Alpha Decay of the Isomers of ^{214}Fr

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(Received 13 June 1968)

Alpha decay from the ground state and an isomeric state of ^{214}Fr has been observed. The ground state has a half-life of 5.0±0.2 msec, and the isomeric state, 3.35±0.05 msec, at an excitation energy of 123 keV. A level scheme for ^{210}At based on several α transitions observed is presented. The similarity of the energy levels of ^{208}Bi with those of ^{210}At suggests that the addition of a proton pair to ^{208}Bi does not significantly alter the nature of the particle-hole interactions observed for ^{208}Bi.

I. INTRODUCTION

THE region around the double-closed shell nucleus ^{208}Pb has been particularly useful in studying residual interactions. Theoretical studies have been made by Kim and Rasmussen in this region using the j-j coupling model with configuration mixing.[1,2] They were able to demonstrate the importance of a tensor component in the shell-model force for odd-odd nuclei.

In the work reported here, we have investigated the effect of adding a proton pair to ^{208}Bi on the coupling characteristics of a proton and a neutron hole. Levels in ^{210}At were populated by α-particle decay of ^{214}Fr. This nuclide, first observed by Griffioen and Macfarlane, is an α-particle emitter with an E_α of 8.55 MeV and a half-life of 3.9 msec.[3] The energy has been recently remeasured by Rotter *et al.* (8.53 MeV)[4] and Valli *et al.* (8.430±0.008 MeV).[5] In the latter work, ^{214}Fr was produced as an electron capture (EC) daughter of ^{214}Ra and the α-particle energy measured by them is significantly different from the values previously obtained.

In order to achieve good α-particle energy resolution and low background we have modified the helium gas recoil transport method[6] so that nuclei with half-lives in the millisecond range could be studied. Details of the system will be published separately.

II. EXPERIMENTAL DETAILS

Targets of ^{208}Pb enriched to 99.3% and 4 mg/cm^2 in thickness were bombarded with ^{11}B ions ranging in energy from 50 to 95 MeV using the Yale heavy-ion accelerator. Recoils ejected from the target were thermalized in helium and swept through a metal capillary tube into an evacuated chamber. The helium jet containing the recoils impinged on a metal collection drum. Most of the Fr recoils adhered to the collector forming a source 1 mm in diam while the bulk of the helium which expanded rapidly from the tip of the capillary was pumped away using a high-speed diffusion pump. A Si(Au) surface barrier detector located 5 mm from the source was used to detect α-particles. An α-particle energy resolution of 25 keV [full width at half-maximum (FWHM)] was maintained throughout the experiment. Energies were measured relative to α particles from the ^{228}Th decay chain.[7] System nonlinearities were accounted for by fitting the calibration curve to a power-series expansion. Precise peak positions were determined by a nonlinear least-squares fit of α-particle groups to a Gaussian shape. This procedure for measuring α-particle energies was found to yield α-particle energies with an accuracy of better than 1.5 keV.

Half-lives were obtained by measuring decay rates of specific α-particle groups between beam bursts. Beam bursts were 2 msec in duration with a frequency of 10/sec.

For excitation function work, the beam energy was degraded using Ni absorbers. The data of Northcliffe were used to calculate the energy of the degraded beam.[8]

III. RESULTS AND DISCUSSION

An α-particle spectrum of products of the ^{208}Pb+^{11}B reaction is shown in Fig. 1. Several α-particle groups were observed between 7.3 and 8.5 MeV which we attribute to the decay of ^{214}Fr. In addition, α decay from lighter isotopes of Fr in the mass range of 208 to 213 was also observed. Isotopes of At, mostly decay daughters of Fr, were also present in the spectrum. Products of multinucleon transfer reactions (e.g., ^{211}Po) were observed but the relatively thick targets used favored the collection of products which were associated with full momentum transfer processes.

[1] Y. E. Kim and J. O. Rasmussen, Phys. Rev. **135**, B44 (1964).
[2] Y. E. Kim and J. O. Rasmussen, Nucl. Phys. **47**, 184 (1963).
[3] R. D. Griffioen and R. D. Macfarlane, Bull. Am. Phys. Soc. **7**, 541 (1962).
[4] H. Rotter, A. G. Demin, L. P. Pashchenko, and H. F. Brinkman, Yadern. Fiz. **4**, 246 (1966) [English transl: Soviet J. Nucl. Phys. **4**, 178 (1967)].
[5] K. Valli, W. Treytl, and E. K. Hyde, Phys. Rev. **161**, 1284 (1967).
[6] R. D. Macfarlane and R. D. Griffioen, Nucl. Instr. Methods **24**, 461 (1963).
[7] A. H. Wapstra, Nucl. Phys. **28**, 29 (1961).
[8] L. C. Northcliffe, Phys. Rev. **120**, 1744 (1960).

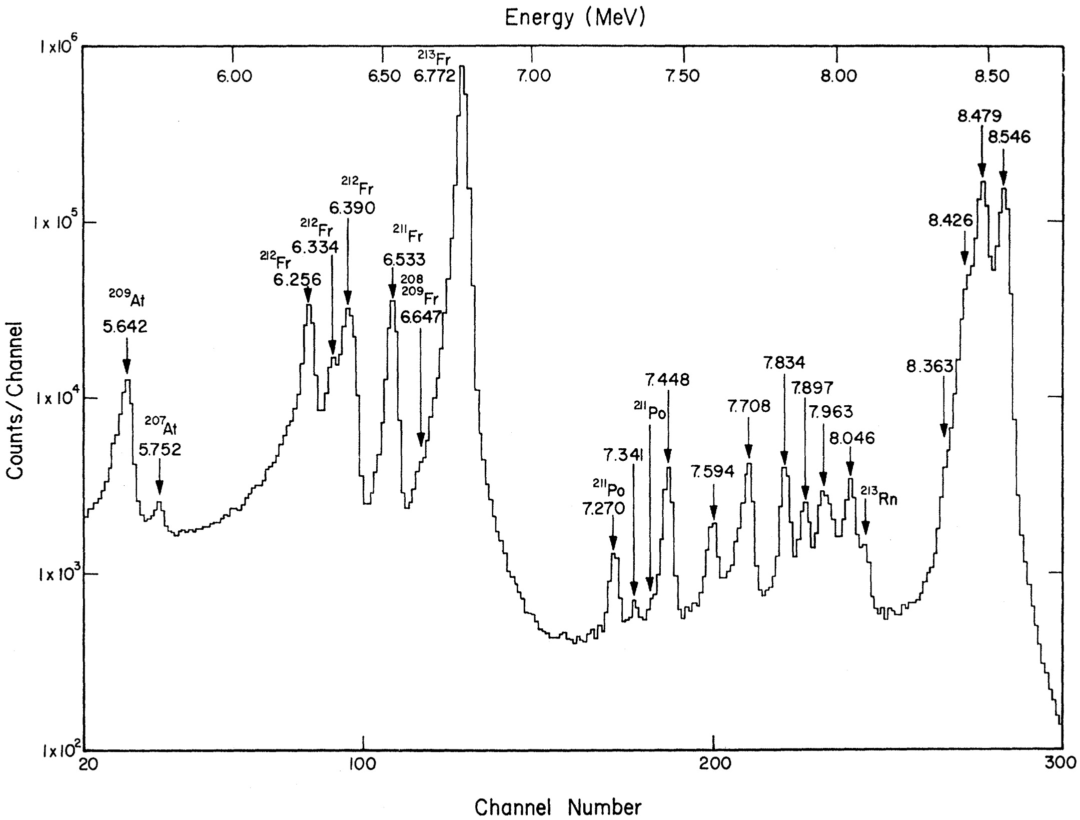

FIG. 1. α-particle spectrum of products of the $^{208}Pb+^{11}B$ reaction at 70-MeV bombarding energy.

A. ^{214m}Fr

Two strong α-particle groups were detected at 8.477 and 8.546 MeV (lab). These groups were observed as a single peak in earlier works using lower energy resolution.[3,4] The half-lives of both of these groups was measured to be 3.35 ± 0.05 msec. Weaker groups were also observed at 8.046, 7.963, 7.708, and 7.594 MeV which had the same half-life as the two main groups.

Excitation functions were measured for these α-particle groups and the results are summarized in Fig. 2. The excitation function for ^{213}Fr ($E_\alpha=6.773$ MeV), corresponding to the reaction, ^{208}Pb(^{11}B,$6n$) ^{213}Fr has a maximum at 80 MeV (lab). For the two major α-particle groups which we are assigning to ^{214}Fr, the excitation functions peak at 72 MeV. Previous work in this region has shown that the excitation function for the (^{11}B,$6n$) reaction relative to the (^{11}B,$5n$) reaction should be shifted upward in energy by 8 to 10 MeV.[9] Thus, 214 is the logical mass assignment for these α-particle groups.

The excitation functions for the weaker groups previously mentioned were found to parallel the data for the stronger groups. On the basis of these results and the half-life measurements we have assigned all of these α-particle groups to a 3.35 msec α-decaying state in ^{214}Fr.

[9] R. D. Griffioen and R. D. Macfarlane, Phys. Rev. **133**, B1373 (1964).

B. ^{214}Fr

When the 8.477-MeV group was fitted to the Gaussian shape for a single line the existence of two additional groups was suggested on the low-energy side at 8.42 and 8.36 MeV (Fig. 1). At low bombarding energies [$\sim$60 MeV (lab)], these α-particle groups were clearly resolved and a spectrum is shown in Fig. 3. They have a half-life of 5.0 ± 0.2 msec. Weaker groups were also observed at 7.897, 7.834, and 7.448 MeV which had the same half-life. The excitation functions for all of these groups were found to have the same energy dependence and to be shifted about 4 MeV lower in bombarding energy relative to the 3.3-msec ^{214}Fr activities. The 5-msec activity was also found to be in lower yield than the 3.3-msec α activity.

The excitation function for this activity peaks at an energy which is somewhat higher than that expected for a (^{11}B,$4n$) reaction leading to ^{215}Fr formation. It seemed more likely that this activity was due to a low-spin state of ^{214}Fr. The presence of a high-spin state, presumably the 3.3-msec activity, could have the observed effect on the yield and energy dependence of the excitation function. This has been clearly seen in other work on the production of isomer pairs in heavy-ion reactions and is the result of the J dependence of

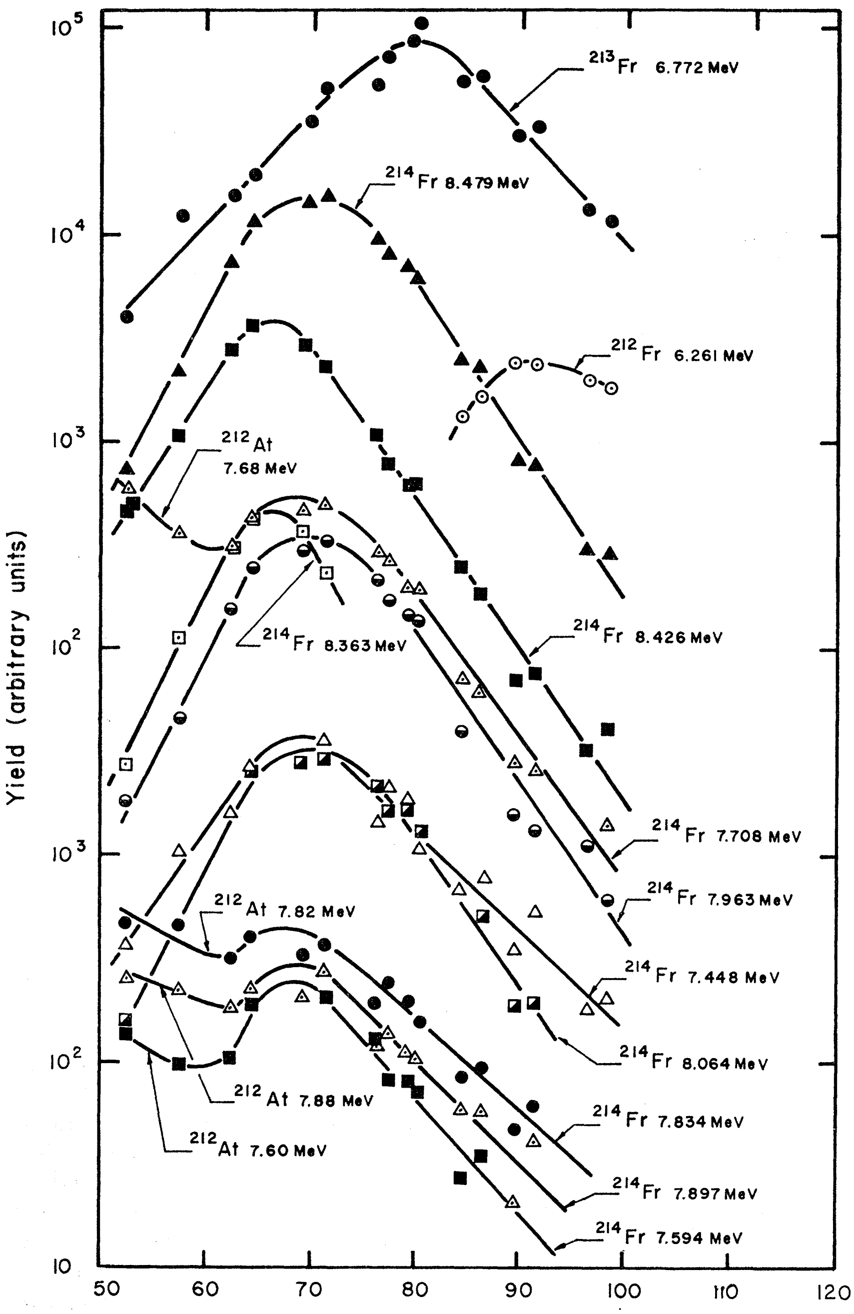

FIG. 2. Excitation functions for the α groups of ^{214}Fr, ^{212}Fr, and ^{213}Fr produced in ^{208}Pb $+^{11}$B bombardments.

neutron and γ emission widths of compound-nuclear states.[10]

To determine whether these α groups were due to a low-spin isomer of ^{214}Fr, we attempted to observe them in the absence of the high-spin member by measuring the α decay of the products of the EC decay of ^{214}Ra. This nuclide has a half-life of 2.6 sec with a large α-decay branch.[5] Electron capture (EC) transitions from the 0^+ ground state of ^{214}Ra should favor low-spin states of ^{214}Fr if they are present.

Figure 4 shows an α-particle spectrum of products from the reaction ^{209}Bi$+^{11}$B at a bombarding energy favoring ^{214}Ra production. The measurement was delayed until 50 msec after the beam burst to allow for decay of the ^{214}Fr produced directly. All of the α groups assigned to the low-spin state of ^{214}Fr were clearly observed and the half-lives were in agreement with the published value for ^{214}Ra. From the intensity of the

[10] R. D. Macfarlane, Phys. Rev. 126, 274 (1962).

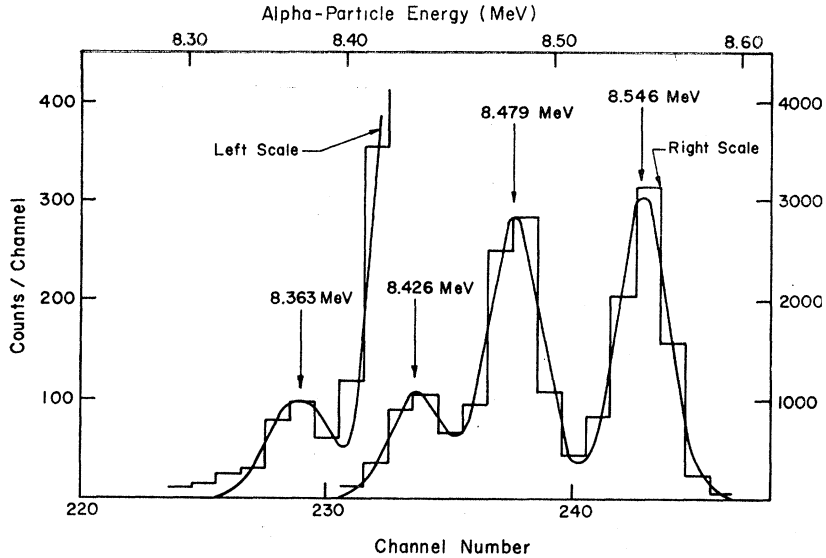

FIG. 3. Portion of an α-particle energy spectrum showing the resolved groups of the low-spin isomer of ^{214}Fr. The ^{11}B bombarding energy was 60 MeV.

^{214}Ra spectrum a value of 0.059±0.004% was obtained for the EC branch of ^{214}Ra. A value of 0.09±0.03% has recently been obtained by Valli and co-workers.[5]

C. Levels of ^{214}Fr

The levels of ^{214}Fr relevant to the work reported here are the ground state and an α-particle emitting isomeric state with a half-life of several milliseconds. We have constructed a decay scheme incorporating all of the observed transitions which is the only scheme we have found which is consistent with our results. This is shown in Fig. 5. Figure 5(A) shows those transitions associated with the low-spin isomer which we are assigning to the ground state. The ground-state to ground-state α-particle transition has a Q value of 8.586±0.005 MeV. This yields a value of -1065 ± 26 keV for the mass excess of ^{214}Fr taking the 1964 mass table[11] values for ^{4}He and ^{210}At. The mass excess of ^{214}Fr is listed as -930 ± 33 keV, but this value was derived from α-decay data for ^{214}Fr before it was known that an isomer pair was involved.

From energy differences, it was determined that the high-spin isomeric level with the 3.3-msec half-life lies at an excitation energy of 123 keV.

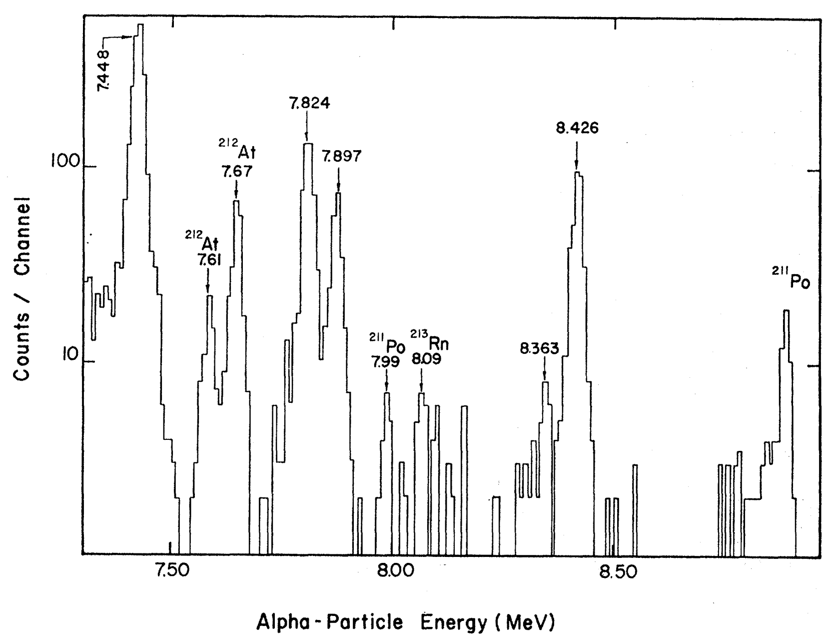

FIG. 4. Spectrum showing the groups associated with the decay of the low-spin isomer of ^{214}Fr produced by EC of ^{214}Ra. The measurement was delayed 50 msec to allow for the decay of ^{214}Fr produced directly by compound nucleus reactions.

[11] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1966).

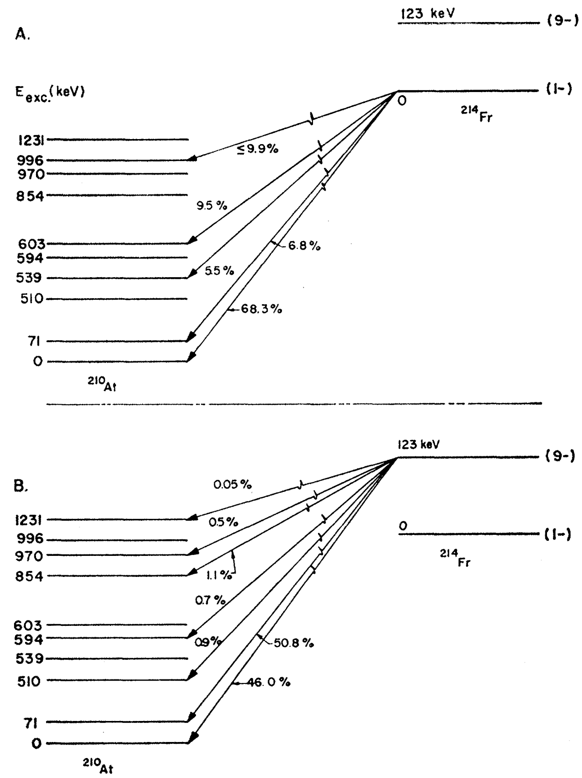

FIG. 5. α-decay scheme of the ^{214}Fr isomers.

It was beyond the scope of the present experiments to determine the spins and parities of these levels or of the ^{210}At levels which will be discussed below. The interpretation of our results is largely based on a comparison with available data on isotones of ^{214}Fr and ^{210}At. A considerable amount of work has been done on ^{210}Bi which is an isotone of ^{214}Fr. Theoretical studies by Kim and Rasmussen of the energy levels of this nuclide have demonstrated the role of tensor forces in the residual interaction.[2] The two lowest-lying levels of ^{210}Bi are 1^-(g.s.) and 0^-(47 keV) and their relative ordering is due to the effect of the tensor force. The next level is 9^-(268 keV) and is a long-lived isomeric state. [These levels are part of a multiplet arising from the coupling of a $(h_{9/2},g_{9/2})$ proton-neutron configuration which is a large component of the total wave function.]

The addition of a proton pair coupled to spin zero to ^{210}Bi apparently does not significantly alter the nature of the residual interaction between the odd proton and neutron. From the results of Jones on the α-particle decay of ^{212}At, it appears that the 1^- level is still retained as the ground state in this nucleus and the high-spin isomeric state is slightly lowered to an energy of 220 keV.[12]

In the case of ^{214}Fr, there is evidence from our results that the ground state is not 0^- because α-particle transitions are observed to both the ground state and the first excited state of ^{210}At. One of these states is thought to be 4^+ and the other 5^+. A $0^- \rightarrow 4^+$ transition is parity forbidden. From what has been observed for ^{210}Bi and ^{212}At and the apparently small perturbation produced by the addition of proton pairs to ^{210}Bi, it seems likely that the ground state of ^{214}Fr is also 1^- and the isomeric state 9^-. The energy of the isomeric state (123 keV) in ^{214}Fr is, however, somewhat lower than for ^{212}At. This might be interpreted as evidence that the six nucleons outside the ^{208}Pb core have produced a significant amount of core polarization.

[12] W. B. Jones, Phys. Rev. **130**, 2042 (1963).

D. Levels of ^{210}At

From the energies of the α-particle groups of the ^{214}Fr isomer pair we have constructed an energy-level scheme for ^{210}At. The results are shown in Fig. 5. Ten levels up to approximately 1.2 MeV have been identified. The energy levels cluster into three distinct groups in a manner very much similar to the energy level sequence for ^{208}Bi. This nuclide, like ^{210}Bi, has also been studied extensively by Erskine and the energy levels have been characterized by (d,t) reaction spectroscopy.[13]

A theoretical study by Kim and Rasmussen[1] on the energy levels of ^{208}Bi revealed the following features which we feel are also relevant for ^{210}At. The ground and first excited state of ^{208}Bi (63 keV) are predominantly $(p_{1/2})^{-1}{}_n(h_{9/2})_p$ coupled to spin 5^+ and 4^+, respectively. The amount of splitting between the two levels reflects the contribution of a tensor force component in the residual interaction. A quintet of levels centered about 600-keV excitation energy has a configuration $(f_{5/2})^{-1}{}_n(h_{9/2})_p$ and another quintet of levels predominantly $(p_{5/2})^{-1}{}_n(h_{9/2})_p$ is centered about 1.1 MeV. Figure 6 shows a comparison of the experimental and theoretical results for ^{208}Bi and our ^{210}At results are included for comparison. The correspondence with the ^{208}Bi energy levels is striking. Although we have made no measurements of spins and parities we can deduce some information from the α-particle decay patterns of the ^{214}Fr isomer pair. Both the states populate the ground state and first excited state of ^{210}At.

TABLE I. Summary of results on ^{214}Fr.

^{214}Fr J^π	E_α(MeV)	^{210}At J^π	Level (keV)	Abundance (%)	Reduced width (MeV)
(1^-)	8.426 ± 0.005	(5^+)	0	68.3	3.97×10^{-3}
(1^-)	8.363 ± 0.005	(4)	71	6.8	1.31×10^{-4}
(1^-)	7.897 ± 0.005	(4^+)	539	5.5	2.31×10^{-3}
(1^-)	7.834 ± 0.005	(5^+)	598	9.5	2.81×10^{-2}
(1^-)	7.448 ± 0.005	(3^+)	996	≤9.9	$\leq1.07\times10^{-1}$
(9^-)	8.546 ± 0.005	(5^+)	0	46.0	1.82×10^{-3}
(9^-)	8.477 ± 0.005	(4^+)	71	50.9	3.08×10^{-3}
(9^-)	8.046 ± 0.005	(6^+)	510	0.9	1.97×10^{-4}
(9^-)	7.963 ± 0.005	(5^+)	598	0.7	1.21×10^{-3}
(9^-)	7.708 ± 0.005	(5^+)	854	1.1	1.15×10^{-2}
(9^-)	7.594 ± 0.005	$\cdots$	971	0.5	$\cdots$
(9^-)	7.341 ± 0.008	(6^+)	1231	0.05	1.77×10^{-3}

[13] J. R. Erskine. Phys. Rev. **135**, B110 (1964).

This is consistent with an assignment of 5^+ and 4^+ for these levels since $l=3$ or 4 α-particle transitions will be predominant in both cases. In the group of levels near 600 keV, the high-spin isomer picks out two of these: the lower-energy member which is 6^+ in ^{208}Bi and another level which could be the 7^+ member of that group. The low-spin isomer populates two different levels in this group and these are presumably the low-spin members (3^+,4^+).

The next group of levels shows a similar pattern. The high-spin ^{214}Fr isomer populates the lower level strongly, which in ^{208}Bi is one of the higher-spin members (5^+). The low-spin isomer apparently has quite a strong transition to the level at 996 keV which may be the 2^+ member since this would involve an $l=1$ α-particle wave. However, there is some evidence that the α group associated with this transition may contain some contribution from ^{211}Po which has a group with the same energy. Because of this we can only quote an upper limit on the intensity of this group.

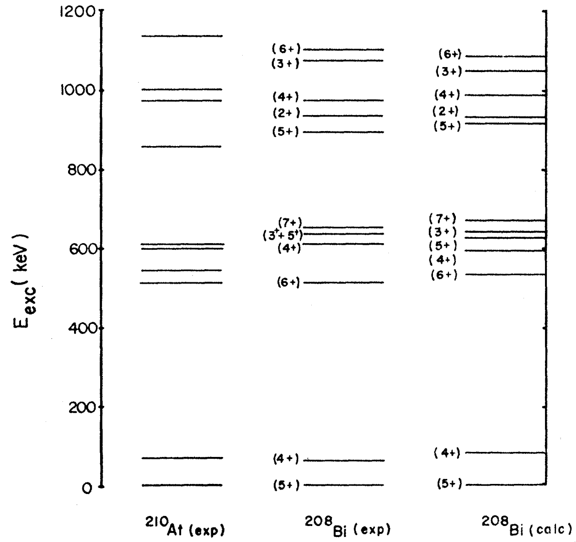

FIG. 6. Comparison of the levels of ^{210}At with those of ^{208}Bi.

IV. ALPHA REDUCED WIDTHS

Table I lists values of the alpha reduced widths calculated[14] for the transitions observed assuming certain spin and parity values for ^{210}At based on analogy with the levels of ^{208}Bi. Some of the features that had been observed by Jones in ^{212}At decay are also present in ^{214}Fr decay. For example, most of the transitions are hindered relative to the decay of neighboring even-even nuclei. The only exception is the transition from the isomeric state to the 854-keV level in ^{210}At. Also, the transition from the isomeric state to the ground state of ^{210}At is more hindered than for the transition to the first excited state. For the α decay of the ^{214}Fr ground state, however, the transition to the ^{210}At ground state is more favored. An understanding of the variation of relative reduced α widths would require detailed knowledge of the wave functions of the states involved.

[14] J. O. Rasmussen, Phys. Rev. **113**, 1593 (1959).

ACKNOWLEDGMENTS

We would like to thank the staff of the Yale heavy-ion accelerator for their support and cooperation. We are also grateful to the National Research Council of Canada and the Research Council of Texas A&M University for their generous financial support.