOI: 10.1103/PhysRevC.72.064319 PACS number(s): 21.10.Tg, 21.10.Hw, 27.80.+w, 21.90.+f

I. INTRODUCTION

Recently we have reported [1] studies of the enhanced $E3$ decays from the 11^- isomers in the neutron-deficient isotopes, ^{190}Pb and ^{192}Pb. In the region of the periodic table near proton number $Z = 82$, specific proton and neutron orbitals couple strongly to the dominant collective mode, the octupole vibration, hence enhanced $E3$ transitions are common and well studied. However, the transitions under discussion here are nearly an order of magnitude more enhanced than expected given the nominal configurations of the 11^- and 8^+, initial and final states. As discussed in Ref. [1] with initial and final state configurations of $\pi[h_{9/2}i_{13/2}]_{(11^-)}$ and $[h^2_{9/2}]_{(8^+)}$, the $11^- \rightarrow 8^+$ transition corresponds in principle to an orbital change of $\pi i_{13/2} \rightarrow \pi h_{9/2}$, a spin-flip transition for which an $E3$ strength of 3–5 W.u. is expected—a type-B transition in the categorization of Ref. [2]. A strength of $\sim$20 W.u. would, in this region, normally be associated with a proton $i_{13/2} \rightarrow f_{7/2}$ configuration change, a stretched, or type-A transition [2]. This anomaly was interpreted [1], in the context of shape coexistence, as evidence that these states were oblate-deformed. It was proposed that the development of deformation induced mixing of the $f_{7/2}$ configuration into the lowest $h_{9/2}$ proton orbitals present in the 8^+ configuration, resulting in more enhanced $E3$ transitions from the 11^- isomer. This mechanism was also offered as an explanation for unexpectedly enhanced $E3$ transitions from 11^- isomers in the neutron-deficient Po isotones.

The question then arises as to whether the mass dependence of the decays in the Pb isotopes follows that observed for the light Po isotones and whether the dependence is consistent with the predictions for the onset of deformation. Towards this goal we report new results for ^{194}Pb ($N = 112$) and ^{196}Pb ($N = 114$), substantially extending the systematics, together with K-constrained potential-energy-surface calculations for a range of neutron-deficient Pb isotopes.

Independent experimental evidence for deformation for the 11^- isomers in ^{194}Pb and ^{196}Pb predicted in various calculations [3,4] includes static quadrupole moments [5] and somewhat indirectly, g-factor measurements [6]. Extensive rotational bands based on the isomers which would be evidence for well-developed deformation have not however, been observed, as discussed in Ref. [7].

Before the present measurements the experimental situation regarding the $E3$ transition moments for ^{194}Pb was similar to that which prompted our earlier re-measurement of ^{192}Pb [1]. That is, the lifetimes and γ-ray branching ratios reported in the literature [11] implied excessively large $E3$ transition strengths. The half-life of the 2933 keV, 11^- isomer had been reported as 124(10) ns and three branches had been observed, 305 and 352 keV $E1$ transitions to the yrast 12^+ and 10^+ states, and a 496 keV $E3$ transition to the 8^+ state. Fant *et al.* [8] gave relative intensities for the 305 and 352 keV transitions but they did not observe the $E3$ branch, whereas Kaci *et al.* [9] gave an intensity for the 496 keV $E3$ γ-ray branch which was equal to that of the 352 keV branch. Combination of these intensities with the reported lifetime leads to an $E3$ strength of 220(93) W.u. This very large value motivated our new measurements aimed at both a more precise lifetime and an independent measurement of the branching ratios.

In ^{196}Pb the 3191 keV, 11^- state has a reported half-life of 72(4) ns [mean-life of 104(7) ns] and decays by 498 and 548 keV $E1$ transitions to the yrast 12^+ and 10^+ states, respectively, however the relative intensity of these branches has not been reported precisely [10]. Quantitative limits on possible $E3$ decays to the known lower-lying 8^+ states have also not been given. The aim of the present measurements was therefore to confirm the lifetime and establish the branches,

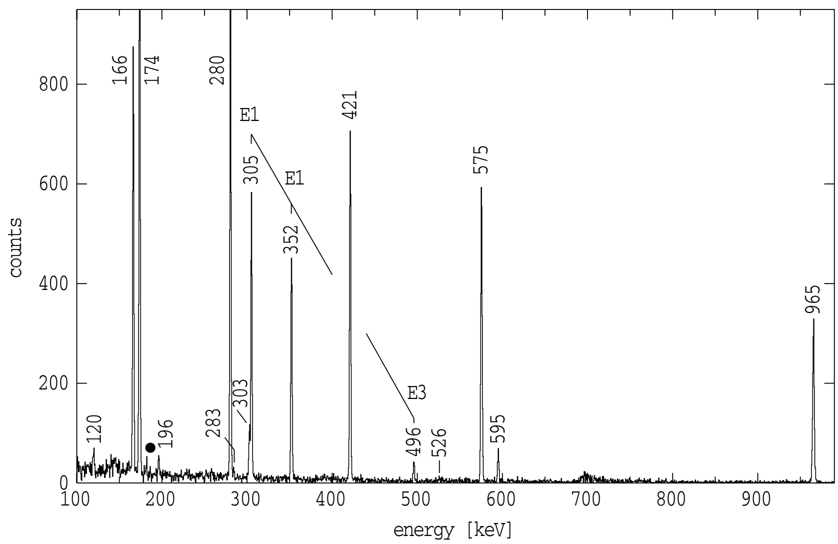

FIG. 1. Spectrum of transitions which follow the decay of the 11^- isomer in ^{194}Pb, produced by combining gates on the 364, 515, 542, 609, and 906, keV lines which feed the isomer. Contaminants are indicated by filled circles.

or at least limit their intensities, to a level which would be significant in terms of establishing the $E3$ systematics. (Note that in the subsequent discussion, mean-lives rather than half-lives are used and state and transition energies are quoted to the nearest keV unless the discussion warrants more precision.)

II. EXPERIMENTAL PROCEDURES AND RESULTS

Measurements for ^{194}Pb and ^{196}Pb were carried out using the CAESAR array in its standard form, comprising six Compton-suppressed Ge detectors and two small-volume planar detectors. In this system, individual time information for all detectors is recorded relative to the pulsed beams provided by the ANU 14UD Pelletron accelerator. The reactions used were ^{170}Er(^{29}Si,5n)^{194}Pb at 147 MeV and ^{170}Er(^{30}Si,4n)^{196}Pb at 138 MeV. Measurements included γ-time singles with optimized timing (slow rise-time rejection) for the detectors and pulsed beams with a time-width of $\sim$1 ns. and a pulse separation of 1.7 μs, as well as full γ-γ-time measurements. The target arrangement used was a 1.9 mg/cm^2 foil enriched in ^{170}Er with a Pb layer evaporated on the rear to stop recoiling nuclei.

The data analysis allowed the selection of time-correlated events with both relative time conditions between pairs of γ-rays and "absolute" time conditions selecting events within and between the beam pulses. This allowed the definitive isolation of transitions preceding and following specific isomeric states.

A. ^{194}Pb

Figure 1 shows the spectrum of γ-rays in ^{194}Pb in a 200 ns period directly after the beam pulse, gated on transitions which feed the 11^- isomer, to isolate the direct and subsequent decays from the 11^- isomer, with minimal contamination. This and similar spectra were analyzed to extract the γ-ray branching ratios from the 11^- and other isomers.

Evidence for previously unknown transitions was also sought. The spectrum in Fig. 1 clearly shows the 305, 352, and 496 keV transitions, with the 496 keV transition nearly an order of magnitude weaker, in contrast to the concensus of earlier results. The measured lifetime is 200(10) ns, slightly longer than that reported earlier. Gamma-ray intensities and the transitions strengths extracted are shown in Table I. All transitions in the spectrum of Fig. 1 are placed including the newly identified 526 keV transition which is just visible in this spectrum, but which is confirmed from other coincidence data. The 120 keV transition is in prompt coincidence with the main gating transitions above the isomer and appears weakly in this spectrum because of time-walk in the large-volume detectors.

A full analysis was also carried using γ-γ-time coincidences in the out-of-beam time region and early-delayed coincidences, as well the projection of intermediate time spectra to isolate the lifetimes of the numerous isomers in this nucleus, and to substantiate the decay paths. The partial level scheme of Fig. 2 incorporates several new decays: a weak 143 keV transition connects the 2581 keV 10^+ state to the (8^+) isomer at 2438 keV and a 106 keV transition is placed as a decay from the 7^- state at 2241 keV to the 2136 keV state. The total conversion coefficient obtained for

TABLE I. Branching ratios and transition strengths for the 11^- isomer in ^{194}Pb.

Initial state $J^{\pi,\tau}$	Final state J^π	E_γ (keV)	I_γ relative	$M\lambda$	α_T	$B(E\lambda)$ e^2 fm$^{2\lambda}$	Transition strength W.u.
11^-, 200(10) ns	12^+	305	48.2(14)	$E1$	0.029	$5.18(32)\times10^{-8}$	$2.40(15)\times10^{-8}$
	10^+	352	45.1(14)	$E1$	0.021	$3.16(20)\times10^{-8}$	$1.46(9)\times10^{-8}$
	8^+_1	496	5.7(6)	$E3$	0.102	$6.55(79)\times10^4$	29.3(35)
	9^-	526	1.1(3)	E2	0.026	$1.06(27)\times10^{-3}$	$1.59(40)\times10^{-5}$

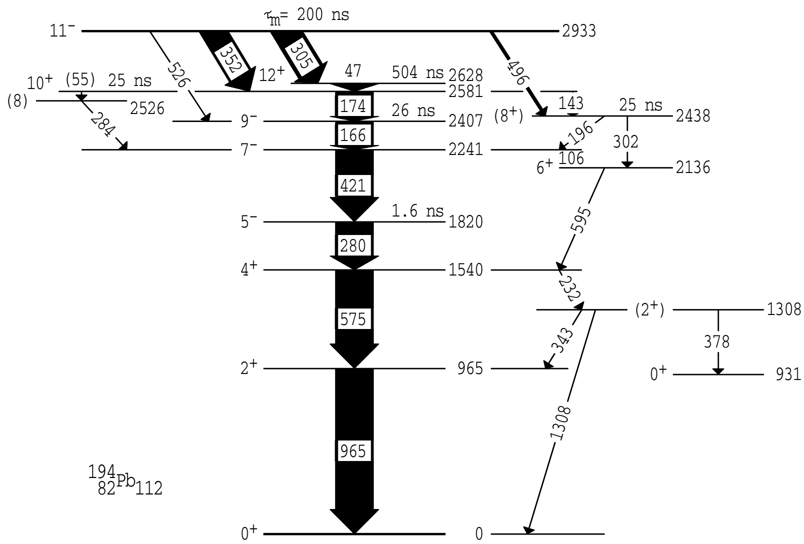

FIG. 2. Partial level scheme for ^{194}Pb and decay of the main isomers. Note that all transitions have been observed in the present work, adding to or confirming the previously known scheme, except for the 343 and 378 keV transitions from the 1308 keV 2^+ state. Mean lives are either from adopted values or in the case of the 11^- isomer, from a weighted mean of the present pulsed-beam and γ-γ-time measurements.

the 106 keV transition from delayed intensity balances is sufficient to assign $E1$ multipolarity and hence make the 6^+ assignment for 2136 keV state firm. The 284 keV transition feeding the 2241 keV state is confirmed but the coincidence data indicate there is a delayed path to the 2526 keV state via an unobserved 55 keV transition. The present lifetime analyses essentially confirm the previously measured lifetimes recorded in the most recent compilation [11] as derived from earlier measurements [12,13]. The only transitions we have not been able to substantiate directly are the 343 and 378 keV branches from the 1308 keV 2^+ state, but it is only populated indirectly via the weak 232 keV transition in the present work, whereas the branches were originally assigned [14] in decay studies in which the 1308 keV state is more strongly populated.

B. ^{196}Pb

Figure 3 is the spectrum of the transitions delayed with respect to the main transitions at 204, 546, and 855 keV feeding the 11^- isomer. The latter will show branches from the isomer and subsequent decays. The 107 keV line in this spectrum is from a known transition in the cascades above, that appears in this spectrum because of time-walk. As is apparent from this spectrum, the proposed 547 keV branch is considerably weaker than the main branch at 498 keV. (This disagrees with the published results of Singh *et al*. [15] but is in agreement with the unpublished work of Plompen [16].)

The partial decay scheme for ^{196}Pb given in Fig. 4 contains the new decays assigned here including a proposed $11^- \rightarrow 8^+$ transition to be discussed below. There is a weak branch identified at 884 keV from the 11^- isomer to the 9^- yrast state at 2308 keV. Possible direct $E3$ branches from the 11^- isomer to previously assigned states would fall at 601 keV for a decay to the 8^+ state at 2591 keV, and 570 keV to the (8^+) state assigned at 2622 keV. The 601 keV transition is unfortunately close to the broad 596 keV ^{74}Ge (n, n') line and hence we can only quote a limit on its intensity, but nevertheless, as is apparent from this spectrum, it can only be weak compared to the 562 keV transition which is clearly visible in the spectrum. Furthermore, no evidence is seen for a 601 keV transition,

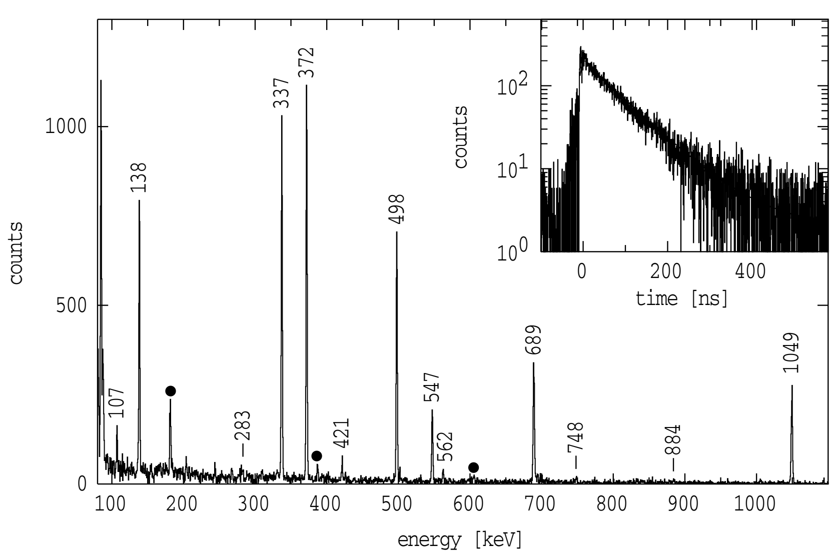

FIG. 3. Spectrum of transitions delayed with respect to γ-rays feeding the 11^- isomer in ^{196}Pb. Contaminants are indicated by filled circles. The inset shows a representative time spectrum from the pulsed-beam data, with a gate on the 498 keV γ-ray.

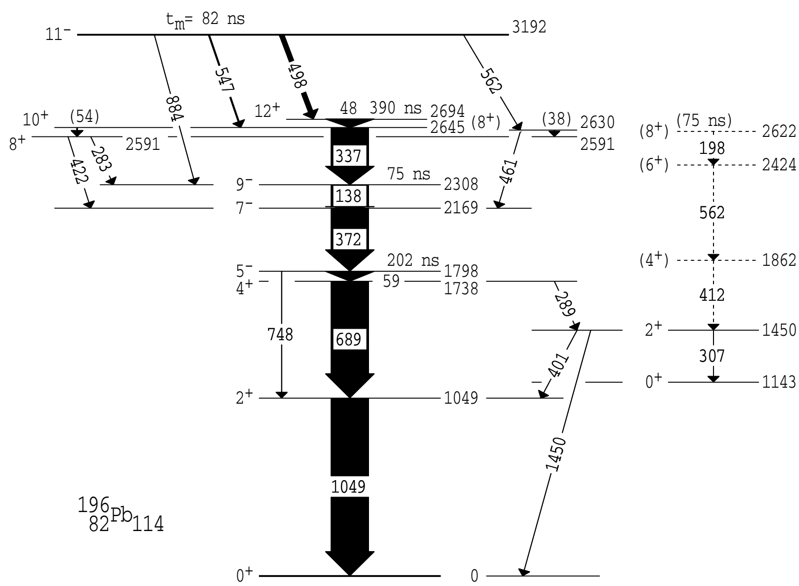

FIG. 4. Partial level scheme for ^{196}Pb and decay of the main isomers. Note that all transitions have been observed in the present work, adding to or confirming the previously known scheme, except for the proposed 8^+ isomer at 2622 keV and the cascade transitions indicated as dashed lines. Mean lives are either from adopted values or, in the case of the 11^- isomer, from the present measurement.

either in the out-of-beam gates on the decays from the 2591 keV state at 283 and 422 keV, or in the gate on the subsequent 372 keV transition.

The weak γ-ray at 572 keV is assigned to a contaminant rather than to an expected 570 keV branch and there is no evidence of the subsequent decays from the 2622 keV state. This is worthy of further comment since the 2622 keV state, which has an assigned lifetime of 75 ns, has only been observed in a single study [17]. This isomer was associated with the expected 8^+ state from the $\pi h^2_{9/2}$ configuration and its reported decay path, as shown on the right of the level scheme (Fig. 4) was via a 198 keV transition feeding 562 keV and 412 keV cascade transitions proposed to form the upper part of a collective band based on the 1143 keV 0^+_2 deformed (oblate) intruder state.

The present measurements are particularly sensitive to isomeric decays in this time region, but as can be seen from the sum of gates on the main decays from the 1450 keV, 2^+_2 state in the out-of-beam time region, shown in Fig. 5, none of the higher band members are observed. This implies that there is no direct population of the 2622 keV isomeric state, and (as indicated above), no significant population of it via the 11^- isomer. The former is surprising since, while the 2622 keV state would be nonyrast, it is not very far from the yrast line, and other nonyrast states are clearly populated. The only members of the previously proposed oblate band observed in the present work (either in prompt or delayed coincidence) are the 1143 keV 0^+_2 state and the 1450 keV 2^+_2 state. To our knowledge, the transitions of energy 412 keV and 562 keV in the proposed 0^+_2 band, and the 8^+ isomer itself, have only been observed in the original study of Penninga *et al.* [17]. That study used the ^{198}Hg$(\alpha, 6n)$ reaction and identified the γ-ray transitions in coincidence with conversion electrons from the 0^+_2-state decay.

The newly observed 562.3 keV transition is placed, on the basis of a variety of coincidence data, as a direct branch from the 11^- isomer to a new state 2629.9 keV, with branches via a 460.5 keV transition to the 7^- state at 2169.4 keV and an unobserved 38 keV transition to the 2591 keV 8^+_1 state. We propose the 2629.9 keV state as an alternative candidate for the 8^+ state from the $\pi h^2_{9/2}$ configuration. The 460.5 keV line and the decays from the 2591 keV state are seen in Fig. 5. Although the intensities are low, the information from the intermediate time spectrum with gates on the 562 and 422 keV transitions (the main decay path) indicate a lifetime of $\sim$12 ns, which in principle corresponds to the combination of lifetimes of the 2591 keV state and the new 2630 keV state. The proposition that the 38 keV transition is of $M1$ character and competes with the 461 keV $E1$ transition is consistent with the transition strengths implied if the 12 ns lifetime is attributed to the 2630 keV state, these strengths being $\sim 3 \times 10^{-8}$ W.u. for the $E1$ transition and $\sim 1.3 \times 10^{-3}$ W.u. for the 38 keV $M1$ transition. Even if the lifetime was shorter it is clear that the $M1$ path is competitive, although it might appear surprising at first sight. The only other plausible spin/parity assignment is 9^- and that would involve an unacceptably large strength for a 38 keV $E1$ transition, competing with a 461 keV E2.

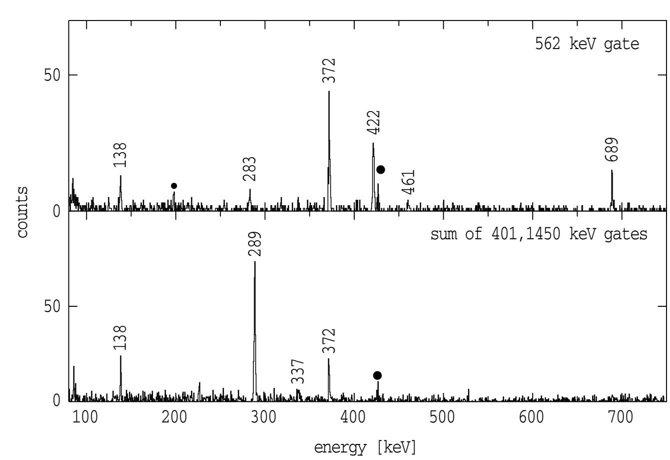

FIG. 5. γ-γ coincidence spectra in the out-of-beam time region with gates as indicated.

TABLE II. Branching ratios and transition strengths for the 11^- isomer in ^{196}Pb.

Initial state $J^{\pi,\tau}$	Final state J^{π}	E_γ (keV)	I_γ relative	$M\lambda$	α_T	$B(E\lambda)\ e^2\ \mathrm{fm}^{2\lambda}$	Transition strength W.u.
11^-, 82(4) ns	12^+	498	68.5(11)	$E1$	0.0097	$4.20(22)\times10^{-8}$	$1.93(10)\times10^{-8}$
	10^+	547	24.5(8)	$E1$	0.021	$1.13(7)\times10^{-8}$	$0.52(3)\times10^{-8}$
	8_2^+	562[a]	5.0(4)	$E3$	0.0695	$5.94(56)\times10^{4}$	26.1(24)
	8_1^+	[601	<1.6	$E3$	0.059	$<1.2\times10^{4}$	<5.1][b]
	9^-	884	2.1(3)	E2	0.009	$3.7(6)\times10^{-4}$	$5.5(8)\times10^{-6}$

[a]Transition to the newly assigned state at 2630 keV.
[b]Transition excluded in the calculation of the other strengths.

The branching intensities (and some limits) on decays from the 11^- isomer are given in Table II together with the transitions strengths extracted.

As well as the decays from the 11^- isomer, the present results also indicate that there is a weak branch from the 12^+ isomer, presumably via the 10^+ state below, to the 2591 keV, 8^+ state, implying another unobserved low-energy transition at 54 keV. Its total intensity is about 0.7% of the 337 keV branch from the 10^+ state.

Comparing the ^{194}Pb and the new ^{196}Pb schemes, the interpretation is that the 8^+ state at 2526 keV in ^{194}Pb is from the $i_{13/2}^{-2}$ neutron-hole multiplet consistent with the feeding from the 10^+ yrast state from the same multiplet, while the lower 8^+ state is from the two-proton, two-hole excitation. In ^{196}Pb, the situation is reversed with the neutron-hole state falling lower as the proton excitations (11^- and 8^+) rise in energy with increasing neutron number.

III. OBLATE DEFORMATION AND ORBITAL MIXING

Although a detailed calculation of $E3$ strengths in a deformed system is outside the scope of the present work, an estimate of the effects expected can be given through a simple mixing model in terms of the $i_{13/2}\to h_{9/2}$ and $i_{13/2}\to f_{7/2}$ components and the respective $h_{9/2}$ and $f_{7/2}$ amplitudes (α and β) in the 11^- configuration. In that case,

$$\begin{aligned} B(E3;11^-\to 8^+) = \frac{17}{23}\times\frac{14}{10}\Bigg\{&\alpha\sqrt{2}U\left(\frac{9}{2},\frac{13}{2},8,3,11,\frac{9}{2}\right)\\ &\times\sqrt{B(E3;i_{13/2}\to h_{9/2})}\\ &+\beta U\left(\frac{9}{2},\frac{13}{2},8,3,11,\frac{7}{2}\right)\\ &\times\sqrt{B(E3;i_{13/2}\to f_{7/2})}\Bigg\}^2, \end{aligned}$$

where the U-factors are normalized Racah coefficients.

Taking the values of 3 W.u. and 22 W.u. identified by Bergstrom and Fant [2] as representative of typical spin-flip and non-spin-flip components, the expected strength (in W.u.) is given by

$$\begin{aligned} M(E3,11^-\to 8^+) \approx{}& [\alpha(h_{9/2})\times 0.632\sqrt{3}\\ &+\beta(f_{7/2})\times 1.0\sqrt{22}]^2 \end{aligned}$$

when numerical factors for the angular momentum coupling coefficients are substituted.

Use of the $h_{9/2}$ and $f_{7/2}$ amplitudes from a representative Nilsson model calculation results in the deformation dependence given in Fig. 6. This illustrates the arguments put forward earlier regarding the effect of mixing in of the $f_{7/2}$ orbital as oblate deformation develops [1]. Note however that the particle-vibration coupling which gives rise to the enhanced strengths associated with specific orbitals may be modified in the presence of deformation, hence this is necessarily a simplistic approach, not appropriate for a quantitative comparison.

IV. PES CALCULATIONS

Calculations to predict the deformations of the 11^- and 8^+ configurations for range of even-even Pb isotopes from $A = 190$–196 were carried out using the method of K-constrained diabatic potential-energy surfaces [18,19]. The calculations were performed within the nonaxial deformed Woods-Saxon potential with approximate particle-number projection achieved using the Lipkin-Nogami prescription. The results for the lower and upper extremes in mass are shown in Fig. 7.

In all cases, well-defined minima were obtained for both 11^- and 8^+ configurations. The calculated excitation energies and deformations for the intrinsic states in the even-even isotopes $^{190-196}$Pb are given in Table III. Comparison of calculated excitation energies with those observed experimen-

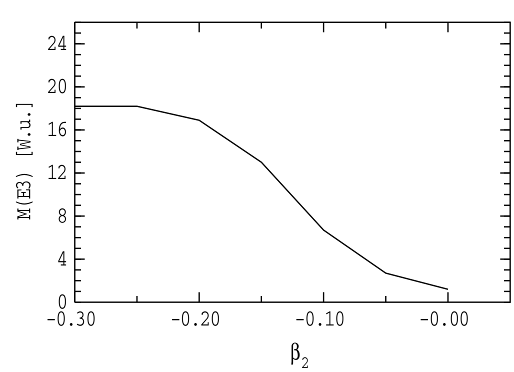

FIG. 6. Estimates of the $E3$ strengths for the 11^- to 8^+ transition in a simple mixing model, as a function of oblate deformation in a typical Pb nucleus.

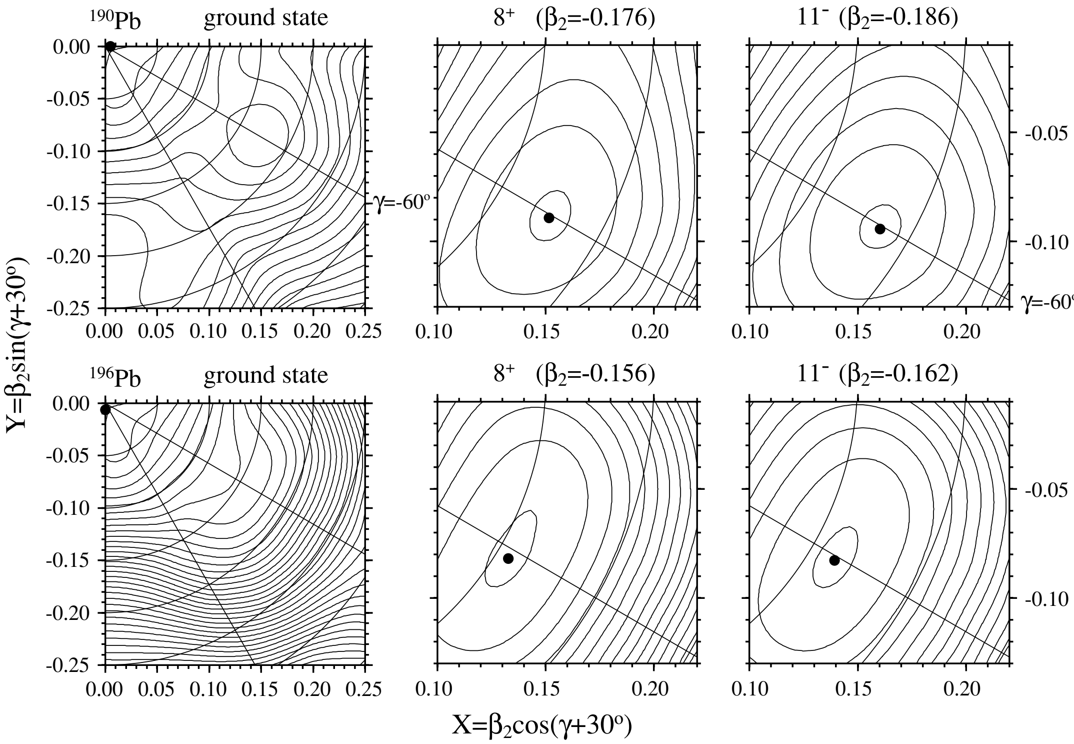

FIG. 7. Potential energy surfaces (PES) for the ground states and $K^{\pi} = 8^{+}$ and 11^{-} states in ^{190}Pb and ^{196}Pb. Note that a different scale is used for the ground state and isomeric surfaces. Minima are indicated by black dots and the contour separation is 200 keV.

tally shows a similar level of agreement for both 11^{-} states and 8^{+} states, with only a small (∼50 keV) discrepancy in absolute excitation energy in ^{190}Pb, increasing to ∼300 keV in ^{196}Pb. The predicted deformations only vary slightly across the isotopes, with a marginally smaller deformation for the 8^{+} configurations compared to the 11^{-} cases.

In contrast, equivalent calculations for the Po isotopes do not in general, produce such well-defined potential minima (a result also of other calculations, see for example Ref. [4]) largely because the two-proton excitation in the Pb cases results in proton-holes which assist in driving the deformation, whereas in the Po cases, the protons already occupy valence orbitals. Recent calculations do suggest that while there are ambiguities in the heavier Po isotopes, the deformation in the lighter isotopes may be better defined [4].

V. DISCUSSION

As indicated in the introduction, recent measurements of magnetic moments confirm the two-proton two-hole assignment to the 11^{-} isomers in ^{194}Pb and ^{196}Pb [6]. In both cases we have now also observed $E2$ transitions to the 9^{-} states, with strengths of only 1.6×10^{-5} W.u. in ^{194}Pb and 0.6×10^{-5} W.u. in ^{196}Pb. These very low values are consistent with the large configuration change, the 9^{-} states being predominantly from the $2f_{5/2}^{-1}1i_{13/2}^{-1}$ two-neutron configuration [6].

The major focus of this study however, is the apparently anomalous behavior of $11^{-} \rightarrow 8^{+}$ $E3$ strengths in the light Pb and Po isotopes. With nominal configurations of $\pi[h_{9/2}i_{13/2}]_{(11^{-})}$ and $[h_{9/2}^{2}]_{(8^{+})}$, (suppressing the two-proton

TABLE III. Calculated deformations and energies for 11^{-} and 8^{+} two-proton states in $^{190-196}$Pb. The γ-deformations are predicted to be neglible.

Nuclide	11^{-}				8^{+}			
	β_2	β_4	E (calc.) (MeV)	E (exp.)	β_2	β_4	E (calc.) (MeV)	E (exp.)
^{190}Pb	−0.186	0.003	2.71	2.659	−0.176	−0.006	2.31	2.252
^{192}Pb	−0.179	−0.003	2.95	2.743	−0.171	−0.012	2.49	2.304
^{194}Pb	−0.170	−0.009	3.23	2.933	−0.163	−0.017	2.70	2.437
^{196}Pb	−0.162	−0.013	3.51	3.192	−0.156	−0.021	2.92	2.622

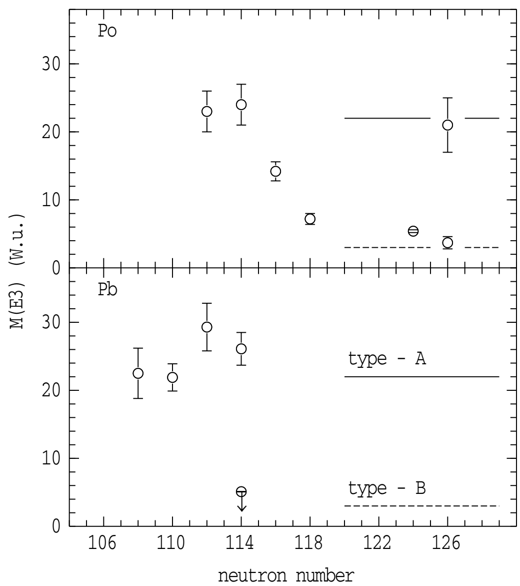

FIG. 8. $E3$ strengths for the 11^- to 8^+ transition in the light Po and Pb isotopes as a function of neutron number. The limit at $N = 114$ in the lower panel corresponds to the 601 keV transition in ^{196}Pb. Two transitions of different character are known for ^{210}Po [21]. Values for other Po nuclei are extracted from the experimental data; ^{208}Po; [22], ^{202}Po; [23,24], ^{200}Po; [25], ^{198}Po; [26,27]. ^{196}Po; [28]. The value for ^{190}Pb has been corrected for specific mixing.

hole component) the $E3$ transition corresponds to an orbital change of $\pi i_{13/2} \rightarrow \pi h_{9/2}$, a spin-flip transition which would imply an $E3$ strength of 3–5 W.u. Strengths of ~20 W.u. would normally be associated with a proton $i_{13/2} \rightarrow f_{7/2}$ configuration change [2] in this region.

In contrast, in the spherical nuclei near the neutron closed shell, these transition strengths are well understood. For example, in the $N = 126$ case of ^{210}Po, $E3$ transitions to each of the competing 8^+ configurations results in the observation of one weak transition to the lower state and a strong transition to the upper state, with strengths which can be reproduced in detail by octupole-vibration-coupled shell-model calculations [20]. The 8^+ state from the $h_{9/2} f_{7/2}$ configuration is considerably higher in energy and mixing of the two configurations is small. This will remain the expectation in spherical translead nuclei until sufficient valence protons are present to give significant population of the $f_{7/2}$ orbital, a situation that will obtain only well above $Z = 82$.

The $11^- \rightarrow 8^+$, $E3$ strengths for the Po and Pb cases are illustrated as a function of neutron number, in Fig. 8, including both $E3$ transitions known in ^{210}Po, the new results obtained here for ^{194}Pb and ^{196}Pb, and the approximate strengths observed for type-A and type-B transitions [2]. (Compare Fig. 4 in Ref [1].)

No points are shown for ^{204}Po and ^{206}Po since the 11^- decays in those cases, bypass the 8^+ state. Also, a possible 11^- isomer was recently identified in the $N = 110$ isotope ^{194}Po by Helariutta *et al*. [29] with a tentative $E3$ decay of 459 keV to a nonyrast 8^+ state, possibly the 8^+ state from the nominal $h_{9/2}^2$ configuration. The measured half-life of 15(2) μs would correspond to an $E3$ strength of 7.4(10) W.u., which would be a distinct drop from the strengths found in the heavier isotopes, however the experimental situation is uncertain, and needs to be clarified.

As discussed previously [1], the rise in strength in the light Po studies was recognized as anomalous [26,28] and could not be explained by either admixtures of the spherical proton $h_{9/2} f_{7/2}$ configuration into the lower 8^+ state, or by invoking increased octupole collectivity that might occur if the *neutron* shell were depleted sufficiently to involve both $i_{13/2}$ and $f_{7/2}$ neutron holes. In the latter case extensive calculations [30,31] do not predict significant ground-state octupole effects until much lower neutron numbers. Specific PES calculations by Wyss [32], for the 11^- and 8^+ configuration in the Pb isotopes also do not show significant octupole susceptibility.

The alternative explanation proposed in our previous work [1] and reiterated here is that the development of oblate deformation automatically results in the hybridization of the Nilsson orbitals, inducing a significant $f_{7/2}$ component into the 8^+ configuration. A number of earlier calculations predicted that the 11^- states (and by implication the 8^+ two-proton states) would become oblate in shape as neutrons are removed (see Ref. [3] for example), consistent with excitation of protons into the downward sloping Nilsson orbitals originating in the $i_{13/2}$ and $h_{9/2}$ proton spherical shells.

In terms of deformed orbitals, the 11^- isomer has the Nilsson configuration $13/2^+[606] \otimes 9/2^-[505]$, while the 8^+ state would be $7/2^-[514] \otimes 9/2^-[505]$. The $13/2^+[606]$ orbital remains predominantly of $i_{13/2}$ parentage with deformation, however, the $7/2^-[503]$ orbital from the higher-lying $f_{7/2}$ spherical configuration mixes with the $7/2^-[514]$ orbital (which emanates from the $h_{9/2}$ shell at sphericity) and essentially exchanges character, as shown in detail in Ref. [1]. At quadrupole deformations of ~ -0.2,the lower $7/2^-$ orbital can have the $f_{7/2}$ configuration as the dominant component, the precise amplitudes depending somewhat on the form of the potential used.

It was noted previously that the rise in the transition strengths in the lighter Po isotopes may parallel the onset of oblate deformation although such a transition is not well defined. However, as shown earlier, the present calculations for the Pb isotopes predict well-defined and similar deformation for all 11^- states in the range $^{190-196}$Pb and a similar, constant, deformation for the 8^+ states. Insertion of the $h_{9/2}$ and $f_{7/2}$ amplitudes from those calculations in the simple formulation given earlier, not surprisingly, results in an essentially constant value of ~16 W.u. for the range of isotopes studied. The new results for ^{196}Pb and ^{194}Pb, the latter of which includes the new assignment for the 8_2^+ state, bear out this prediction in qualitative terms, the $E3$ strengths being approximately constant within errors, across the full range of isotopes from $^{190-196}$Pb.

The 11^- intrinsic states are observed at their lowest energy with respect to the yrast line in ^{190}Pb and they occur at progressively higher excitation energy as neutrons are added. Presumably because such states become increasingly more weakly populated, the equivalent 11^- state has not been identified in ^{198}Pb or the heavier isotopes. It is unlikely therefore that the present systematics can be extended to neutron numbers as high as has been reached in the Po isotopes.

VI. SUMMARY AND CONCLUSIONS

A detailed study of the lifetimes and decay branches of the 11^- isomers in ^{194}Pb and ^{196}Pb has been carried out, with a focus on the expected $E3$ branches to 8^+ intrinsic states. Anomalies with respect to previously reported branching intensities in ^{194}Pb have been resolved and a strength of 29(4) W.u. established. $E3$ branches to previously known 8^+ states in ^{196}Pb have not been observed but an $E3$ decay to a new state at 2630 keV is proposed, with a deduced strength of 26(2) W.u. This casts some doubt on the previous assignments of a two-proton isomeric 8^+ state at 2622 keV. The enhanced $E3$ strengths are interpreted as evidence for admixtures of the $\pi h_{9/2} f_{7/2}$ configuration into what is notionally the $\pi h_{9/2}^2$, 8^+ state known in the spherical Pb isotopes, a mixing which can be taken as a signature of the development of a moderate but stable oblate deformation in both 11^- and 8^+ intrinsic states, driven by two-proton excitations across the $Z = 82$ shell.

ACKNOWLEDGMENTS

We would like to thank the staff of the Heavy Ion Accelerator Facility for their support and particularly Bob Turkentine for target preparation. Ramon Wyss provided valuable input on the possibility of a general octupole susceptibility. This work is supported in part by the Australian Research Council, Discovery project DP0343027.

[1] G. D. Dracoulis, T. Kibédi, A. P. Byrne, A. M. Baxter, S. M. Mullins, and R. A. Bark, Phys. Rev. C **63**, 061302(R) (2001).
[2] I. Bergström and B. Fant, Phys. Scripta **31**, 26 (1985).
[3] R. Bengtsson and W. Nazarewicz, Z. Phys. A **334**, 269 (1989).
[4] N. A. Smirnova, P.-H. Heenen, and G. Neyens, Phys. Lett. **B569**, 151 (2003).
[5] K. Vyvey, D. Borremans, N. Coulier, R. Coussement, G. Georgiev, S. Teughels, G. Neyens, H. Hubel, and D. L. Balabanski, Phys. Rev. C **65**, 024320 (2002); K. Vyvey *et al.*, Phys. Rev. Lett. **88**, 102502 (2002); K. Vyvey, D. L. Balabanski, and G. Neyens, Eur. Phys. J. A **22**, 1 (2004).
[6] K. Vyvey, G. D. Dracoulis, A. N. Wilson, P. M. Davidson, A. E. Stuchbery, G. J. Lane, A. P. Byrne, and T. Kibédi, Phys. Rev. C **69**, 064318 (2004).
[7] G. D. Dracoulis, G. J. Lane, A. P. Byrne, T. Kibédi, A. M. Baxter, A. O. Macchiavelli, P. Fallon, and R. M. Clark, Phys. Rev. C **69**, 054318 (2004).
[8] B. Fant *et al.*, J. Phys. G: Nucl. Part. Phys. **17**, 319 (1991).
[9] M. Kaci *et al.*, Nucl. Phys. **A697**, 3 (2002).
[10] Z. Chunmei, W. Gongqing, and T. Zhenlan, Nucl. Data Sheets **83**, 145 (1998).
[11] E. Browne and B. Singh, Nucl. Data Sheets **79**, 277 (1996).
[12] J. J. Van Ruyven, J. Penninga, W. H. A. Hesselink, P. Van Nes, K. Allaart, E. J. Hengeveld, H. Verheul, M. J. A. de Voigt, Z. Sujkowski, and J. Blomqvist, Nucl. Phys. **A449**, 579 (1986).
[13] M. Pautrat, J. M. Lagrange, A. Virdis, J. S. Dionisio, Ch. Vieu, and J. Vanhorenbeeck, Phys. Scripta **34**, 378 (1986).
[14] P. Van Duppen, E. Coenen, K. Deneffe, M. Huyse, and J. L. Wood Phys. Rev. C **35**, 1861 (1987).
[15] A. K. Singh *et al.*, Nucl. Phys. **A707**, 3 (2002).
[16] A. J. M. Plompen, "Collective and quasiparticle excitations in light Pb Isotopes" Academisch Proefschrift, Vrije Universiteit te Amsterdam, 1993, (unpublished).
[17] J. Penninga, W. H. A. Hesselink, A. Balanda, A. Stolk, H. Verheul, J. van Klinken, H. H. Riezebos, and M. J. A. de Voigt, Nucl. Phys. **A471**, 535 (1987).
[18] F. R. Xu, P. M. Walker, J. A. Sheikh, and R. Wyss, Phys. Lett. **B435**, 257 (1998).
[19] F. R. Xu, Chin. Phys. Lett. **18**, 750 (2001).
[20] A. E. Stuchbery, A. P. Byrne, G. D. Dracoulis, B. Fabricius, and T. Kibédi, Nucl. Phys. **A555**, 355 (1993).
[21] L. G. Mann, K. H. Maier, A. Aprahamian, J. A. Becker, D. J. Decman, E. A. Henry, R. A. Meyer, N. Roy, W. Stoffl, and G. L. Struble, Phys. Rev. C **38**, 74 (1988).
[22] A. R. Poletti, G. D. Dracoulis, A. P. Byrne, A. E. Stuchbery, B. Fabricius, T. Kibédi, and P. M. Davidson, Nucl. Phys. **A615**, 95 (1997).
[23] B. Fant, T. Weckström, and A. Källberg, Phys. Scripta. **41**, 652 (1990).
[24] O. Häusser *et al.*, Nucl. Phys. **A273**, 253 (1976).
[25] T. Weckström, B. Fant, T. Lönnroth, V. Rahkonen, A. Källberg, and C.-J. Herrlander, Z. Phys. A **321**, 231 (1985).
[26] A. Maj *et al.*, Z. Phys. A **324**, 123 (1986).
[27] A. Maj, H. Grawe, H. Kluge, A. Kuhnert, K. H. Maier, J. Recht, N. Roy, H. Hübel, and M. Guttormsen, Nucl. Phys. **A509**, 413 (1990).
[28] D. Alber *et al.*, Z. Phys. A **339**, 225 (1991).
[29] K. Helariutta *et al.*, Eur. Phys. J. A **6**, 289 (1999).
[30] G. A. Leander, R. K. Sheline, P. Möller, P. Olanders, I. Ragnarsson, and A. J. Sierk, Nucl. Phys. **A388**, 452 (1982).
[31] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[32] R. Wyss (private communication).