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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 γ 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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Keywords: Nuclear structure; Gamma-ray transitions; Isomers; Shell model; Neutron-rich nuclei; Deep-inelastic collisions; Multi-nucleon transfer

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The observation and characterisation of excited states in nuclei near ^{208}Pb is especially important for our understanding of the nuclear shell model. The single- and few-particle excitations provide information on the single-particle energies, residual interactions and transition strengths, the basic ingredients required for the prediction of the properties of more complex configurations. The lack of suitable (stable) beams and targets which would allow access to the neutron-rich nuclei via fusion-evaporation reactions accounts for the paucity of information about excited states in isotopes beyond ^{208}Pb. While low-spin states have been studied in ^{210}Pb with the $^{208}\mathrm{Pb}(t,p)$ and $^{208}\mathrm{Pb}(t,p\gamma)$ 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 $\nu g^2_{9/2}$ configuration were observed with the $^{210}\mathrm{Pb}(t,p)$ 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 $^{210}\mathrm{Pb}(t,d)$ reaction [6] has provided mainly the single-particle states, and $(\alpha$–$\gamma)$-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 $g_{9/2}$, $i_{11/2}$ and $j_{15/2}$ neutron orbitals, with the lowest yrast levels expected to arise from the $\nu g^3_{9/2}$ and the $\nu g^2_{9/2} i_{11/2}$ 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 can 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 $\mathrm{mg/cm^2}$ ^{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–gamma-time 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 2.3×10^9 events were collected, of which 1.1×10^9 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

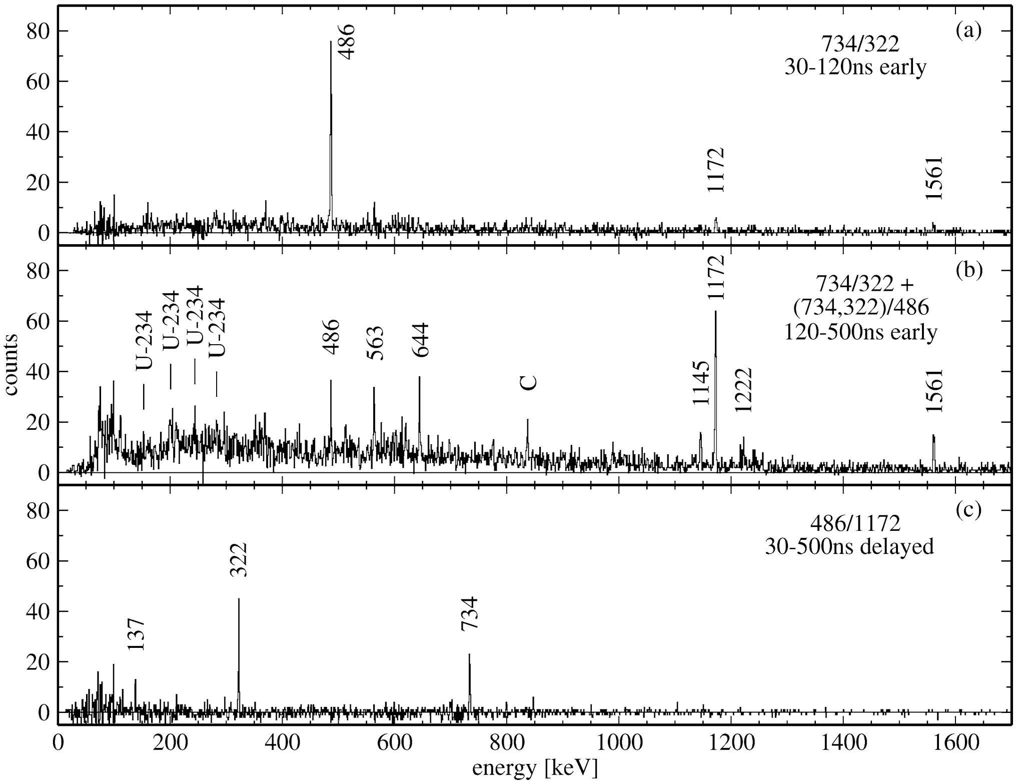

Fig. 1. Coincidence spectra double-gated by γ-ray energy and with additional early and delayed time difference requirements, showing different parts of the main transition cascade in ^{211}Pb and illustrating the presence of two isomeric states. The γ rays assigned to ^{211}Pb are labelled by their energy, an unidentified contaminant is labelled C and γ rays from the coincident target-like fragment (^{234}U) are also labelled. (a) γ rays preceding both the 734 and 322 keV transitions by between 30 and 120 ns. (b) Sum of spectra for γ rays preceding by between 120 and 500 ns the following pairs of transitions: 734/322 keV, 734/486 keV and 322/486 keV. (c) γ rays which are emitted between 30 and 500 ns after both the 486 and 1172 keV transitions.

$A \leqslant 212$. Since all lead isotopes with $A \leqslant 212$ 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 γ 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 γ-ray prominent in the spectrum of γ 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)

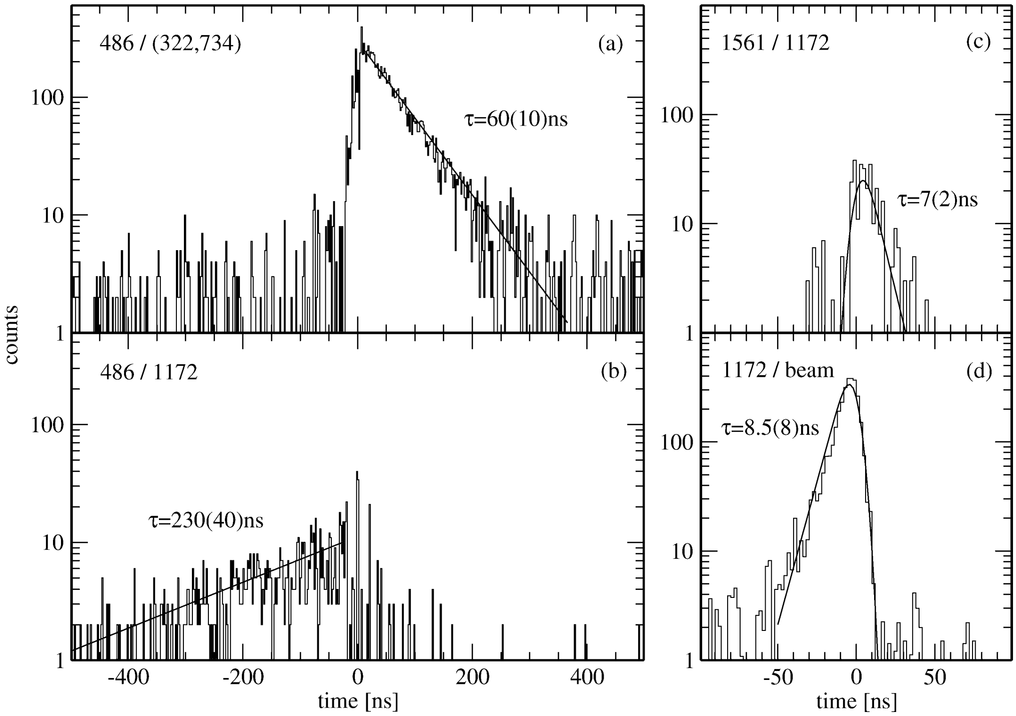

Fig. 2. (a)–(c) Selected spectra showing the time difference between the detection of the marked pairs of γ rays in ^{211}Pb. (First γ ray in list: START, second: STOP.) Note that panel (a) is a sum of two time-difference spectra. Panel (d) shows the time of detection of the 1172 keV γ ray with respect to the beam pulse. This spectrum was produced from the sum of two γ-time matrices, each themselves gated by a coincidence with 734 or 486 keV γ 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 $\nu g_{9/2}^3$ 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 $\nu g_{9/2}^2 i_{11/2}$ 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 Δ 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,

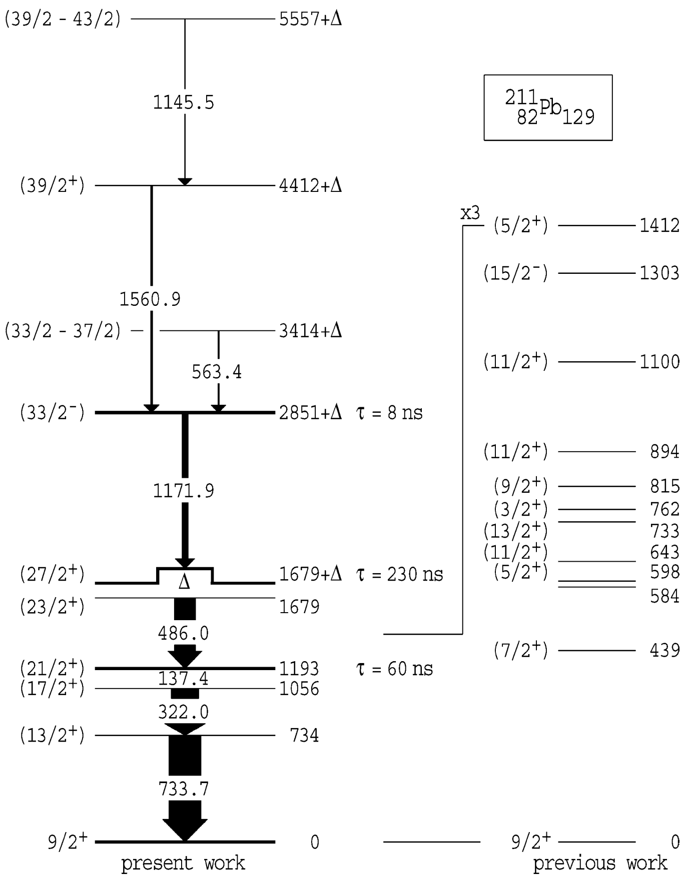

Fig. 3. Level scheme established for ^{211}Pb from previous work [6,7] and the present experiment. In the present level scheme, the widths of the arrows correspond to the estimated relative γ-ray intensities, while the uncertainties in the γ-ray energies vary from ~ 0.2 keV for the most intense transitions to ~ 0.5 keV for the weak transitions.

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 $(\nu g^3_{9/2})_{21/2^+}$ level.

Above the $27/2^+$ state, the next set of valence configurations should arise from the $g_{9/2}i_{11/2}j_{15/2}$ $(I \leqslant 35/2)$ and $i_{11/2}j^2_{15/2}$ $(I \leqslant 39/2)$ configurations giving $33/2^-$ and $39/2^+$ states respectively, with enhanced $j_{15/2} \to g_{9/2}$, 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. A spin of $39/2^+$ 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

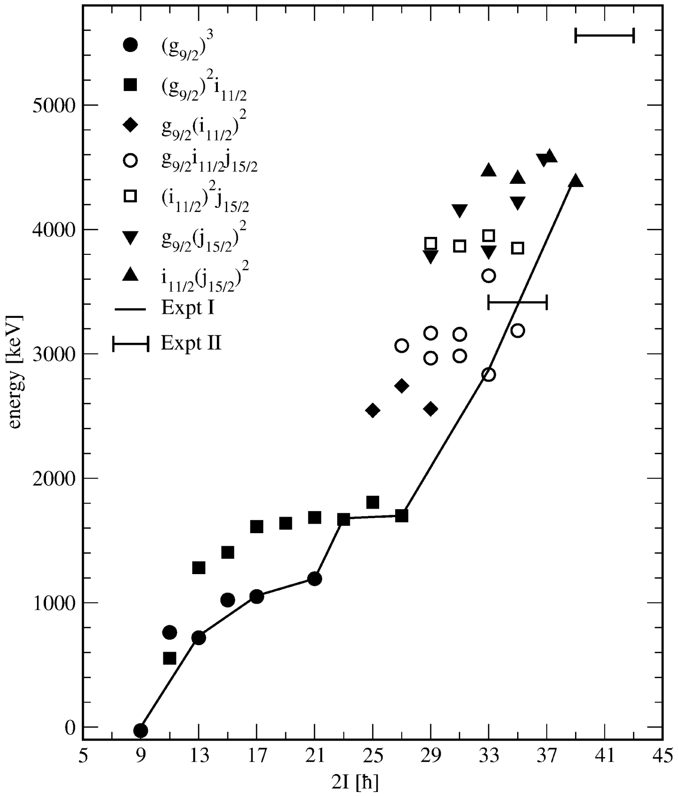

Fig. 4. Calculated excitation energies for selected yrast and near-yrast states in the empirical shell model. Filled/open symbols denote positive/negative parity states, respectively. The solid line connects the observed states for which a spin/parity and configuration assignment has been made. The unobserved $27/2^+ \to 23/2^+$ transition is assumed to have an energy $\Delta = 29$ keV, in agreement with the calculations. The horizontal bars represent the probable range in spin for the states at $3414 + \Delta$ and $5557 + \Delta$ keV.

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 $g^3_{9/2}$, $g^2_{9/2} i_{11/2}$, $g^2_{9/2} j_{15/2}$, $g_{9/2} i_{11/2} j_{15/2}$ and $i_{11/2} j^2_{15/2}$ configurations. 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 ^{209}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 α-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 $g^2_{9/2} i_{11/2}$ configuration will have an important contribution. Although

Table 1
Comparison of measured and calculated excited-state energies for ^{211}Pb

Spin	E_{expt}	E_{theory}[1]	$E_{\text{theory}} - E_{\text{expt}}$	Reference	Configuration
$(3/2^+)$	762	790	+28	[7]	$\nu g^3_{9/2}$
$(5/2^+)$	598	616	+18	[7]	
$7/2^+$	439	421	−18	[7]	
$9/2^+_1$	0	−26	−26	[7][2]	
$(9/2^+_2)$	815	852	+37	[7]	
$(11/2^+)$	894	762	−132	[7]	
$13/2^+$	734	713	−21	[7][2]	
$(15/2^+)$		1003			
$17/2^+$	1056	1050	−6	[2]	
$21/2^+$	1193	1193	0	[2]	
(?)	584			[7]	
$11/2^+$	643	553	−90	[7]	$\nu g^2_{9/2} i_{11/2}$
$21/2^+$		1644			
$23/2^+$	1679	1670	−9	[2]	
$25/2^+$		1765			
$27/2^+$	$1679 + \Delta$	1699	$+20 - \Delta$	[2]	
$15/2^-$	1303	1340	+37	[6]	$\nu g^2_{9/2} j_{15/2}$
$33/2^-$	$2851 + \Delta$	2834	$-17 - \Delta$	[2]	$\nu g_{9/2} i_{11/2} j_{15/2}$
$39/2^+$	$4412 + \Delta$	4378	$-34 - \Delta$	[2]	$\nu i_{11/2} j^2_{15/2}$

[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 $\nu g^2_{9/2} i_{11/2}$ 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 $\nu g^3_{9/2}$ 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 $7/2^+ \to 9/2^+$ 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 $\nu g^3_{9/2}$ configurations the M1 transition is forbidden.

The calculated energy for the $23/2^+$ state from the $g^2_{9/2} i_{11/2}$ 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 $g^2_{9/2} i_{11/2}$ 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 $\nu g_{9/2} i_{11/2} j_{15/2}$ 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 γ-ray decay.

The experimental state at $4412 + \Delta$ keV lies very close to the calculated $[\nu i_{11/2} j^2_{15/2}]_{39/2^+}$ yrast state (see Fig. 4). An E2 decay to the calculated

Table 2
Transition strengths and neutron effective charges in heavy lead nuclei

Nucleus	Transition	Configurations	$B(\mathrm{E}\lambda)_{\mathrm{expt}}$ (e^2 fm$^{2\lambda}$)	$B(\mathrm{E}\lambda)_{\mathrm{theory}}$ (e^2 fm$^{2\lambda}$)	e_{eff}
^{210}Pb	$8^+ \to 6^+$	$g_{9/2}^2$	46(5)	46(5) [1]	0.96(4) [2]
^{211}Pb	$21/2^+ \to 17/2^+$	$g_{9/2}^3$	104(18)	91(10) [3]	1.07(12)
^{211}Pb	$27/2^+ \to 23/2^+$	$g_{9/2}^2 i_{11/2}$	75^{+14}_{-19} [4]	54(8)	1.2(2)
^{212}Pb	$8^+ \to 6^+$	$g_{9/2}^4$	2.1(5)	5.1(6) [5]	0.60(12)
^{211}Pb	$33/2^- \to 27/2^+$	$g_{9/2} i_{11/2} j_{15/2} \to g_{9/2}^2 i_{11/2}$	$71(18) \times 10^3$	$66(14) \times 10^3$ [6]	
^{211}Pb	$39/2^+ \to 33/2^-$	$i_{11/2} j_{15/2}^2 \to i_{11/2} j_{15/2} g_{9/2}$	$\geqslant 15 \times 10^3$ [7]	$100(22) \times 10^3$ [8]	

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

$[\nu g_{9/2} j_{15/2}^2]_{35/2^+}$ state would have low energy and would also be inhibited because the required single-particle transition is the spin-flip case, $i_{11/2} \to g_{9/2}$. Other possibilities are lower energy M2 transitions or a high-energy E3 transition to the observed $[\nu g_{9/2} i_{11/2} j_{15/2}]_{33/2^-}$ state. The latter would be an enhanced, octupole-coupled $j_{15/2} \to g_{9/2}$ neutron transition similar to the $33/2^- \to 27/2^+$ 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 ^{211}Pb and ^{212}Pb with predicted values derived from the $8^+ \to 6^+$ transition in ^{210}Pb [2]. Pure configurations are assumed in all cases so that the quadrupole properties of the $g_{9/2}^n$ states are related by simple geometric factors. The wavefunction of the $23/2^+$ level in ^{211}Pb is calculated to be 73% $|(g_{9/2}^2)_{6^+} \otimes i_{11/2}\rangle$ and 27% $|(g_{9/2}^2)_{8^+} \otimes i_{11/2}\rangle$. If the value of $\langle i_{11/2} \| \mathrm{E2} \| i_{11/2}\rangle$ is taken from Ring et al. [19] to be $-39.3\ e^2\ \mathrm{fm}^4$, the strength of the $27/2^+ \to 23/2^+$ transition is dominated by the $g_{9/2}$ neutrons. The measured E2 transition strengths in ^{211}Pb 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 ^{208}Pb. In stark contrast, the deduced effective charge from the 8^+ isomer in ^{212}Pb [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 ^{212}Pb would be due to pair-scattering of particles out of the $g_{9/2}$ orbital, which would increase the expected $B(\mathrm{E2})$ and worsen the discrepancy. It would be instructive in the future to compare these $B(\mathrm{E2})$ 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 $\widetilde{j_{15/2}} \to \widetilde{g_{9/2}}$, E3 strength of $67(14) \times 10^3\ e^2\ \mathrm{fm}^6$ from ^{209}Pb [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 ^{211}Pb 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 $\nu g_{9/2}^4$ configuration in ^{212}Pb have been measured with the $^{210}\mathrm{Pb}(t,p)^{212}\mathrm{Pb}$ reaction [4] and the γ-ray transitions below the 6^+ level identified in Refs. [5,21]. Empirical shell-model calculations performed with the same interaction as for ^{211}Pb deviate from experiment 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 $\nu g^n_{9/2}$ 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 as in ^{211}Pb or, should it move below the $23/2^+$ state, very long lived. Corresponding 16^+ yrast isomers from the $\nu g^{n-1}_{9/2} i_{11/2}$ configuration are predicted for the even nuclei. As the $j_{15/2}$ level is expected to come down in energy, the $[\nu g^3_{9/2} i_{11/2} j_{15/2}]_{33/2^-}$ 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 $4.412 + \Delta$ 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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