α decay of ^{216}Fr and ^{212}At

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The alpha and coincident gamma decays of ^{216}Fr and ^{212}At in secular equilibrium with 0.8 s ^{224}Pa and 26.1 ms ^{220}Ac have been studied with emphasis on the level scheme of ^{212}At. The level structure has been interpreted in terms of the shell model configurations $\pi(h_{9/2})^3_{9/2}\nu(g_{9/2})$, $\pi(h_{9/2})^2_{0+}(f_{7/2})\nu(g_{9/2})$, and $\pi(h_{9/2})^3_{9/2}\nu(i_{11/2})$. These configurations are then compared with the calculated configurations in ^{212}At and with the corresponding experimental configurations in ^{210}Bi and ^{212}Bi. In all three cases plots of the experimental energies vs the spin show the expected inverted parabola shape, but as we move farther away from the ^{208}Pb closed shells, the inverted parabolas become more compressed. [S0556-2813(96)03911-8]

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I. INTRODUCTION

The odd-odd nuclei just beyond the double closed shell at ^{208}Pb are an interesting and important testing ground for the shell model. ^{210}Bi, with only one proton and one neutron beyond the closed shell, has been heavily studied. The lowest-lying configurations $\pi(h_{9/2})\nu(g_{9/2})$, $\pi(h_{9/2})\nu(i_{11/2})$, and $\pi(f_{7/2})\nu(g_{9/2})$ all have the expected inverted parabola structures in spin vs energy plots. That is, the lowest and highest spins in the configurations are relatively low in energy, whereas the intermediate spins lie higher in energy. Recently we have studied the odd-odd nuclei ^{212}Bi [2] and ^{216}At [1] following alpha decays from the parent ^{228}Pa. Whereas the data and spin members of the configurations in these nuclei are much less complete than in ^{210}Bi, we have been aided by theoretical calculations of the configurations in the case of ^{212}Bi by Warburton [3].

In general, we find that the complexity of the spectroscopy increases enormously as we add valence nucleons. Nonetheless, it is still possible to see aspects of the shell model configurations particularly in ^{212}Bi. The energy spacings of the configurations are more compressed and as we reach ^{216}At the particle-particle structure begins to change to a mixed particle-hole structure in which the attractive p-n matrix elements of the particle-particle configurations are forced to compete with the repulsive p-n matrix elements of the particle-hole configurations. The result is a flattening of the inverted parabola of spin vs energy for the configurations prior to its reversal into the normal particle-hole parabola.

In a recent study of the levels in ^{220}Ac, we also studied the levels in ^{216}Fr and ^{212}At which are in secular equilibrium with ^{220}Ac [4], using alpha decay spectroscopy. ^{212}At is a particularly interesting nucleus because it is a kind of ‘‘mirror nucleus’’ to ^{212}Bi. While ^{212}At has three protons and one neutron beyond ^{208}Pb, ^{212}Bi has one proton and three valence neutrons.

The alpha decaying 1^- ground state and 9^-($T_{1/2}$ = 0.12 s) isomeric state of ^{212}At were identified very early [5]. Use of the ^{208}Pb (^{7}Li,3n) reaction led to the observation [6] of a number of high spin states, three of which are isomeric, and all of which funnel down through the 9^- isomeric state at 223 keV. Study of the ^{209}Bi(α,n)^{212}At reaction [7] led to the observation of an additional 5^- isomeric state ($T_{1/2}$ = 32 $\pm$ 1 ns) and a number of other low spin and high spin states, which were interpreted in terms of the shell model. However, an important aspect of this study was thrown into doubt by the recent Nuclear Data Sheets interpretation [8] of the (α,n) data [7] which found it necessary to change the 0^- state at 55.1 keV to 1^- or 2^- because of the mixed $M1$ + $E2$ multipolarity of the 308.9 and 290.7 keV transitions populating the 55.1 keV state.

The purpose of this alpha decay study, in addition to the experimental data obtained with, however, no new levels, is to see if we can throw additional experimental light on configurations in ^{212}At such as $\pi(h_{9/2})^3\nu(g_{9/2})$, $\pi(h_{9/2})^3\nu(i_{11/2})$, and $\pi(h_{9/2})^2(f_{7/2})\nu(g_{9/2})$, and compare them with the ‘‘mirror’’ configurations in ^{212}Bi and with calculations.

II. EXPERIMENTAL METHODS AND RESULTS

^{212}At ($T_{1/2}$ = 0.315 s) was studied by observing the alpha decay of ^{216}Fr ($T_{1/2}$ = 0.70 μs), which was in secular equilibrium with ^{224}Pa ($T_{1/2}$ = 0.8 s) [8], along with ^{220}Ac ($T_{1/2}$ = 26 ms). The ^{224}Pa was produced using the reaction ^{209}Bi (^{18}O,3n), a 96 MeV ^{18}O beam, and a current of ~0.6 μA, from the Grenoble SARA accelerator. ^{209}Bi targets were self supporting with a 1.5 mg/cm^2 thickness. A He-jet system was used for transporting the resulting activity to a tape transport which in turn moved the activity in front of two different experimental arrangements. In one, singles alpha and gamma and alpha-gamma coincidences were recorded. In the other arrangement, singles alpha, gamma and

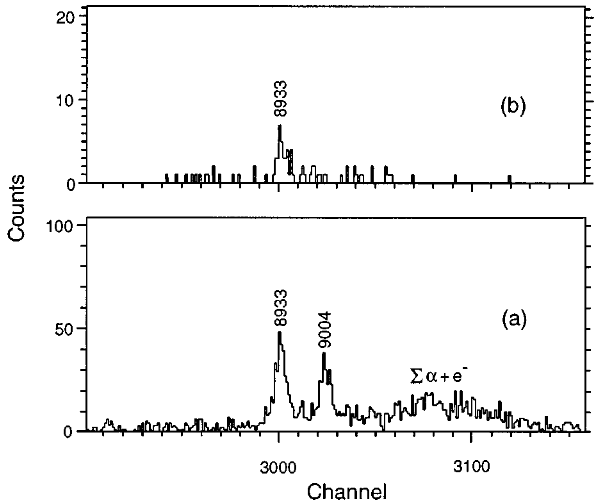

FIG. 1. Alpha spectra of ^{216}Fr in coincidence with gamma rays. Alpha energies are labeled in keV. (a) ^{216}Fr alphas in coincidence with all-gamma rays. Note the broad peak at higher energies labeled $\Sigma\alpha + e^-$. It is the sum peak of alphas and a number of the conversion electrons. (b) ^{216}Fr alphas in coincidence with the 160.3 keV gamma ray of ^{212}At.

electron, alpha-gamma, alpha-electron, and alpha-gamma-electron coincidence measurements were recorded simultaneously. Collection measurement cycles were 2 s, appropriate to the 0.8 s half-life of ^{224}Pa.

The high energy alpha spectrum in coincidence with all gammas is shown in Fig. 1(a), while the high energy alpha spectrum in coincidence with the 160.3 keV gamma is shown in Fig. 1(b). The two alpha peaks in Fig. 1(a) correspond to the 9004 keV ground state to ground state ^{216}Fr to ^{212}At transition and the 8933 keV alpha transition which is depopulated by a strong gamma cascade. The 9004 keV alpha transition is observed in spite of being a ground state to ground state transition because it has a relatively short half-life (700 ns) and is in coincidence with a very strong 133.3 keV $E2$ transition in ^{216}Fr. The $E2$ multipolarity of this transition has been assigned both by the K/L ratio of the electron conversion lines and by the half-life (71 ± 5 ns) of the corresponding level. In Fig. 1(b), using a 160.4 keV gate, the 9004 keV alpha drops out as expected.

Of special interest is the balance in the loop of energies between the 1^- and 3^- states in ^{216}Fr and ^{212}At. More specifically, if one takes the energies of the 9004 keV alpha, adds the 133.3 keV energy in the ^{216}Fr level scheme, and subtracts the 205.3 keV level of the ^{212}At level scheme, making the necessary alpha recoil corrections, one obtains the 8933 keV alpha energy observed. Furthermore, taking into account the partial lifetime of the 8933 keV alpha, the hindrance factor of the 8933 keV alpha is 4, while that of the 9004 keV alpha is 2.5. We see therefore that the two alpha decay paths of the loop correspond to unhindered alpha decays between the same spins and configurations. This is shown in the level scheme of Fig. 2, which will be discussed at length in the latter part of this section, and forms the backbone of the ^{212}At level structure.

The gamma-ray spectrum in coincidence with the 8933 keV alpha particle populating the 3^- level in ^{212}At in an allowed unhindered decay [Fig. 1(b)] is shown in Fig. 3, and the resulting gamma-ray energies, intensities, and multipolarities are given in Table I. Table II lists the alpha groups, their intensities, hindrance factors, and the proposed transition type in the decay of ^{216}Fr to ^{212}At. In addition to the expected K x rays of At, rather strong chance coincidences from the K x rays of Fr are observed.

It is well established [8] that the ground state of ^{212}At ($t_{1/2} = 0.315$ s, $J^\pi = 1^-$) and the 223 keV state ($t_{1/2} = 0.12$ s, $J^\pi = 9^-$) alpha decay to a large number of low-lying states in ^{208}Bi. However, the great majority of the intensities from both the 1^- and 9^- states in ^{212}At go to the 5^+ ground state and 4^+ first excited state at 62.9 keV members of the $\pi h_{9/2} \nu p_{1/2}$ configuration. In this experiment we have been able to measure alpha groups in coincidence with the 62.9 keV gamma transition. In this way we are able to see the alpha depopulation of both the 1^- ground state (g.s.) and 9^- 223 keV state in ^{212}At. The results are shown in Fig. 4. Because of the limited resolution, some of the alpha groups correspond to the population of two levels in ^{208}Bi. Furthermore, some of the alpha groups previously observed populating levels in ^{208}Bi are not observed in Fig. 4 because they do not connect with the 4^+ states at 62.9 keV, as required by the coincidence relationship. These alpha populations are also shown in the level scheme of Fig. 2.

The level scheme of Fig. 2 shows the connections between the levels in ^{216}Fr, ^{212}At, and ^{208}Bi. These connections are alpha decays and the corresponding alpha energies, intensities, and hindrance are given to the right of the ^{212}At and ^{212}Bi level schemes. In the case of the alpha decays populating the 5^+ and 4^+ ground state and first excited state of ^{208}Bi, the alpha energies, intensities, and hindrance factors are taken from the *Table of the Isotopes* [9]. The levels in ^{212}At are mostly taken from the results of Refs. [6] and [7]. The very low hindrance factors in the alpha decays of the 1^- ground state and the 3^- 133.3 keV states of ^{216}Fr require

TABLE I. Gamma transition in ^{212}At in coincidence with ^{216}Fr alphas.

$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)/100_\alpha$	Multipol.	Comments
45.0 (0.1)	0.15 (0.05)	$M1$	$I(45)/I(160)$ agreement for $M1$ cascade
55.0 (0.2)	~0.03		Feeding not identified
160.3 (0.1)	1.0 (0.2)	$M1$	$(X_K/\gamma)_{\rm expt} = 3 \pm 1$
X_K(At)	3.0 (0.5)		0.1($E1$); 2.7($M1$); 0.3($E2$)

TABLE II. Alpha lines observed in the ^{216}Fr → ^{212}At decay.

$E\alpha(\Delta E\alpha)$ keV	$I\alpha(\Delta I\alpha)$%	HF	Transition proposed
8811[a] (15)	~0.2	280	$1^- \rightarrow (3^-)$ $l = 2$
8861[a] (15)	0.5 (0.2)	180	$1^- \rightarrow (2^-)$ $l = 2$
8933 (8)	4 (1)	4	$3^- \rightarrow 3^-$ $l = 0$
9004 (5)	95 (1)	2.5	$1^- \rightarrow 1^-$ $l = 0$

[a]Weak alpha lines observed in coincidence with 45.0 and 160.3 keV gamma transitions in a second high statistics and closer geometry experiment.

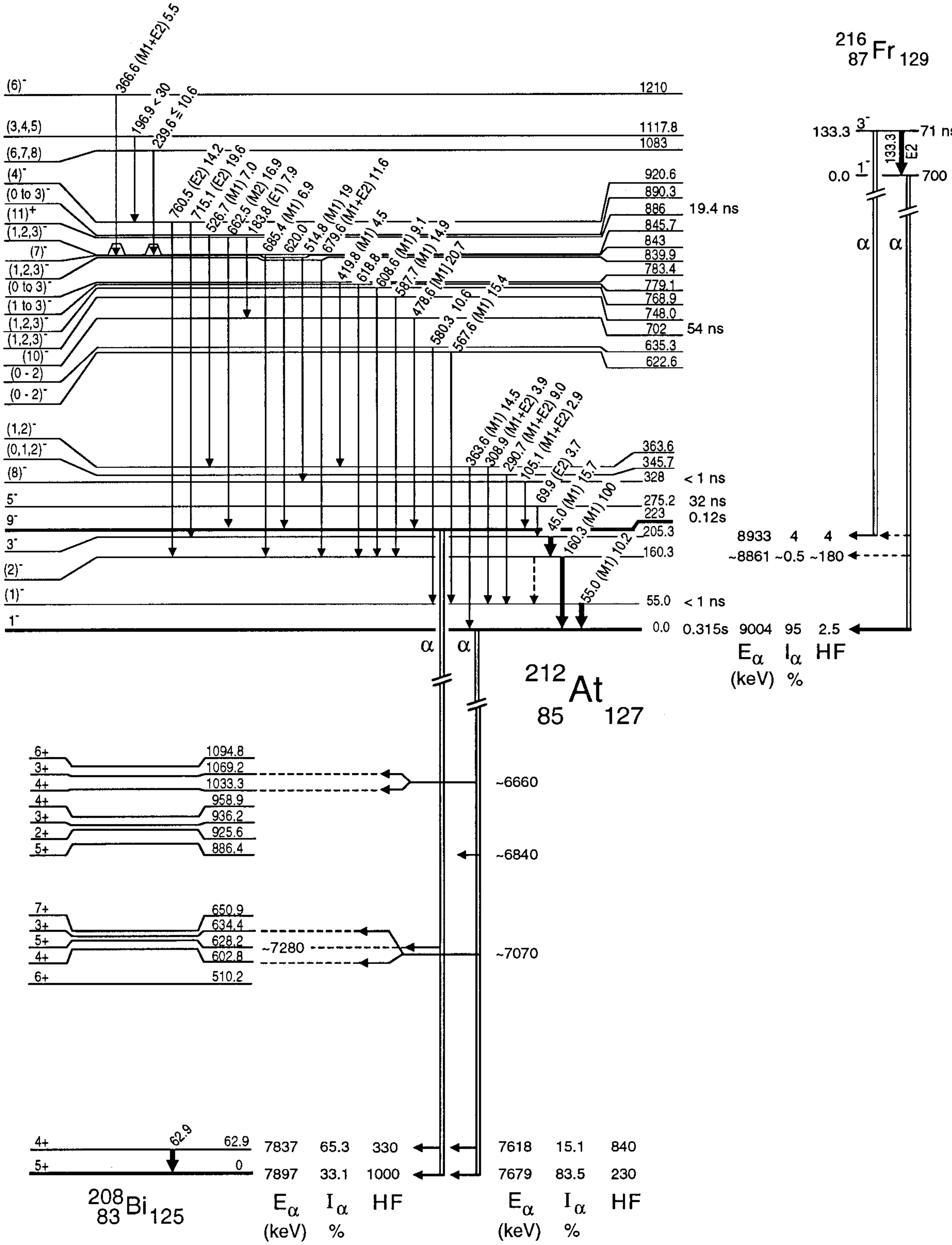

FIG. 2. Partial level schemes of ^{216}Fr, ^{212}At, and ^{208}Bi with emphasis on ^{212}At. To the right of the ^{212}At and ^{208}Bi level schemes the alpha energies, intensities, and hindrance factors (HF's) are given. For the higher levels in ^{208}Bi only the approximate alpha energies are given. The bold vertical arrows are the gamma rays observed in these experiments. Other gamma rays were observed in the ^{208}Pb (^{7}Li,3n) and ^{209}Bi (α,n) reactions [6,7].

that the populated ground state and 205.3 keV state in ^{212}At have spin parity 1^- and 3^-, respectively. Furthermore, the consecutive $M1$ decays from the 3^- state to the 1^- ground state through the 160.3 keV state require that this state have spin 2^-. The 275.2 keV state which decays into the 3^- 205.5 keV state by an $E2$ transition without decay into any of the lower energy low spin states implies $J^\pi = 5^-$. The spin-parity assignments of the g.s., 205, 160, and

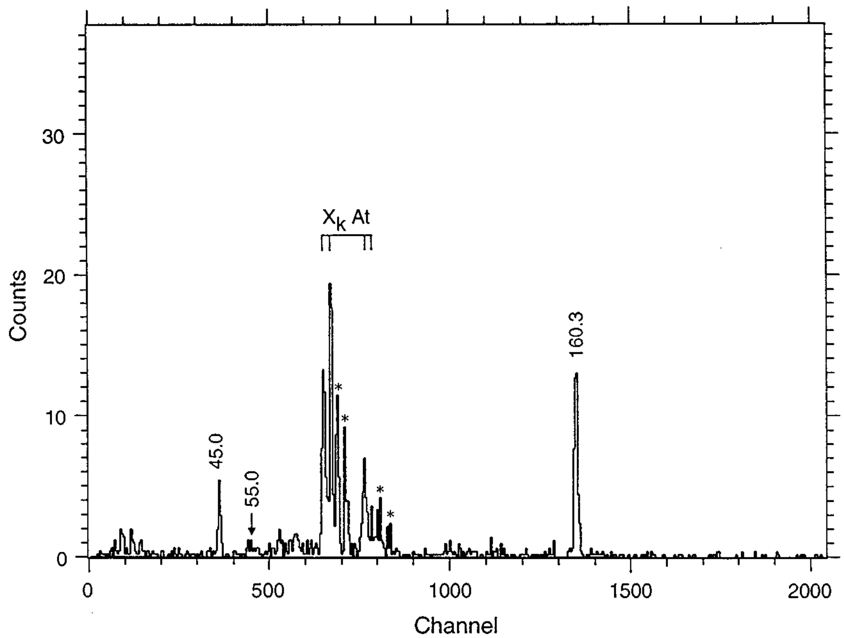

FIG. 3. Gamma-ray spectrum observed in coincidence with the 8933 keV alpha. Gamma rays are labeled in keV. The K x rays of At are indicated. Asterisks label K x rays of Fr which are in chance coincidence with the 8933 keV alpha.

275 keV states have been previously suggested [8]. In some cases we have been able to give more definite assignments. The dashed transition between the 160.3 and 55.0 keV states is required for intensity balances. All alpha and gamma transitions observed in these experiments are shown in bold lines to distinguish them from transitions observed in other experiments.

Although there can be no doubt about the existence of the other levels in Fig. 2 (not observed by us) and, for the most part, the parities of these levels because of the observed multipolarities, the spins of many of these levels have not been determined with certainty. Using the available data, we have attempted to make the most reasonable level assignments which are in agreement with those in the Nuclear Data Tables [8]. In some cases the data are insufficient to avoid multiple assignments.

III. DISCUSSION OF THE LEVEL SCHEME

As in ^{212}Bi, we expect the low-lying shell model configurations of ^{212}At to have the inverted parabola structure in a plot of spin vs energy. However, the low-lying configurations will have a three-proton–one-neutron configuration. Indeed, the lowest-lying configurations should be $\pi(h_{9/2})^3\nu(g_{9/2}),\pi(h_{9/2})^3\nu(i_{11/2})$, and $\pi(h_{9/2})^2(f_{7/2})\nu(g_{9/2})$.

Shell model calculations using the coupling of the $g_{9/2}$, $i_{11/2}$, and $jj_{15/2}$ orbitals of ^{209}Pb to the seniority-1 levels in ^{211}At have been used by Lönnroth *et al.* [7] to calculate the levels in ^{212}At. These calculated levels are shown in Fig. 5 with the corresponding configurations. The levels of all three configurations are mixed. This is especially true for the two excited configurations which lie close together in energy. Even so, we see quite clearly the inverted parabola structure of these calculated levels.

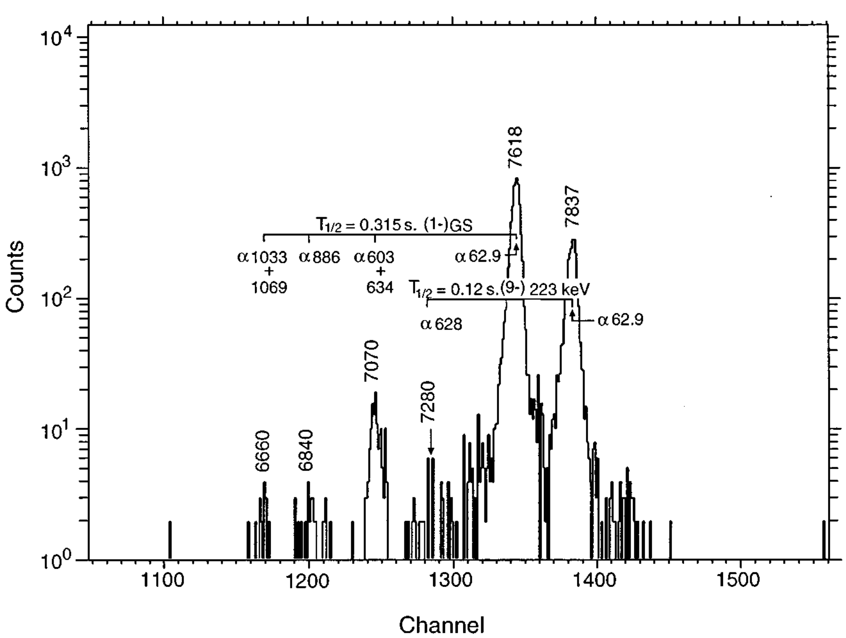

FIG. 4. Alpha spectrum of ^{212}At in coincidence with the 62.9 keV gamma of ^{208}Bi. Alpha energies are labeled in keV. The ladder system connected with various alpha groups (labeled by the levels populated) is used to point out the alpha branching from the ground state of ^{212}At and from the isomeric 9^- state.

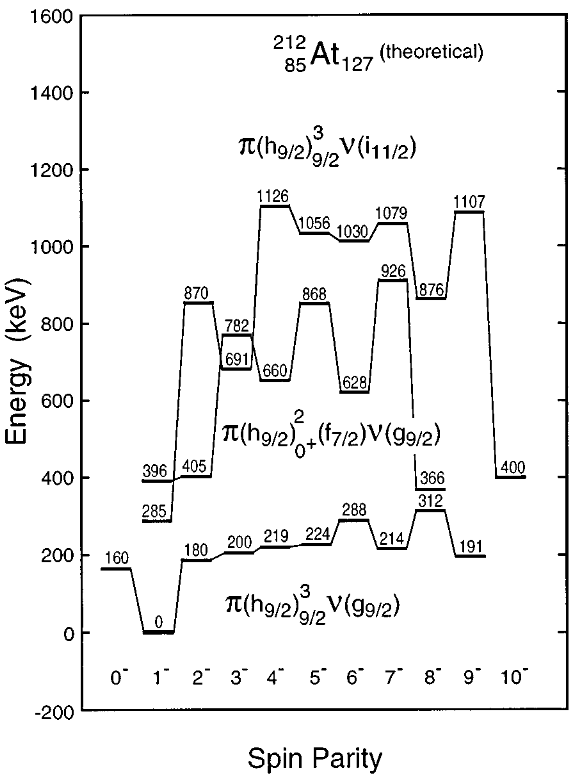

FIG. 5. Calculated [7] level structure of ^{212}At. Energies are given in keV and configurations, indicated.

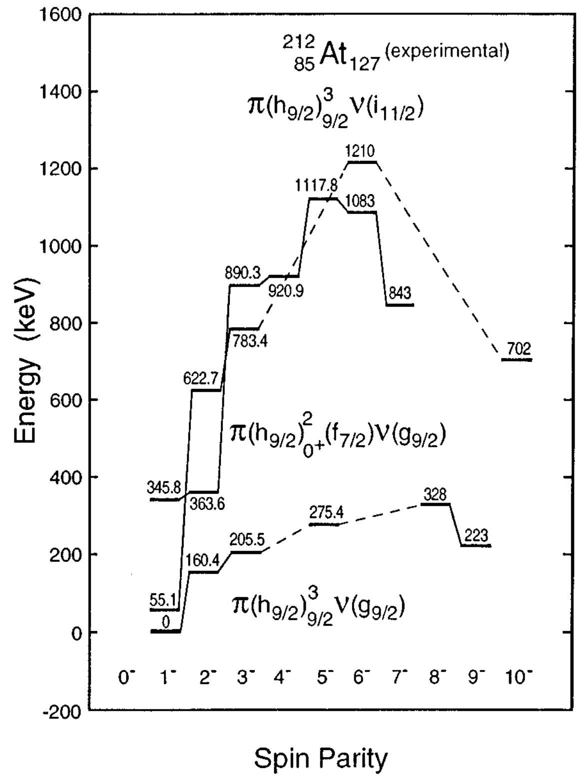

FIG. 6. Experimental level structure of ^{212}At with energies labeled in keV, and the indicated configurations connected by lines. Dashed lines imply unobserved states for certain configurations.

Using the experimental levels of Fig. 2, we have made a plot of spin vs energy for ^{212}At corresponding to the theoretical plot of Fig. 5. The result is shown in Fig. 6. We have allowed ourselves the latitude to choose among the various assigned spin possibilities in order to fit the theoretical expectations. Note especially the very tentative assignment of the 1083 and 1117.8 keV states as 6^- and 5^-, respectively, in Fig. 6, even though only a single gamma ray with unknown multipolarity depopulates these states. If we make these assumptions, however, we get a surprisingly good correspondence between the experimental levels of Fig. 6 and the theoretical levels of Fig. 5. In particular, we see quite clearly the inverted parabola structure in the experimental levels.

In Fig. 7 the experimental levels of ^{210}Bi, ^{212}Bi, and ^{212}At are compared. Whereas ^{210}Bi has only two quasiparticles beyond the double closed shell ^{208}Pb nucleus, ^{212}Bi and ^{212}At have four quasiparticles beyond ^{208}Pb. The four-quasiparticle structure causes an increase in the level density and complexity in ^{212}Bi and ^{212}At. There is considerable similarity in the ground state configurations of ^{212}Bi and ^{212}At both in the range of energies and the general spacings of the corresponding levels. One also notes a flattening of the inverted parabolas in spin vs energy plots of ^{212}Bi and ^{212}At as the configurations take the first step from particle-particle to particle-hole structures. Specifically, one notes that the experimental energy range of the parabola for the

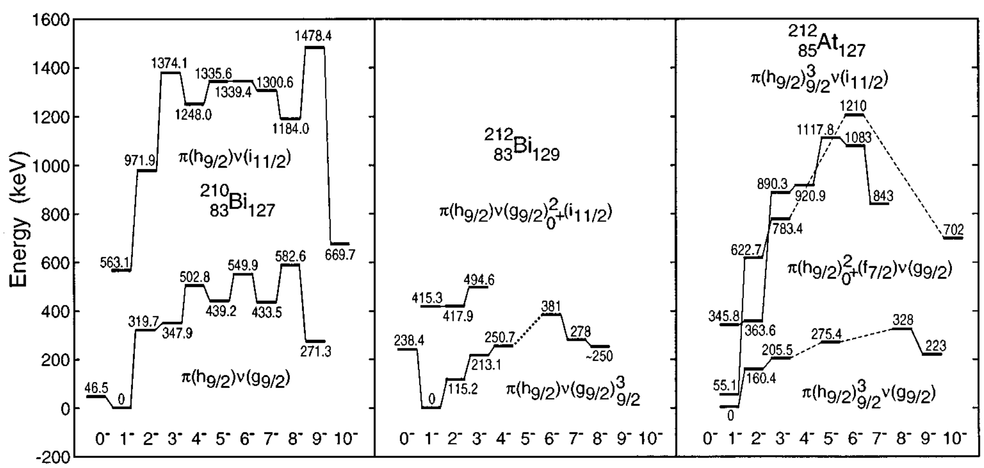

FIG. 7. Comparison of the experimental level structures of ^{210}Bi [10], ^{212}Bi [1], and ^{212}At. Energies are given in keV and configurations are indicated.

ground state configuration is 582.6 keV for ^{210}Bi, while it is considerably less—381 and 328 keV—for ^{212}Bi and ^{212}At, respectively.

IV. CONCLUSION

Using the alpha decay of ^{216}Fr, we have been able to study the levels in ^{212}At. Although no new levels have been observed, through alpha-gamma coincidence studies, spin parities and configurations can be suggested. ^{212}At with only four particles beyond ^{208}Pb is interpreted with the shell model using the configurations $\pi(h_{9/2})^3_{9/2}\nu(g_{9/2})$, $\pi(h_{9/2})^2_{0+}(f_{7/2})\nu(g_{9/2})$, and $\pi(h_{9/2})^3_{9/2}\nu(i_{11/2})$. Comparison of spin vs level energy plots of ^{212}Bi and ^{212}At shows a considerable similarity, whereas there is a greater parabolic spreading of the energies in ^{210}Bi.

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