Level structure of ^{211}Pb

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The level structure of ^{211}Pb has been studied using the α decay of ^{215}Po in secular equilibrium with ^{219}Rn. Extremely weak α's and coincident γ rays populate six new levels and a considerable fraction of the $(g_{9/2})^3$ configuration in ^{211}Pb. Previous calculations of the $(g_{9/2})^3$ configuration in ^{211}Pb fit nicely with the observed states and suggest spins and parities. Comparison of the low-lying experimental states in ^{211}At and ^{211}Pb show considerable similarity which is presumably due to the $(9/2)^3$ configuration. [S0556-2813(98)02212-2]

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I. INTRODUCTION

It has been recognized for a long time that the ^{208}Pb nucleus forms a reasonably inert core, and therefore nuclei with a few nucleons on either side of this core can be treated advantageously with the shell model, especially when perturbations with the core vibrations are included. If now one considers the special case of three identical nucleons beyond the ^{208}Pb core, the resulting nuclei would be either ^{211}At with three protons beyond the closed shell, or ^{211}Pb three neutrons outside ^{208}Pb.

Indeed, ^{211}At has been experimentally studied using both in-beam γ spectroscopy [1] and decay scheme spectroscopy [2,3]. Furthermore, a theoretical treatment with the shell model describes the energy levels well [1] and when core vibrations are added [4] the transition probabilities can be understood.

However, much less is known about the structure of ^{211}Pb. The α decay of the $9/2^+$ ground state of ^{215}Po goes almost exclusively (>99.9%) to the $9/2^+$ ground state of ^{211}Pb with hindrance factor (HF) 1.4, with, however, very weak branches (~0.034 and ~0.022%) to states at 438.9 and ~447 keV, respectively [5]. In addition, nuclear reaction spectroscopy has been utilized to study the ^{211}Pb levels employing the reaction ^{210}Pb$(t,d)^{211}$Pb [6]. Angular distributions of the deuterons populating the strongest states from this reaction showed ℓ values of 4, 6, 7, and 2, corresponding to $g_{9/2}$, $i_{11/2}$, $j_{15/2}$, and $d_{5/2}$ shell-model configurations. These configurations are then assigned [6] to the ground state, 639, 1303, and 1412 keV states in ^{211}Pb. However, the weak states at 438.9 and ~447 keV observed in ^{215}Po α decay were not observed in the nuclear reaction spectroscopy.

In view of the 126 neutron closed shell and the 82 proton closed shell in ^{211}At and ^{211}Pb, respectively, the ground-state configurations for these nuclei are expected to be $(h_{9/2})^3$ and $(g_{9/2})^3$. It would then be very interesting to compare the couplings of these three spin 9/2 particles in ^{211}At and ^{211}Pb both experimentally and theoretically. Fortunately, when the calculations of the ^{211}At levels were undertaken, similar calculations were also done for ^{211}Pb. However, the nuclear reaction spectroscopy experiment [6] set an upper limit of ≤1% for the members of the $(g_{9/2})^3$ configuration other than the ground state.

Because of the large number of missing states from the $(g_{9/2})^3$ configuration in ^{211}Pb and the possibility of comparing ^{211}At and ^{211}Pb both experimentally and theoretically, we decided to study the α decay of ^{215}Po again, in spite of the fact that we knew α branchings to the ^{211}Pb states must be very weak.

II. EXPERIMENTAL METHODS AND RESULTS

In our experiment the ^{215}Po source (1.781 ms) was in secular equilibrium with ^{219}Rn (3.96 s). The ^{219}Rn parent was obtained as recoil nuclei from ^{223}Ra (11.435 d). We put a massless ^{223}Ra source (~5μc) in front of a transport tape at 2 mm distance in vacuum. The ^{219}Rn recoils leaving the source were implanted into the tape which was moved between α and γ detectors every 10 s. The measurement required two weeks, during which time we collected 10^5 sources of ^{219}Rn. The ^{223}Ra was originally in secular equilibrium with ^{227}Ac (21.8 y) which was purchased several years ago from the Radiochemical Center at Amersham, England.

The ^{223}Ra was separated from the ^{227}Ac activity by heating it to 1600 °C and collecting it on a 30 μm Al foil. The very thin ^{223}Ra source produced in this manner is well separated from the ^{227}Ac and ^{227}Th which do not begin to evaporate appreciably until ~1900 °C. Within a minute after evaporation, ^{223}Ra is in secular equilibrium with ^{219}Rn and ^{215}Po; within a few hours it is also in equilibrium with ^{211}Pb (36.1 m), ^{211}Bi (2.14 m), and ^{211}Po (0.516 s).

The sources produced in this way were used in α-γ coincidence experiments. The α detector had a full width at half maximum (FWHM) of 17 keV, while the coaxial Ge detector was used for its 20% efficiency for γ and x radiation in spite of its lesser resolution of ~2 keV (FWHM).

Because greater than 99.93% of the α decay of ^{215}Po goes to the ^{211}Pb ground state it was not possible in our experiment to see either good α or γ singles spectra. We were,

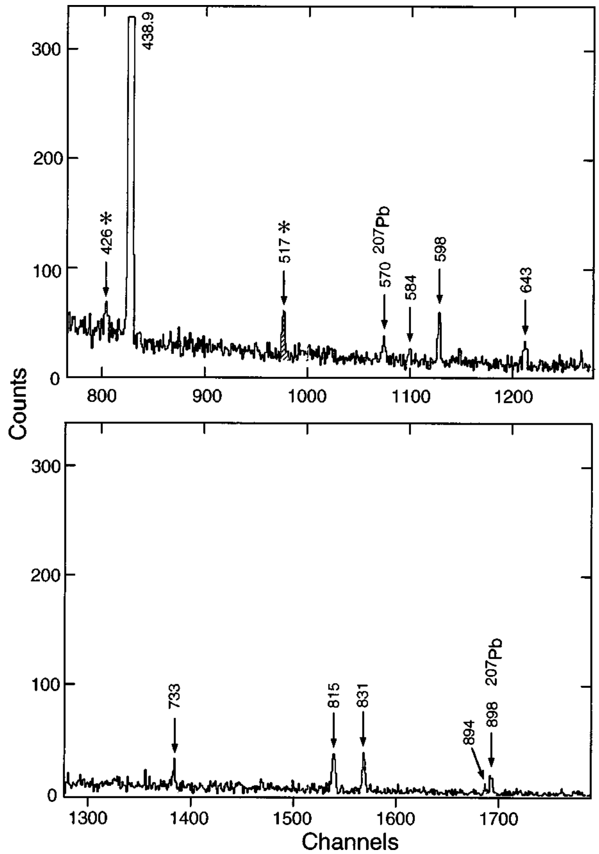

FIG. 1. γ spectrum observed in coincidence with the 6450–7000 keV α's of ^{215}Po with energies labeled in keV. Those γ's with asterisks arise from random α-γ coincidences involving the extremely strong 7384 keV ground state to ground state ^{215}Po α (see Fig. 2). Two of the γ's are also identified as ^{207}Pb secular equilibrium impurities.

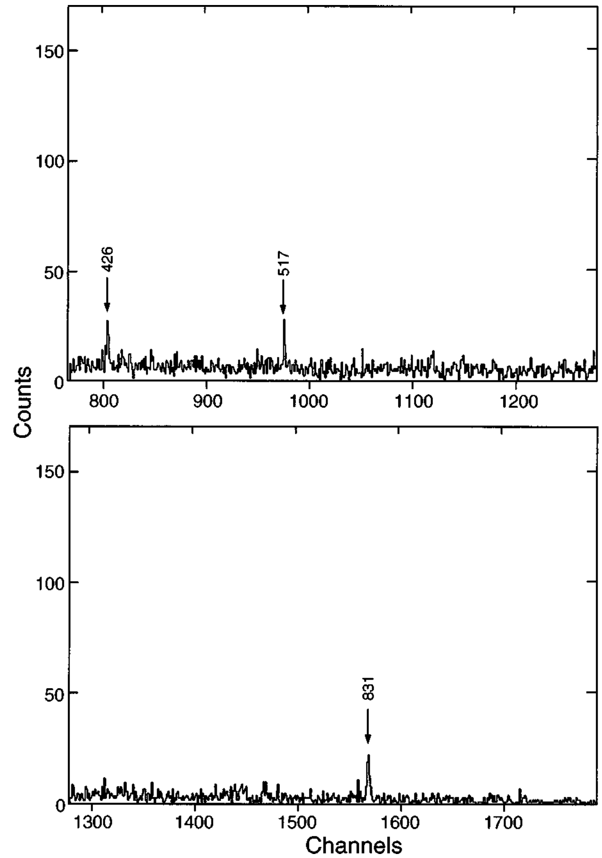

FIG. 2. γ spectrum arising from the random coincidences with the 7384 keV ground state to ground state ^{215}Po α (see Fig. 1).

however, able to see the very weak γ's in coincidence with the 6450–7000 keV α's of ^{215}Po. They are shown in the two panels of Fig. 1. The 570 and 898 keV γ rays of Fig. 1 correspond closely to the strongest γ rays in ^{207}Pb following the α decay of ^{211}Po and are labeled ^{207}Pb. Three other γ rays in Fig. 1 are labeled with an asterisk. They are random coincidences as shown in Fig. 2 by the fact that they are observed in random coincidence with the extremely strong 7384 keV ground state to ground state $^{215}\text{Po}\rightarrow{}^{211}\text{Pb}$ α. Because of the extreme weakness of all the γ rays except the 438.9 keV γ depopulating the excited levels in ^{211}Pb, we have found the reproducibility and accuracy of the γ rays in Figs. 1 and 2 are less than that normally obtained using Ge detector systems. For that reason the γ ray energies are given only to one keV except in the case of the 438.9 keV γ which is believed to be accurate to ± 0.2 keV. We did not confirm the level at $\sim$447 keV in spite of the previously observed rather high α feeding (0.022%) [5].

After locating the very weak γ's using coincidence experiments we were then able to do γ-α coincidence experiments on each of the γ's to determine the energies of the ^{215}Po α's which populate them. These coincidence experiments are shown in the panels of Figs. 3 and 4. The ordering in these panels is from highest energy α's to lower energy alphas, corresponding to lower energy excited states to higher energy excited states in ^{211}Pb. In Fig. 3, panel (a) presents α coincidences with the 438.9 keV γ; panel (b), with the 584 keV γ; panel (c), with the 598 keV γ; and panel (d), with the 643 keV γ. In Fig. 4, panel (a) presents α coincidences with the 733 keV γ; panel (b), with the 815 keV γ; panel (c), with the 894 keV γ; and panel (d) shows that the 898 keV γ is in coincidence with the 6586 keV α of ^{211}Po.

In Fig. 5 the gamma spectrum in coincidence with the 6952 keV α is displayed. The ratio of the K x-ray intensity to that of the 438.9 keV γ (X_K/γ) was determined to be 3.4 $\pm 1.0\times 10^{-2}$. The theoretical value for an $E2$ transition is 2.8×10^{-2}, whereas that for an $M1$ transition is 1.3 $\times 10^{-1}$. Thus the 438.9 keV transition is largely $E2$, although one cannot rule out a small amount of $M1$.

III. ENERGY-LEVEL SCHEME OF ^{211}Pb

The energy-level scheme of ^{211}Pb below 895 keV, as determined in this study, is given in Fig. 6. To the extreme right the energies of the populating α's, in keV, their intensities in percent, and their hindrance factors (HF's) are given. Energy levels are given as horizontal lines and γ transitions as vertical lines. The γ transition depopulating the 762 keV and denoted by the dashed vertical line is inferred but not actually observed from the fact that the 438.9 keV γ is in coincidence with both the 6952 and 6634 keV α's. Since the 762 keV level is therefore observed only through its population by the very imprecise α of 6634$\pm$ 15 keV, its energy is shown in parentheses. In a similar way the γ transition de-

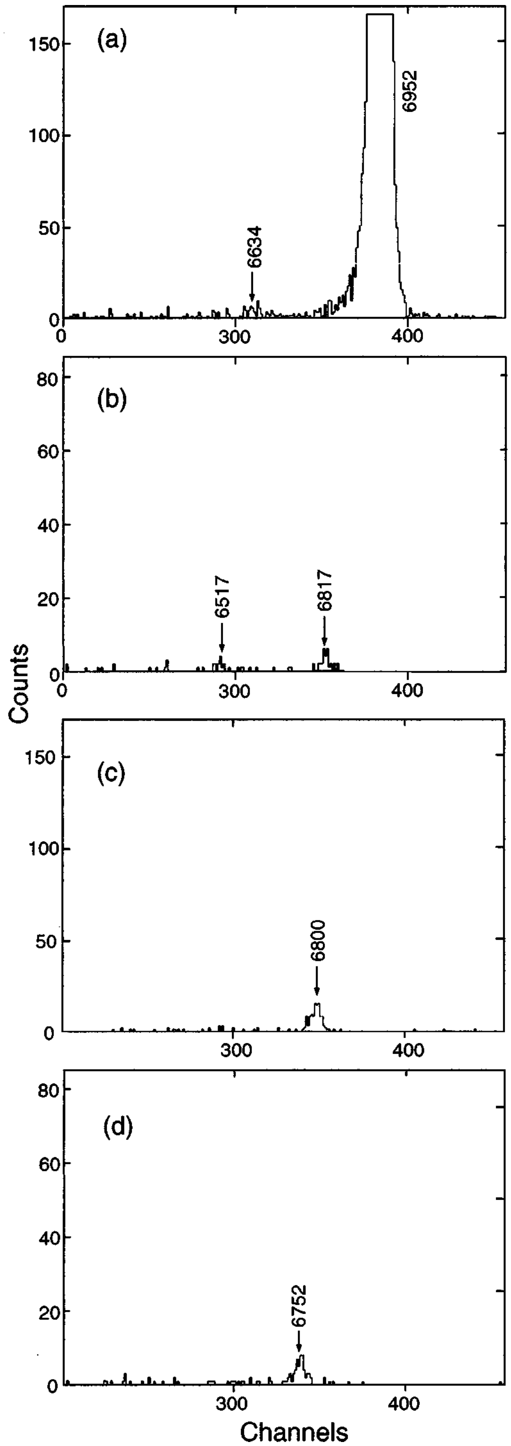

FIG. 3. α spectra of ^{215}Po in coincidence with various weak γ's of ^{211}Pb. (a) Coincidences with 438.9 keV γ, (b) coincidences with 584 keV γ, (c) coincidence with 598 keV γ, (d) coincidence with 643 keV γ.

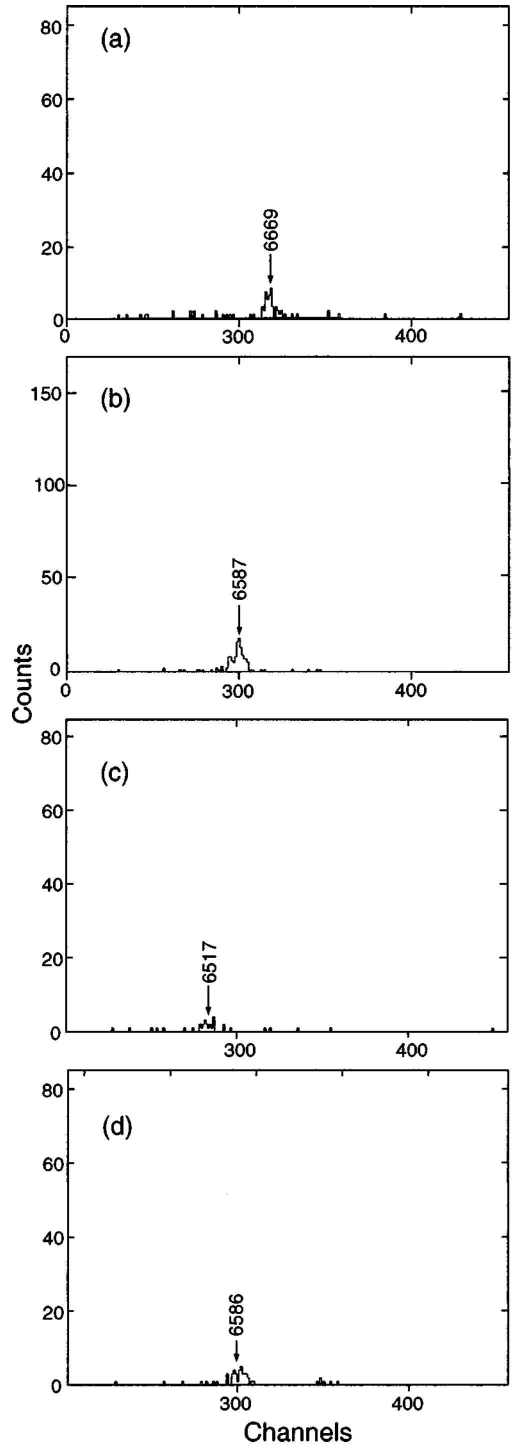

FIG. 4. α spectra of ^{215}Po and ^{211}Po in coincidence with various weak γ's of ^{211}Pb and ^{207}Pb, respectively. (a) Coincidence with 733 keV γ, (b) coincidence with 815 keV γ, (c) coincidence with 894 keV γ, (d) coincidence with the 898 keV γ of ^{207}Pb.

populating the 894 keV transition is inferred by the fact that the 584 keV gamma is in coincidence with both 6817 and 6517 keV α's. To the left, two calculations [4,7] are compared with our experimental results.

The placement of the levels, with the possible exception of the 762 keV level, is quite certain. This results because the sum of the energies of the γ transitions and the α energies populating the state (after recoil effects are taken care of) add up to the energy of the α populating the ground state [7384(s) keV] within experimental error. The more accurate magnetic spectrographic value of the α energy populating the ground state of 7386.2 (0.8) keV agrees within errors with our measurement.

In contrast with the established level structure, most of the spin assignments are very uncertain. The ground-state spin of ^{211}Pb is $9/2^+$ [5] as implied by the low HF (1.3) of the α decay of the $9/2^+$ ground state of ^{215}Po. Furthermore, the 643 keV state corresponds very closely to the 639 $\pm$10 keV

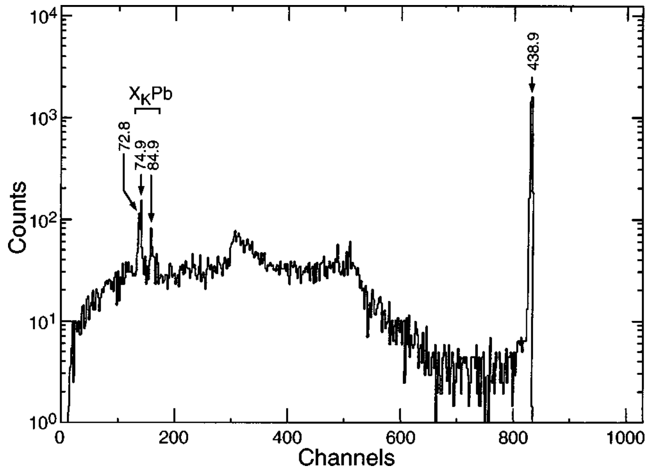

FIG. 5. γ spectrum in coincidence with the 6952 keV α of ^{215}Po. Using the X_K/γ ratio, it is possible to show that 438.9 keV γ is largely $E2$ (see text).

state, with $i_{11/2}$ shell-model assignment, observed in the ^{210}Pb$(t,d)^{211}$Pb reaction [6]. Thus only the ground state with spin-parity $9/2^+$ and the 643 keV state with spin-parity $11/2^+$ and configurations $(g_{9/2})^3_{v=1}$ and $(g_{9/2})^2 i_{11/2}$, respectively, have definite assignments. For other states we use the HF's and comparison with theory. The $7/2^+$ assignment for the 438.9 keV state is quite probable. All theoretical treatments place the 7/2 state as the first excited state of the $(9/2)^3$ configurations, very close to the experimentally observed values. Furthermore, the $E2(+M1)$ multipolarity of the 438.9 keV transition is consistent with this assignment. The $9/2^+$ assignment of the 815 keV state is reasonable since a small admixture of the ground state might be expected to lower its HF to the observed value of 120. Of the remaining unassigned states the 762 keV state with assigned spin $3/2^+$ and the 584 keV state have higher HF's than the other three states. The required $\ell=4$ α decay to the $3/2^+$ state at 762 keV would imply a higher HF like $\sim$ 1000 as observed. The remaining three states with HF's between 400 and 850 are assigned to the lowest-lying members of the $(g_{9/2})^3$ configuration using the theoretical treatment of Ref. [4]. The agreement is surprisingly good. Nonetheless we emphasize again that the only definite spin parities in ^{211}Pb are the ground state and the 643 keV state. It must also be remembered that the three states with HF's between 400 and 850 are assigned in just the way to make them fit with theory. It should also be noted that the 584 keV state is not assigned a spin and parity. It is populated with a much higher hindrance factor in the α decay of ^{215}Po than any other state in ^{211}Pb and presumably has a reasonably high spin in view of the tentative γ decay from the 894 keV state.

IV. DISCUSSION

With the exception of the unassigned state at 584 keV, the experimental ^{211}Pb level structure of Fig. 6 agrees well with the level structure expected from the configuration $(g_{9/2})^3$ with the appended $(g_{9/2})^2 i_{11/2}$ configuration at 643 keV. The

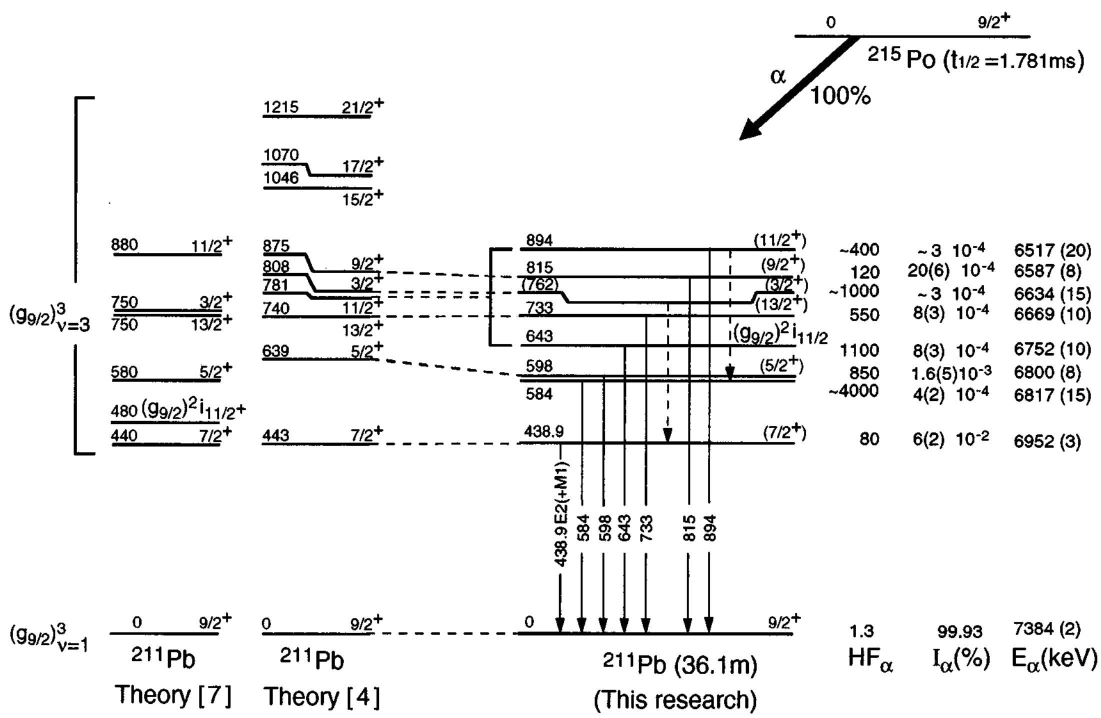

FIG. 6. Energy-level scheme of ^{211}Pb up to 894 keV resulting from the present study, together with two theoretical calculations. α energies in keV (together with their errors), intensities in percent, and hindrance factors (HF's) populating the levels are shown to the right. Transitions are shown as vertical lines with their energies in keV. Dashed lines represent transitions which can be inferred from the coincidence data but have not been explicitly observed. Energies of the levels are shown to the left, and spins and parities (except for the 584 keV level) are shown to the right.

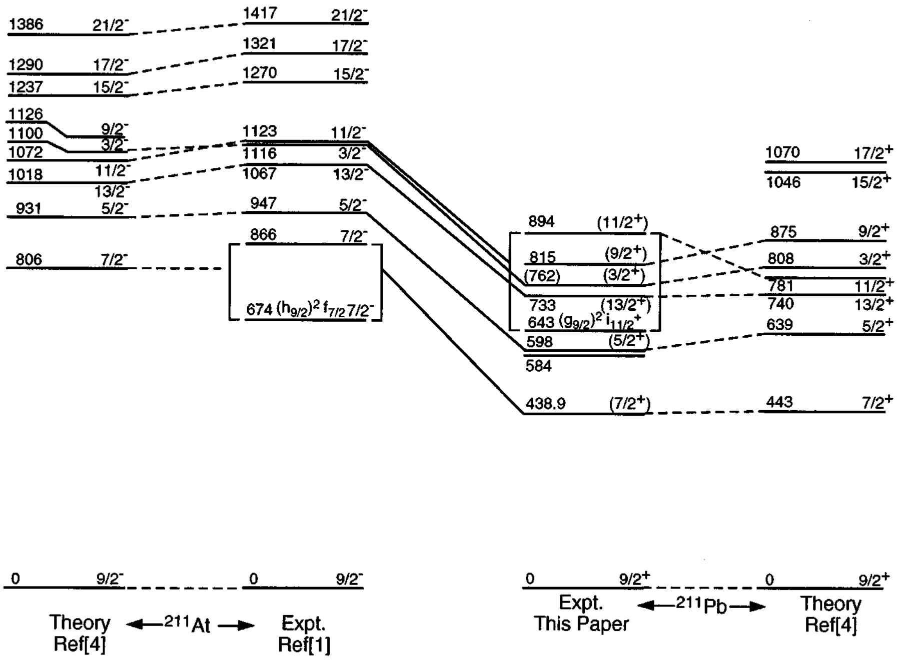

FIG. 7. Comparison of the experimental and theoretical level structure of ^{211}At (left) and ^{211}Pb (right). Mixing with other configurations and one member of the $(9/2)^3$ configurations is shown with brackets in the experimental level schemes.

$11/2^+$ member of the $(g_{9/2})^2 i_{11/2}$ configuration and the $11/2^+$ member of the $(g_{9/2})^3$ configuration are expected to mix. This is shown by the bracket in the experimental spectrum of Fig. 6. This mixing may also explain why the $11/2^+$ state in the theoretical spectrum of Ref. [7] in Fig. 6 lies higher than that of Ref. [4] which took no account of the mixing. This in turn may also explain the minor discrepancy between the $11/2^+$ states in the theoretical spectrum of Ref. [4] and the experimental spectrum.

It is of considerable interest to compare the $(h_{9/2})^3$ and $(g_{9/2})^3$ configurations of ^{211}At and ^{211}Pb, respectively. Since each involves the $(9/2)^3$ configuration, we could expect a very similar gross structure. Both the experimental and theoretical comparisons are made in Fig. 7. The experimental data for ^{211}At are taken from Ref. [1] whereas theoretical treatments for both ^{211}At and ^{211}Pb are those of Ref. [4]. Just as in the case of ^{211}Pb where failure to include the $(g_{9/2})^2 i_{11/2}$ configuration causes an effect on the energy of the $11/2^+$ state, so also in ^{211}At the failure to include the $(h_{9/2})^2 f_{7/2}$ configuration causes an energy effect on the $7/2^-$ state calculated in Ref. [4]. However, again the experimental-theoretical comparison for ^{211}At is very good. Furthermore, the spin parities of the states are more uniquely determined and the entire sequence of the $(h_{9/2})^3$ configuration is observed [4].

Perhaps most impressive is the amazing similarity between the level structures of ^{211}At and ^{211}Pb in Fig. 7. Although both ^{211}At and ^{211}Pb have 211 total nucleons, it seems that the more expanded level structure of ^{211}At results from the smaller core of 82 protons in ^{211}At in contrast with the larger core of 126 neutrons in ^{211}Pb. Furthermore, this difference is beautifully mirrored in both experiment and theory.

V. CONCLUSIONS

Using the α decay of ^{215}Po, a considerable fraction of the states of the $(g_{9/2})^3$ configuration in ^{211}Pb have been observed. The experimental states of ^{211}Pb are compared with theoretical calculations and with the low-lying states of ^{211}At with the $(h_{9/2})^3$ configuration. A very impressive similarity in the $(9/2)^3$ configurations in ^{211}Pb and ^{211}At is observed.

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