On the character of three 8^+ states in ^{192}Pb

A.N. Wilson^{1,2,a}, M.C. East¹, G.D. Dracoulis¹, A.P. Byrne^{1,2}, R.M. Clark³, P.M. Davidson^{1,b}, P. Fallon³, A. G3rgen^{3,c}, G.J. Lane¹, A.O. Macchiavelli³, and D. Ward³

¹ Department of Nuclear Physics, Research School of Physics and Engineering, Australian National University, Canberra, ACT 0200, Australia

² Department of Physics, Australian National University, Canberra, ACT 0200, Australia

³ Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Received: 27 October 2009 / Revised: 29 November 2009

Published online: 9 January 2010 – © Societ3 Italiana di Fisica / Springer-Verlag 2010

Communicated by B. Ananthanarayan

Abstract. Three low-lying 8^+ states have been identified in ^{192}Pb . A newly observed cascade of γ -rays built directly on the 8_1^+ state is compared to the previously identified, weakly rotational band above the $11^- \pi i_{13/2}$, $h_{9/2}$ isomer in the same nucleus, and to analogous structures in ^{194}Pb . The similarity of all four structures lends support to the suggestion that the 8_1^+ configurations are of a similar oblate deformation to the 11^- isomers. The excitation energies of all three 8^+ states in ^{192}Pb and ^{190}Pb are compared to systematics. The possibility that one of the 8^+ states in ^{192}Pb is associated with a prolate shape is discounted.

1 Introduction

The evolution with decreasing neutron number of both the shapes and single-particle configurations of excited states in neutron-deficient Pb isotopes has been the focus of a great deal of attention, both theoretically and experimentally, over the last two decades (see for example [1–5] and references therein). Between the spherical region around the $N = 126$ closed shell and the well-deformed region around $N = 104$ lies a transitional region where the nuclear shape depends sensitively on both the position of the neutron Fermi surface and the details of the nuclear mean field. Clear evidence for the coexistence at low energies and low angular momenta of spherical, oblate and prolate shapes has been observed in Pb isotopes with $104 \leq N \leq 108$ [6–9]. In the region with $110 \leq N \leq 116$, the low-lying states are dominated by spherical and oblate configurations [10–13]. The systematic changes in the relative energies and depths of these minima with decreasing neutron number provide a sensitive test of nuclear models.

The present work focuses on low-lying 8^+ excitations in ^{192}Pb , and uses them as a probe to further investigate the structure of Pb isotopes with $108 \leq N \leq 112$.

1.1 8^+ states in neutron-deficient Pb isotopes

In the spherical shell model, the lowest energy 8^+ state in Pb nuclei close to but below the $N = 126$ shell closure is formed by the coupling of two holes in the $\nu i_{13/2}$ orbital. As the neutron Fermi surface moves further from the shell closure, the possibility of yrast and near-yrast deformed states introduces further mechanisms for the generation of 8^+ states, including proton excitations and collective motion. Two low-lying 8^+ states have been identified in the nuclei ^{196}Pb [14,15], ^{194}Pb [14,16,17] and ^{192}Pb [10,11,18]. In each case, one of the 8^+ states has been interpreted as the 8^+ member of the $\nu i_{13/2}^{-2}$ multiplet associated with a spherical or near spherical shape. While the other 8^+ state was originally also interpreted as a spherical shell model $\pi h_{9/2}^2$ state, Dracoulis *et al.* have argued that the otherwise anomalously strong $E3$ transition from the 11^- , $\pi i_{13/2}$, $h_{9/2}$ isomeric state to these states indicates a mixed $\pi(h_{9/2}f_{7/2})^2$ wave function and hence significant oblate deformation [14,18].

When the neutron Fermi level reaches the lower half of the $i_{13/2}$ sub-shell, the Pb isotopes start to exhibit pronounced prolate deformations at very low excitation energies, which compete favorably with oblate shapes at non-zero spin. Only one 8^+ state, a member of a collective rotational band associated with a prolate shape, has been identified in Pb isotopes with $N < 106$ [19–21]. The 8_1^+ and 8_2^+ states observed in the $N = 106$ nucleus ^{188}Pb are interpreted as associated with predominantly prolate and predominantly oblate shapes, respectively [7].

^a e-mail: Anna.Wilson@anu.edu.au

^b Present address: Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia.

^c Present address: CEA Saclay, DAPNIA/SPhN, Bat. 703, l’Orme des Merisiers, F-91191 Gif-sur-Yvette, France.

The $N = 108$ isotope ^{190}Pb has until now represented a unique case in the Pb isotopes in which three 8^+ states have been firmly identified below 3.2 MeV [9]. These states have been interpreted as arising from the interference of three coexisting shape minima, with the 8_1^+ and 8_2^+ states assigned strongly mixed oblate and spherical wave functions and the 8_3^+ state thought to be a member of a prolate rotational band.

In the present work, we report on the observation of a third low-lying 8^+ state in the $N = 110$ isotope ^{192}Pb and discuss the character of the three 8^+ states in both ^{192}Pb and ^{190}Pb .

1.2 Previous studies of low- and intermediate-spin near-yrast levels in ^{192}Pb

There have been several studies of the structure of ^{192}Pb . Most pertinent to the present analysis are those of the yrast and near-yrast states at low to intermediate spins carried out by Lagrange *et al.* [10], Plompen *et al.* [11] and Dracoulis *et al.* [18,22].

Lagrange *et al.* observed states up to $I \approx 12\hbar$ and $E = 2743$ keV. Three isomers were identified, at excitation energies of 2581, 2625 and 2743 keV, to which spins and parities of 10^+ , 12^+ and $(10^-, 11^-)$ were assigned, respectively. In addition to this, spin and parity $I^\pi = 8^+$ were firmly assigned to a state at 2521 keV and tentatively assigned to a lower-energy state at 2304 keV. The precise lifetime measurements subsequently made by Dracoulis *et al.* [18,22] resulted in significantly revised mean lives for the three isomers of $\tau_{10^+} = 236(10)$ ns, $\tau_{12^+} = 1.6$ μs and $\tau_{11^-} = 1.09(3)$ μs , as well as a firm assignment of 11^- to the state at 2743 keV.

Plompen *et al.* [11] extended the level scheme to higher spins, including structures built on each of the three isomers. Most importantly for the present work, they confirmed the previously tentative assignment of $I^\pi = 8^+$ to the state at 2304 keV and identified an additional state at 2562 keV which directly fed the 6^+ state via a 641 keV transition, to which they assigned no spin or parity. This state was also observed in recent work by Dracoulis *et al.* [22], where it was found to be fed following the decay of the 10^+ isomeric state. This implied the presence of an unobserved 19 keV transition connecting the state to the 10^+ isomer, and suggested a tentative assignment of $I^\pi = (8^+)$.

2 Experimental details

The experiment was carried out using the Gammasphere array at Lawrence Berkeley National Laboratory. High-spin states in ^{192}Pb were populated in the reaction $^{168}\text{Er}(^{29}\text{Si}, 5n)^{192}\text{Pb}$. The target consisted of a 1.1 mg/cm² layer of ^{168}Er on a 5 mg/cm² Pb backing. The beam was provided by the 88" Cyclotron at an energy of 154 MeV. The frequency of the cyclotron was 15.5 MHz, resulting in a pulsed beam structure with a pulse separation of 64.5 ns. An event was accepted when, after Compton suppression,

Fig. 1. The spectrum of transitions in delayed coincidence with the 162 keV transition.

signals were obtained from at least 4 of the 102 Ge detectors in the array. The time of detection (relative to the RF pulse of the cyclotron) was recorded as well as the energy of each γ -ray in an event. The experimental set-up allowed γ -rays to be detected and correlated up to ≈ 800 ns after any particular beam pulse. Data were collected for 3 days, during which time 1.5×10^9 events were recorded.

3 Results

The presence of the three known isomers in the decay of ^{192}Pb allows the use of time-correlated γ -ray spectroscopy to select subsets of the data following population of excited states in a fusion reaction. The results of the present work rely on two such subsets: i) states populated following the decay of the 10^+ isomer at 2581 keV, and ii) states which decay via prompt paths to the ground state, bypassing all isomers.

3.1 The 8_3^+ state

The previously known inter-isomeric $11^- \rightarrow 10^+$ 162 keV transition, which carries approximately 95% of the γ -ray intensity feeding the 10^+ state, provides an efficient and clean gate with which to isolate decays following this isomer.

Figure 1 shows the spectrum of transitions in delayed coincidence with the 162 keV $11^- \rightarrow 10^+$ inter-isomeric transition, with an additional requirement that the 162 keV transition was itself delayed relative to the beam pulse by between 20 and 775 ns. The γ -rays in the spectrum are those which have been detected in a period 30–775 ns after the gating transition. This spectrum provides a detailed picture of the paths connecting the 10^+ isomer and the ground state. The presence of a small peak at 641 keV confirms the feeding of the state de-excited by this transition following the decay of the 10^+ isomer [22].

The observed 641 keV transition and the inferred 19 keV transition must carry a total of four units of angular momentum. Although the assignment of electric

Fig. 2. The spectrum of transitions in prompt coincidence with both the 641 keV $8_3^+ \rightarrow 6^+$ and 854 keV $2^+ \rightarrow 0^+$ transitions. Filled circles mark known contaminant peaks.

quadrupole nature to both transitions is perhaps the most likely possibility, other assignments ($E/M3$ and $E/M1$, respectively, for example) are not impossible. In previous studies, the low strength of the 641 keV transition prevented an angular-correlations measurement to establish its multipolarity.

The high statistics of the present data has allowed the observation of *prompt* feeding of the 2562 keV state. Figure 2 shows the spectrum obtained by requiring prompt coincidence (± 30 ns) with both the 641 keV transition and the 854 keV $2^+ \rightarrow 0^+$ transitions. The two peaks marked by filled circles are contaminants brought in by the presence of a 642 keV transition in a structure feeding the 10^+ isomer [23] (the relatively short lifetime of this state means that correlations across it are not insignificant within the prompt coincidence requirement used here).

In addition to the known $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions at 501 and 565 keV, two other peaks are visible at 626 and 742 keV. Inspection of the coincidence data shows that these transitions, which are not in coincidence with each other, directly feed the state de-excited by the 641 keV transition. No evidence for either transition was found in the out-of-beam spectra, or in spectra in delayed coincidence with any of the known isomers. Similarly, no evidence for these transitions was found in spectra gated by the delayed detection of one of the transitions below the 10^+ isomer. Together, these results show that they bypass the known isomers and that the states they de-excite do not have significant lifetimes. Although several very low-intensity peaks were visible in spectra gated on these new transitions, no higher-lying structures could be unambiguously identified above them.

The identification of prompt paths feeding the 2562 keV state allows the isolation of the promptly fed component of the 641 keV transition de-exciting the 2562 keV state. With feeding via the isomers excluded, reasonably strong alignment can be assumed for the recoiling nucleus. It has therefore been possible to perform a DCO analysis for the 641 keV transition by gating on these prompt paths. A ratio $R_{DCO} = I_\gamma(\theta_{90})/I_\gamma(\theta_{fb})$ where θ_{90} included detectors at angles between 80° and 100°

Fig. 3. Values of R_{DCO} obtained for the 641 keV transition compared to known stretched $E2$ and stretched $E1$ transitions in ^{192}Pb .

and θ_{fb} included detectors at angles $< 40^\circ$ and $> 140^\circ$, was used to distinguish between stretched quadrupole and stretched dipole transitions. Figure 3 compares the value of R_{DCO} obtained for the 641 keV transition to those obtained for known stretched $E2$ and $E1$ transitions in the same nucleus. The result is consistent with an $E2$ assignment, strongly supporting the assignment of $I^\pi = 8^+$ to the 2562 keV level and the implied $E2$ assignment to the unobserved 19 keV transition.

The data thus indicate the coexistence of three 8^+ states between excitation energies of 2.0 and 2.6 MeV. The levels fed through the decay of the 10^+ isomer, illustrating the relative positions of the three 8^+ states, are shown in fig. 4. The intensities of all the transitions detected following the decay of this isomer (obtained from the spectrum shown in fig. 1) balance to within 1%, suggesting that there are no other significant paths between any of the levels in fig. 4.

3.2 Structures feeding the 8_2^+ and 8_1^+ states

The data were searched for feeding of the 8_2^+ and 8_1^+ states via prompt paths. Figure 5 shows the spectrum obtained by requiring prompt coincidence with both the 599 keV $8_2^+ \rightarrow 6^+$ and 854 keV $2^+ \rightarrow 0^+$ transitions. The known $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ transitions at 501 and 565 keV are marked. The filled circles mark peak brought in to the spectrum due to coincidences across the relatively short-lived 10^+ isomer. The lack of any other peaks in the spectrum suggests that the 8_2^+ state is fed exclusively by the 60.7 keV transition de-exciting the 10^+ isomer, with no significant feeding this level via prompt pathways.

In contrast, the 8_1^+ state is fed promptly by both weakly collective and non-collective structures, as well as by the decay of both the 11^- and 10^+ isomers [11,18]. In the present work, an additional structure has been

Fig. 4. Partial level scheme showing the decays from the 10^+ state.

Fig. 5. The spectrum of transitions in prompt coincidence with both the 599 keV $8_2^+ \rightarrow 6^+$ and 854 keV $2^+ \rightarrow 0^+$ transitions. The filled circles mark peaks present due to coincidences across the 236 ns 10^+ isomer.

observed built directly upon the 8_1^+ level, consisting of a cascade of $M1$ and crossover $E2$ transitions. A partial level scheme showing this structure is shown in fig. 6. The spectrum shown in fig. 7 was obtained by requiring prompt coincidence with both the 854 keV $2^+ \rightarrow 0^+$ transition and either the 856 or 857 keV transitions identified in the new structure. $B(M1)/B(E2)$ ratios derived from the measured γ -ray branching ratios for levels within this structure are in the range $10\text{--}20 (\mu_N/\text{eb})^2$.

Also shown in fig. 6 is the sequence of magnetic dipole and crossover electric quadrupole transitions built on the 11^- isomer. This structure, which is repeated in neigh-

Fig. 6. Partial level scheme showing the structure built on the 8_1^+ level in ^{192}Pb . The widths of the arrows represent the intensities of the transitions relative to the 486.4 keV and 530.7 keV transitions, respectively.

Fig. 7. The spectrum of transitions in prompt coincidence with both the $2^+ \rightarrow 0^+$ 854 keV transition and either the 856 or 857 keV transitions.

boring isotopes, has been interpreted as a weakly collective oblate band [8].

4 Nature of the 8^+ states

4.1 Mechanisms for generating near-yrast 8^+ states in ^{192}Pb

The three observed 8^+ states in ^{192}Pb are likely to contain admixtures of all of the lowest-lying unperturbed wave functions representing the different quasiparticle excitations and different deformations available to the nucleus.

If the nucleus were spherical, the only mechanisms for generating 8^+ states at low excitation energies would be $\nu i_{13/2}^{-2}$, $\pi h_{9/2}^2$, $\pi h_{11/2}^{-1} h_{9/2}$ and $\pi i_{13/2}^2$ excitations, although the latter two of these would be expected to be at a significantly higher energy than the former.

If the nucleus has a significant oblate deformation the $h_{9/2}$ proton orbital mixes with the $f_{7/2}$ orbital, and the 8^+ state associated with this deformation is therefore better described as $\pi(h_{9/2} f_{7/2})^2$ than $\pi h_{9/2}^2$. Quasineutron excitations within the $i_{13/2}$ shell may also generate 8^+ states

Fig. 8. Aligned angular momenta and kinematic moments of inertia of the structures built directly on the 8_1^+ and 11^- states in ^{192}Pb and ^{194}Pb .

at oblate deformation while remaining relatively pure. A more strongly collective oblate deformation may result in a rotational band containing an 8^+ state, as observed in ^{188}Pb [7].

Prolate deformation also allows rotation, and therefore the possibility of another highly collective, rotational 8^+ state. However, most calculations suggest that a well-defined moderate prolate minimum does not form in Pb isotopes with $N > 108$, so prolate rotational states and quasiparticle excitations within a prolate minimum are unlikely at low energies.

4.2 The 8_1^+ state

The observation of the structure shown in fig. 6 in the present work reinforces the suggestion that this state is associated with an oblate deformation similar to that of the 11^- isomer, *i.e.* $\epsilon \lesssim -0.1$ [18]. In fact, a similar structure has been reported above the 8_1^+ in ^{194}Pb [16], although no comparison with the 11^- oblate band was drawn in that work. Figure 8 compares the aligned angular momenta I_x and the kinematic moments of inertia $\mathcal{J}^{(1)}$ for the structures built on the 8_1^+ and 11^- states in both ^{192}Pb and ^{194}Pb . The similarity between the sequences suggests that the structures above the 8^+ states in both nuclei may be associated with similar configurations to the 11^- states. The in-band $B(M1)/B(E2)$ ratios for the structure built on the 8_1^+ state obtained in the present work are similar to those obtained for the structure built on the 11^- state, again suggesting similar related configurations and similar deformations.

4.3 The 8_2^+ state

The yrast 12^+ and 10^+ states have the characteristics of relatively pure $\nu i_{13/2}^{-2}$ excitations associated with a spherical shape. One of the unperturbed states contributing

to the 8^+ wave functions is thus the 8^+ member of this same multiplet. The strong decay branch from the 10^+ isomer suggests that the wave function of the 8_2^+ state is dominated by this neutron configuration, and indeed the present data support the $B(E2)$ value measured by Dracoulis *et al.* [22]. The present results therefore support the previous assignment of this state as corresponding to a spherical shape.

4.4 The 8_3^+ state

The nature of the dominant component of the 8_3^+ state is more problematic. Since the 8_1^+ and 8_2^+ states can be interpreted as predominantly oblate and spherical, respectively, a natural assumption might be that this state has a relatively large component corresponding to a collective prolate shape, with a spherical admixture due to the near degeneracy with the 8_2^+ state. While the presence of the unobserved 19 keV transition connecting the 10^+ isomer to this state may indicate a non-negligible spherical component, the fact that there is no evidence for any structure resembling a prolate rotational band, either feeding or de-exciting this state, makes such an interpretation unlikely. Similarly, it is unlikely that it is the member of a collective rotational band based on an oblate shape.

Figure 9 compares the excitation energies of the three 8^+ states in ^{192}Pb to states in neighbouring isotopes. The 8^+ states in ^{192}Pb and ^{190}Pb are indicated by filled diamonds.

Panel (a) shows these states alongside 8^+ , 10^+ and 12^+ states identified as arising from the two-quasineutron $\nu i_{13/2}^{-2}$ configuration associated with a spherical shape. The dashed line indicates a polynomial fit to the energies of the 10^+ states. The solid line is the same fit but with a negative-energy offset, adjusted so that it passes through the 8^+ states in ^{194}Pb and ^{196}Pb predominantly associated with the spherical configuration. The 8_2^+ state in ^{192}Pb sits almost exactly on this line, strongly suggesting that it too can be identified as the two-quasineutron spherical state. This is consistent with the arguments presented above. It is interesting to note, however, that none of the three 8^+ states in ^{190}Pb are consistent with the observed trend. In fact, all three are depressed in energy compared to expectations based on the 10^+ and 12^+ systematics. This cannot be explained by mixing between the three observed states alone, since that would result in at least one state lying *higher* than expected.

Panel (b) shows the three 8^+ states in ^{192}Pb and ^{190}Pb alongside 11^- and 8^+ states identified as arising from the two-proton $\pi i_{13/2}$, $h_{9/2}$ and $\pi(h_{9/2}f_{7/2})^2$ configurations, respectively, both of which can be associated with an oblate deformation. The dashed line indicates a polynomial fit to the energies of the 11^- states. The solid line is the same fit scaled so that it passes through the 8^+ states in ^{190}Pb , ^{194}Pb and ^{196}Pb predominantly associated with the oblate configuration. The 8_1^+ states in both ^{192}Pb and ^{190}Pb lie closest to this line, supporting their assignment as being associated with an oblate shape. This is consistent with the interpretation of the structure above the 8_1^+

Fig. 9. Comparison of the energies of the three 8^+ states in ^{190}Pb and ^{192}Pb (solid diamonds) with 8^+ states in neighbouring isotopes. (a) Comparison with 8^+ states identified as predominantly associated with the spherical minimum. The energies of the 10^+ state from the same spherical two-neutron configuration are included. (b) Comparison with the 8^+ states identified as predominantly associated with the oblate minimum. The energies of the 11^- two-proton state, firmly associated with oblate deformation are included. (c) Comparison with the 8^+ states identified as predominantly associated with the prolate minimum. The energies of the 6^+ member of the prolate band are included. The solid and dashed lines are polynomial fits to the data (see text for details).

state in ^{192}Pb as a weakly collective rotational band analogous to that above the 11^- isomer.

Panel (c) shows the three 8^+ states in ^{192}Pb and ^{190}Pb alongside 6^+ and 8^+ states identified as members of the prolate rotational band in the lighter isotopes. The dashed line indicates a polynomial fit to the energies of the 6^+ states. The solid line is the same fit, scaled so that it passes through the 8^+ states in the same bands. This line passes in between the 8_2^+ and 8_3^+ states in ^{190}Pb ; assignment of the 8_3^+ in ^{190}Pb to a predominantly collective prolate shape is preferred, since that state is part of what appears to be a rotational cascade. However, this line passes significantly higher than any of the three observed 8^+ states in ^{192}Pb . In fact, the 8^+ member of the prolate band would be expected to be quite non-yrast and therefore difficult to observe. Again, the depression of all three states relative to expectations based on systematics cannot be explained by mixing among these three states alone.

These results suggest that an assignment of the 8_3^+ state to a collective prolate shape can be ruled out. (This is consistent with calculations suggesting that no true prolate minimum forms at moderate deformations in Pb isotopes with $N \geq 110$.) Alternative possibilities include the

$\nu i_{13/2}^{-2}$ excitation in the oblate minimum and the $\pi h_{9/2}^2$ configuration associated with a spherical shape. In the latter case, a weak branch from the 8_3^+ state to the 8_1^+ state might be expected. No such transition has been observed in the present data, giving an upper limit of 8% of the $8_3^+ \rightarrow 8_1^+$ strength. (It is worth noting, however, that a 2.5% branch is observed from the 8_2^+ state to the 8_1^+ state.) It is also not clear whether distinct $\nu i_{13/2}^{-2}$ or $\pi h_{9/2}^2$ states associated with a spherical well should be expected, since most calculations suggest that the spherical and oblate minima are separated by a relatively small barrier.

The presence of a third 8^+ state not associated with a collective prolate shape has implications for the interpretation of the three 8^+ state in ^{190}Pb . While in previous work these states were described in terms of interference between three competing shapes, the presence of the third 8^+ in ^{192}Pb suggests that more configurations may be involved. The depression of all the states relative to the systematic expectations for the spherical two-neutron hole 8^+ may indicate that the 8_3^+ in ^{190}Pb is not predominantly spherical. Instead, it may share the same structure as the 8_3^+ in ^{192}Pb .

5 Conclusions

There is strong evidence for three 8^+ states within an interval of 300 keV below 2.6 MeV in ^{192}Pb . The properties of transitions feeding and de-exciting these states have been used to confirm previous suggestions that the 8_1^+ state is predominantly associated with a two-proton excitation at oblate deformation, while the 8_2^+ state is predominantly associated with a two neutron-hole excitation at sphericity [22]. Comparison of the energies of the three 8^+ states in each of ^{192}Pb and ^{190}Pb to systematics based on states in neighboring nuclei suggests that, in both cases, the three states cannot simply be explained in terms of mixing between one state from each of the prolate, oblate and spherical minima. All three states in ^{190}Pb are lower than expected for the spherical quasineutron state, and all three states in ^{192}Pb are lower than expected for the prolate rotational band member.

The authors would like to thank Bob Turkentine for the excellent quality of the target, and the operators of the 88" Cyclotron at LBNL for their assistance during the experiment. ANW gratefully acknowledges the support of the Scottish Universities Physics Alliance through a SUPA Fellowship. This work was carried out with support from the Australian Nuclear Science and Technology Organization through grant no. 02/03 - H-01, the Australian Research Council through grant no. DP0451780 and the US Department of Energy under Contract No. AC03-76SF00098.

References

1. R. Bengtsson, W. Nazarewicz, Z. Phys. A **334**, 269 (1989).
2. W. Nazarewicz, Phys. Lett. B **305**, 195 (1993).
3. V. Hellemans, S. De Baerdemacker, K. Heyde, Phys. Rev. C **77**, 064324 (2008).
4. M. Bender, P. Bonche, T. Duguet, P.-H. Heenen, Phys. Rev. C **69**, 064303 (2004).
5. R.R. Rodríguez-Guzmán, J.L. Egido, L.M. Robledo, Phys. Rev. C **69**, 054319 (2004).
6. A.N. Andreyev *et al.*, Nature (London) **405**, 430 (2000).
7. G.D. Dracoulis, G.J. Lane, A.M. Baxter, T. Kibédi, A.O. Macchiavelli, P. Fallon, R.M. Clark, Phys. Rev. C **67**, 05130(R) (2003).
8. G.D. Dracoulis, G.J. Lane, A.M. Baxter, T. Kibédi, A.O. Macchiavelli, P. Fallon, R.M. Clark, Phys. Rev. C **69**, 054318 (2004).
9. G.D. Dracoulis, A.P. Byrne, A.M. Baxter, Phys. Lett. B **432**, 437 (1998).
10. J.M. Lagrange, M. Pautrat, J.S. Dionisio, Ch. Vieu, J. Vanhorenbeeck, Nucl. Phys. A **530**, 437 (1991).
11. A. Plompen *et al.*, Nucl. Phys. A **562**, 61 (1993).
12. J. Penninga *et al.*, Nucl. Phys. A **471**, 535 (1987).
13. J.J. van Ruyven *et al.*, Nucl. Phys. A **449**, 579 (1986).
14. G.D. Dracoulis, G.J. Lane, T.M. Peaty, A.P. Byrne, A.M. Baxter, P.M. Davidson, A.N. Wilson, T. Kibédi, F.R. Xu, Phys. Rev. C **72**, 064319 (2005).
15. A.J.M. Plompen, *Collective and quasiparticle excitations in light Pb isotopes*, Academisch Proefschrift, Vrije Universiteit te Amsterdam, 1993 (unpublished).
16. M. Kaci *et al.*, Nucl. Phys. A **697**, 3 (2002).
17. A. Lopez-Martens, PhD Thesis, CSNSM-Orsay, France, 1997 (unpublished).
18. G.D. Dracoulis, T. Kibédi, A.P. Byrne, A.M. Baxter, S.M. Mullins, R.A. Bark, Phys. Rev. C **63**, 061302(R) (2001).
19. R. Julin *et al.*, Eur. Phys. J. A **15**, 189 (2002).
20. J.F.C. Cocks *et al.*, Eur. Phys. J. A **3**, 17 (1998).
21. T. Grahn *et al.*, Nucl. Phys. A **801**, 83 (2008).
22. G.D. Dracoulis *et al.*, in preparation.
23. A.N. Wilson *et al.*, in preparation.