High-spin isomers and three-neutron valence configurations in $^{211}$Pb

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Abstract

Deep-inelastic reactions between a beam of 1360 MeV $^{208}$Pb ions and a thick $^{238}$U target have been used to populate the neutron-rich nucleus $^{211}$Pb. The observation of its $\gamma$ decay has allowed identification of excited states up to the highest spin which can be formed from the three valence neutrons, including identification of three high-spin isomers. Level energies and transition strengths are compared to shell-model calculations with empirical interactions and predictions are made for the expected behaviour of more neutron-rich lead isotopes. The evidence for a possible increase in the neutron effective charge moving away from the $N = 126$ shell gap is evaluated.

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The neutron–neutron interaction is not well defined. In particular, two-neutron states are not known and, therefore, deep inelastic reactions [3], most of the expected singular matrix elements have been measured in 210 Pb. Configuration were observed with the 210 Pb(α,α′) 212 Pb the 0+ state in isotopes beyond 208 Pb. While low-spin states have been studied in 210 Pb with the 208 Pb(t, p) and 208 Pb(t, pγ) reactions [1,2] and a few high-spin states have been found with γ-ray spectroscopy following deep inelastic reactions [3], most of the expected simple two-neutron states are not known and, therefore, the neutron–neutron interaction is not well defined. In 212 Pb the 0+, 2+, 4+, 6+ and 8+ levels from the vg9/2 0 configuration were observed with the 210 Pb(t, p) reaction [4] and one isomer, probably the 8+ level, has been identified as a product in the relativistic fragmentation of 238 U [5]. For 211 Pb, the 210 Pb(t, d) reaction [6] has provided mainly the single-particle states, and (α–γ)-coincidences in the decay of 215 Po have established seven low-lying states of low spin [7].

The structure of the yrast states in 211 Pb should be particularly simple and therefore well suited for testing the shell model and the residual interactions. The primary valence configurations will involve only the g9/2, i11/2 and j15/2 neutron orbitals, with the lowest yrast levels expected to arise from the vg9/2 0 and the vg9/2 i11/2 configurations, for which all the relevant diagonal matrix elements have been measured in 210 Pb [1–3]. Therefore, these states can be calculated without free parameters and the results compared to experiment. Further predictions for even more neutron-rich nuclei may then be made more reliably.

Until the development of appropriate radioactive ion beams, spallation of 238 U and multi-nucleon transfer reactions offer the best chance of studying excited states in 211 Pb. A number of measurements have been performed using deep-inelastic reactions and neutron-rich beams such as 48 Ca, 64 Ni, 76 Ge, 136 Xe and 208 Pb, incident on 208 Pb targets [3,8–10]. However, to date, none have yielded sufficient population of 211 Pb to allow the identification of high-spin states. The present experiment, which combined the high γ-ray detection efficiency of Gammasphere with deep-inelastic reactions between 238 U and 208 Pb nuclei, has been more successful.

The experiment was performed at Argonne National Laboratory with a beam of 1360 MeV 208 Pb ions from the ATLAS accelerator. The pulsed beam with ~ 0.3 ns width and 1.65 μs separation was incident on a 50 mg/cm2 238 U target, thick enough to stop both beam- and target-like reaction products. Typical stopping times are ~ 2 ps so that most γ rays are emitted from nuclei at rest, with the notable exception of a strong flux of Doppler-broadened γ rays from Coulomb excitation of the 238 U target. The γ rays were observed with Gammasphere, consisting of 101 Compton-suppressed detectors. Gamma–gammatime coincidence data were collected with a composite trigger, requiring three or more Compton-suppressed γ rays to be in coincidence for the in-beam events and two or more Compton-suppressed γ rays for the out-of-beam events. Approximately 2.3 × 109 events were collected, of which 1.1 × 109 were fold-three or greater.

The total γ-ray spectrum was extremely complicated, with transitions observed from deep-inelastic reaction products, Coulomb excitation (predominantly of the 238 U target), fission fragments, as well as a large X-ray flux from both the beam and target. The production of clean spectra for the weakly-populated, neutron-rich products of deep-inelastic reactions often required elaborate multi-fold gating on both γ-ray energies and/or the times of detection of γ rays, both with respect to the beam pulse and also each other. These gating procedures were greatly facilitated through the use of the computer analysis code Blue [11], which allowed the fast creation of coincidence spectra and matrices with complex sets of gates. Some details of the experiment and analysis have been described in earlier publications [12,13].

The seven low-lying states assigned in 211 Pb by Liang et al. [7], include a level at 733 keV with a tentative spin and parity of 13/2+. Therefore, the γ rays in coincidence with the 733.7 keV transition shown in Fig. 1 are candidates for placement in the 211 Pb level scheme. The presence of a number of isomers is clear from the time correlations. Furthermore, the 234 U ground state rotational band transitions are in clear coincidence with the observed delayed cascade, which implies that the γ rays are from a lead isotope with
A \leq 212. Since all lead isotopes with $A \leq 212$ have well-known states [3,5,10] except for $^{211}$Pb, these observations provide firm identification that the cascade involving the 734 keV transition is in $^{211}$Pb. Although the spectrum in Fig. 1(b) is double-gated to give a clean spectrum with mainly $^{211}$Pb transitions, the $^{234}$U ground-state band transitions can still be seen. Note that to produce $^{211}$Pb and $^{234}$U as binary fragments, one neutron must be emitted during the deep-inelastic process. Previous measurements have shown that neutron emission is common in energetic multi-nucleon transfer [14].

The $\gamma$ rays observed fall into four groups separated by three isomers with meanlives of 60, 230, and 8 ns. The most delayed group, shown in Fig. 1(c), consists of 137, 322, and 734 keV lines. A delayed intensity balance gives the total conversion coefficient for the $137$ keV transition as $\alpha_T = 1.4(5)$ resulting in a clear E2 assignment (theoretical values are 0.194, 3.94 and 1.72 for E1, M1 and E2 transitions, respectively). A limit of $\alpha_T < 0.15$ for the 322 keV transition is obtained, suggesting E1 ($\alpha_T = 0.025$) or E2 ($\alpha_T = 0.096$) character rather than M1 ($\alpha_T = 0.375$).

Fig. 1(a) indicates that a 486 keV line lies above the 734/322/137 keV group, with an intervening isomer of 60(10) ns clearly apparent from the time difference spectrum shown in Fig. 2(a). The 1172 keV $\gamma$-ray prominent in the spectrum of $\gamma$ rays which precede the 486 keV transition shown in Fig. 1, is placed directly feeding the 230(40) ns isomer, whose lifetime can be seen in Fig. 2(b). Further evidence that the 1172 keV transition is the lowest in this group of transitions can be seen in the time spectra of Fig. 2(c).
Fig. 2. (a)–(c) Selected spectra showing the time difference between the detection of the marked pairs of $\gamma$ rays in $^{211}$Pb. (First $\gamma$ ray in list: START, second: STOP.) Note that panel (a) is a sum of two time-difference spectra. Panel (d) shows the time of detection of the 1172 keV $\gamma$ ray with respect to the beam pulse. This spectrum was produced from the sum of two $\gamma$-time matrices, each themselves gated by a coincidence with 734 or 486 keV $\gamma$ rays, respectively. The fitted time curves and lifetime results are also shown.

and (d) which establish that the 1172 keV transition decays from another isomer with a meanlife of 8(2) ns. Coincidence relationships and measured intensities in various double-gated coincidence spectra establish the rest of the level scheme as shown on the left in Fig. 3.

The 644 and 1222 keV transitions in Fig. 1(b) appear to feed the 4412+ $\Delta$ keV level in parallel with the 1146 keV transition, although the coincidence information is marginal. Hence, they have not been firmly placed in the level scheme.

The low absolute yield and lack of spin alignment in multi-nucleon transfer reactions precludes conventional angular distribution and/or correlation analysis for spectroscopic assignments. Nevertheless, with only three valence neutrons outside doubly-magic $^{208}$Pb, reliable spin assignments are possible in $^{211}$Pb for the yrast three-neutron configurations by making a comparison between experiment and the results of empirical shell model calculations. This approach is used below.

The lowest levels of $^{211}$Pb will obviously belong to the $\nu g_{7/2}^{3}$ configuration. As in analogous cases, such as the $\pi h_{9/2}^{3}$ configuration in $^{211}$At [15], a 21/2$^+$ isomer is expected, with a decay cascade of three E2 transitions of increasing energy proceeding through 17/2$^+$ and 13/2$^+$ levels to the 9/2$^+$ ground state. This is in line with the experimental observation.

Levels immediately above the 21/2$^+$ isomer presumably belong to the multiplet from the $\nu g_{5/2}^{2}f_{11/2}$ configuration, where the highest spin state of 27/2$^+$ is again expected to be an isomer since the 25/2$^+$ level is calculated to lie higher (see below). Because the 23/2$^+$ and 27/2$^+$ states are calculated to lie very close in energy their order cannot be accurately predicted, however, the measured lifetime of 230(40) ns agrees with that expected for a low-energy 27/2$^+ \rightarrow 23/2^+$, E2 transition (see below), hence an unobserved transition of energy $\Delta$ is included in the level scheme shown in Fig. 3. If the 27/2$^+$ state fell below the 23/2$^+$ state, its only decay path would be via an M3 transition,
which would lead to a lifetime in the millisecond region. Note that the 21/2+ level from this configuration is calculated to be close to, but above, the 23/2+ state. If it were below, it would offer the 23/2+ state an alternative decay path, but this low energy branch would be weak compared to the much higher energy 486 keV transition to the (7/2+) level.

Above the 27/2+ state, the next set of valence configurations should arise from the \( g_{9/2}^3 i_{15/2} \) and \( i_{13/2}^2 j_{15/2} \) (\( I \leq 35/2 \)) and \( i_{11/2} j_{15/2} \) (\( I \leq 39/2 \)) configurations giving 33/2− and 39/2+ states respectively, with enhanced \( j_{15/2} \rightarrow g_{9/2} \), E3 transitions connecting them. The observed 8(2) ns meanlife is appropriate for the 33/2− state and confirms the spin and configuration assignment, while a 1560 keV E3 transition from the 39/2+ state should be ~7 times faster, resulting in a lifetime too short to be observed in the present experiment. Nevertheless, the 39/2+ assignment is made on the basis of the energy agreement with the empirical shell-model calculation (see below) and the expectation that yrast states will be preferentially populated. As \( \frac{3}{2}^+ \) is the highest that can be formed from the three valence neutrons so that any higher-lying states must result from core excitations. Since all the spin and parity assignments rely on shell model comparisons, they are placed in brackets in Fig. 3, but this is not done in the detailed discussion and comparison with shell-model calculations below.

The levels of \(^{211}\)Pb can be directly calculated in the framework of the shell model if the \(^{208}\)Pb core is assumed to be inert and only the three valence neutrons are active at low excitation energy. The results of
empirical shell-model calculations which use single-particle energies and interaction-matrix elements deduced from experimental data are shown in Fig. 4. A detailed comparison between these calculations and experiment is presented in Table 1 for selected excited states from the $g_{9/2}$, $i_{11/2}$ neutron orbitals. Note that these calculations ignore the effects of configuration mixing.

Only the $g_{9/2}$ and $i_{11/2}$ neutron orbitals will contribute to the $27/2^+$ isomer and levels below. The two single-particle energies are taken from the $g_{9/2}$ ground state and $i_{11/2}$ first excited state in $^{208}$Pb, while the interaction between the $g_{9/2}$ neutrons is taken from the $0^+$, $2^+$, $4^+$, $6^+$, $8^+$ multiplet of levels in $^{210}$Pb [2]. The interaction between $g_{9/2}$ and $i_{11/2}$ neutrons is also needed to calculate the $23/2^+$ and $27/2^+$ levels. The $10^+$, $8^+$, and $4^+$ levels from this configuration have been measured in $^{210}$Pb [1,3] and unpublished results on this nucleus from the present experiments [16] provide a candidate for the $9^+$ state, 312 keV above the known $10^+$ level. The other levels are not known, so the $6^+$ and $7^+$ matrix elements were scaled from the analogous $\pi f_{7/2} h_{9/2}$ multiplet in $^{210}$Po, while the $1^+$, $2^+$, $3^+$ and $5^+$ couplings are taken from Kuo and Herling [17]. The (uncertain) lower spin couplings are not needed to calculate the yrast $23/2^+$ and $27/2^+$ levels.

The states of lower spin in Table 1 (and shown in Fig. 3) are taken from Liang et al. [7] who assigned spins based not only on hindrance factors in $\alpha$-decay, but also guided by shell-model calculations. The origin of the level at 584 keV is not understood, but for all other states the agreement between calculated and measured energies is very good, except for the two $11/2^+$ states, for which the $g_{9/2} i_{11/2}$ configuration will have an important contribution. Although
Table 1
Comparison of measured and calculated excited-state energies for $^{211}$Pb

<table>
<thead>
<tr>
<th>Spin</th>
<th>$E_{\text{expt}}$</th>
<th>$E_{\text{theory}}$</th>
<th>$E_{\text{theory}} - E_{\text{expt}}$</th>
<th>Reference</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3/2$^+$)</td>
<td>762</td>
<td>790</td>
<td>+28</td>
<td>[7]</td>
<td>$^{9/2}_1$</td>
</tr>
<tr>
<td>(5/2$^+$)</td>
<td>598</td>
<td>616</td>
<td>+18</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>7/2$^+$</td>
<td>439</td>
<td>421</td>
<td>-18</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>9/2$^+_1$</td>
<td>0</td>
<td>-26</td>
<td>-26</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>(9/2$^+_2$)</td>
<td>815</td>
<td>852</td>
<td>+37</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>(11/2$^+$)</td>
<td>894</td>
<td>762</td>
<td>-132</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>13/2$^+$</td>
<td>734</td>
<td>713</td>
<td>-21</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td>(15/2$^+$)</td>
<td>1056</td>
<td>1003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17/2$^+$</td>
<td>1193</td>
<td>1193</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>21/2$^+$</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>23/2$^+$</td>
<td>1679</td>
<td>1670</td>
<td>-9</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>25/2$^+$</td>
<td>1765</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27/2$^+$</td>
<td>1679 + $\Delta$</td>
<td>1699</td>
<td>+20 $\rightarrow$ $\Delta$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>15/2$^-$</td>
<td>1303</td>
<td>1340</td>
<td>+37</td>
<td>[6]</td>
<td>$^{9/2}_2/15/2$</td>
</tr>
<tr>
<td>33/2$^-$</td>
<td>2851 + $\Delta$</td>
<td>2834</td>
<td>-17 $\rightarrow$ $\Delta$</td>
<td>2</td>
<td>$^{9/2}_2/11/2,15/2$</td>
</tr>
<tr>
<td>39/2$^+$</td>
<td>4412 + $\Delta$</td>
<td>4378</td>
<td>-34 $\rightarrow$ $\Delta$</td>
<td>2</td>
<td>$^{11/2}_1/3/2$</td>
</tr>
</tbody>
</table>

1 Normalised with $E_{\text{theory}} = E_{\text{calculated}} - 42$ keV.
2 Also/only observed in present work.

not observed in the present measurement, we note that the unique parity $j_{15/2}$ state at 1303(10) keV [6] is calculated to lie at 1340 keV using the Kuo–Herling interaction.

The only high-spin member of the $^{9/2}_2/11/2$ configuration for which the energy has been measured is the 23/2$^+$ state. The discrepancy between the calculation and experiment is small and similar to that for the $^{9/2}_1$ levels, with the good agreement suggesting that configuration mixing is small. This is further supported by our OXBASH calculation using the interaction of Warburton and Brown [18], which gives mixing below 1% for the 17/2$^+$ and higher states. Furthermore, the 7/2$^+ \rightarrow 9/2^+$ transition is measured by Liang et al. to have pure or predominantly E2 character [7]. This is a strong argument that configuration mixing is indeed small, since the single-particle estimate favors an M1 transition by a factor 2000 over E2, while for pure $^{9/2}_2$ configurations the M1 transition is forbidden.

The calculated energy for the 23/2$^+$ state from the $^{9/2}_2/11/2$ configuration is within 9 keV of experiment, giving some indication of the accuracy of the calculations, while the 25/2$^+$ state is calculated to lie 66 keV above the 27/2$^+$ state (both also from the $^{9/2}_2/11/2$ configuration). Therefore, it seems safe to assume that the 25/2$^+$ lies above the 27/2$^+$ state, which would therefore be isomeric, calculated to lie 29 keV above the 23/2$^+$ state. This agrees with our experimental observations.

The isomeric level at 2851 + $\Delta$ keV, depopulated by the 1172 keV transition, lies in the region of the high-spin states from the $^{9/2}_2/11/2,15/2$ configuration. Using the interactions deduced from the 10$^+$, 11$^-$, and 13$^-$ states in $^{210}$Pb [3], the 33/2$^-$ state is calculated to lie lowest at 2834 keV. The energy difference $E_{\text{th}}(33/2^-) - E_{\text{th}}(27/2^+) = 1135$ keV is close to the 1172 keV transition that is measured. Alternative spin assignments have been explored, but they cannot reproduce the energy of the level and its slow $\gamma$-ray decay.

The experimental state at 4412 + $\Delta$ keV lies very close to the calculated $[vi_{11/2}]^2_{15/2}39/2^+$ yrast state (see Fig. 4). An E2 decay to the calculated
Table 2
Transition strengths and neutron effective charges in heavy lead nuclei

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Transition</th>
<th>Configurations</th>
<th>$B(E2)_{\text{expt}}$ (e$^2$ fm$^4$)</th>
<th>$B(E2)_{\text{theory}}$ (e$^2$ fm$^4$)</th>
<th>$\epsilon_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>210Pb</td>
<td>8$^+$ → 6$^+$</td>
<td>$\delta g_{9/2}$</td>
<td>46(5)</td>
<td>46(5)</td>
<td>0.96(4)</td>
</tr>
<tr>
<td>211Pb</td>
<td>21/2$^+$ → 17/2$^+$</td>
<td>$\delta g_{9/2}$</td>
<td>104(18)</td>
<td>91(10)</td>
<td>1.07(12)</td>
</tr>
<tr>
<td>211Pb</td>
<td>27/2$^+$ → 23/2$^+$</td>
<td>$\delta g_{9/2}$</td>
<td>75$^{+14}_{-19}$</td>
<td>54(8)</td>
<td>1.2(2)</td>
</tr>
<tr>
<td>212Pb</td>
<td>8$^+$ → 6$^+$</td>
<td>$\delta g_{9/2}$</td>
<td>2.1(5)</td>
<td>5.1(6)</td>
<td>0.60(12)</td>
</tr>
<tr>
<td>211Pb</td>
<td>33/2$^-$ → 27/2$^+$</td>
<td>$\delta g_{9/2}$</td>
<td>71(18) × 10$^3$</td>
<td>66(14) × 10$^3$</td>
<td>0.85(9)</td>
</tr>
<tr>
<td>211Pb</td>
<td>39/2$^+$ → 33/2$^-$</td>
<td>$\delta g_{9/2}$</td>
<td>$\geq 15 \times 10^3$</td>
<td>$100(22) \times 10^3$</td>
<td>0.85(9)</td>
</tr>
</tbody>
</table>

1 Reference value.
2 Assumes pure configurations. Contrast with $\epsilon_{\text{eff}} = 0.88$ from Deccan et al. [2] corrected for mixing.
3 $1.985 \times B(E2; 210\text{Pb}, 8^+ \rightarrow 6^+)$.
4 Using theoretical transition energy of 29 keV, with error covering the range 18 to 60 keV.
5 $1/9 \times B(E2; 210\text{Pb}, 8^+ \rightarrow 6^+)$.
6 $0.987 \times B(E3, 15/2^- \rightarrow 89/2^-)$.
7 From experimental lifetime $\tau < 5$ ns.
8 $1.507 \times B(E3, 15/2^- \rightarrow 89/2^-)$.

The 2$^+$ state would have low energy and would also be inhibited because the required single-particle transition is the spin-flip case, $i_{11/2} \rightarrow g_{9/2}$. Other possibilities are lower energy M2 transitions or a high-energy E3 transition to the observed $[v9/2j_{15/2}]_{15/2^+}$ state. The latter would be an enhanced, octupole-coupled $j_{15/2} \rightarrow g_{9/2}$ neutron transition similar to the $33/2^- \rightarrow 27/2^+$ transition and would be favoured over the lower energy M2 decays. Note that the calculated energy difference between the states is 1544 keV, very close to the observed transition energy of 1561 keV.

The first part of Table 2 compares the measured E2 transition strengths in 211Pb and 212Pb with predicted values derived from the $8^+ \rightarrow 6^+$ transition in 210Pb [2]. Pure configurations are assumed in all cases so that the quadrupole properties of the $g_{9/2}$ states are related by simple geometric factors. The wavefunction of the $23/2^+$ level in 211Pb is calculated to be 73% $|(g_{9/2})_{8^+} \otimes i_{11/2})$ and 27% $|(g_{9/2})_{8^+} \otimes i_{11/2})$. If the value of $[i_{11/2}]_2$ [2] is taken from Ring et al. [19] to be $-39.3$ e$^2$ fm$^4$, the strength of the $27/2^+ \rightarrow 23/2^+$ transition is dominated by the $g_{9/2}$ neutrons. The measured E2 transition strengths in 211Pb agree with the theoretical predictions, confirming the proposed structure, while the deduced effective neutron charge is approximately constant with a possible slight rise moving away from 208Pb. In stark contrast, the deduced effective charge from the $8^+$ isomer in 212Pb [5] shows a marked reduction to 0.60(12). It should be noted that the difficult lifetime measurement in Ref. [5] had low statistics and the possibility of feeding from a high-lying isomer could not be discounted [5]. The main correction to the wave functions in 212Pb would be due to pairing scattering of particles out of the $g_{9/2}$ orbital, which would increase the expected $B(E2)$ and worsen the discrepancy. It would be instructive in the future to compare these $B(E2)$ values with the results of realistic shell-model calculations that include full configuration mixing.

The second part of Table 2 compares the measured E3 transition strengths with values calculated using angular momentum coupling and the empirical $j_{15/2} \rightarrow g_{9/2}$. E3 strength of $67(14) \times 10^3$ e$^2$ fm$^6$ from 209Pb [20], which includes the enhancement from coupling to the octupole vibration (as indicated by the tilde). Excellent agreement is obtained.

With the new information from 211Pb and the prospect of new experimental information on heavy, neutron-rich nuclei becoming available following the development of radioactive beam facilities, it is timely to consider the likely behaviour of the heavier isotopes. The $0^+, 2^+, 4^+, 6^+$, $8^+$ levels from the $v9/2$ configuration in 212Pb have been measured with the 210Pb($t, p$) 212Pb reaction [4] and the $\gamma$-ray transitions below the $6^+$ level identified in Refs. [5,21]. Empirical shell-model calculations performed with the same interaction as for 211Pb deviate from
periment by $-50$ keV for the ground state, rising to $-110$ keV for the $8^+$ level. The deviations were much smaller in $^{211}$Pb, but in the same direction. Calculations with configuration mixing may reproduce this deviation, which is similar to the behaviour observed in the $N = 126$ isotones [22].

The present data allow an extrapolation to predict the gross features of the structure along the yrast line of the heavier lead isotopes to $^{216}$Pb. This is similar to the extrapolation along the $N = 126$ isotones above $^{208}$Pb to $^{216}$Th [23,24], where the main features can be determined from the two- and three-particle nuclei $^{210}$Po and $^{211}$At. Certainly the $\nu g_{9/2}$ $8^+$ and $6^+$ levels in the even and the $21/2^+$ states in the odd isotopes will continue to be yrast isomers. Also, it is likely that the $27/2^+$ level will continue to be isomeric, either an E2-decaying isomer in $^{211}$Pb or, should it move below the $23/2^+$ state, very long lived. Corresponding $16^+$ yrast isomers from the $\nu g_{9/2}^0 i_{11/2}$ configuration are predicted for the even nuclei. As the $j_{15/2}$ level is expected to come down in energy, the $[\nu g_{9/2}^0 i_{11/2} j_{15/2}]_{33/2}^-$ level in $^{213}$Pb and heavier odd-mass isotopes should develop an even longer, easily measured lifetime.

In conclusion, high-spin states in $^{211}$Pb, including three isomeric states, have been identified up to the highest spins which can be formed from the three valence neutrons. Comparisons with empirical shell-model calculations have allowed the assignment of spins, parities and single-particle configurations up to a $39/2^+$ state at $4.412 \pm \Delta$ MeV. The new results are used to make predictions of the expected behaviour for yrast states in the heavier lead isotopes, including expected $27/2^+$ and $33/2^-$ isomers in the odd-mass nuclei and $8^+$ and $16^+$ isomers in the even-mass nuclei. The measured lifetimes in $^{211}$Pb are suggestive of a possible increase in the neutron effective charge moving away from $^{208}$Pb. The rather long measured lifetime for the $8^+$ isomer in $^{212}$Pb conflicts with this trend, implying that a remeasurement of this lifetime would be justified.

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