Decay of mass-separated $^{199}Po^m$ and $^{199}Po^g$

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Sources of $^{199}Po^m$ and $^{199}Po^g$ have been produced and mass separated on line. Multiscaled spectra of γ rays, x rays, and conversion electrons, and γ-γ and γ-x-ray coincidences were measured. The $M4$ isomeric transition of the $\frac{13}{2}^+$ state of ^{199}Po, with a half-life of 4.17 min, was observed for the first time, permitting the placement of the $\frac{13}{2}^+$ and $\frac{5}{2}^-$ levels above the $\frac{3}{2}^-$ ground state. Also, the placement of the $\frac{13}{2}^+$ state in Po together with previously reported α-decay Q values made possible the location of the $\frac{13}{2}^+$ isomeric state in ^{195}Pb. From an analysis of γ-γ-t coincidence data and energy sums, 26 transitions were placed in a decay scheme between 23 levels in ^{199}Bi. On the basis of systematics the population of a $\frac{1}{2}^+$ isomeric state in ^{199}Bi was deduced. The isomeric ($M4$) transition to the $\frac{9}{2}^-$ ground state was not observable in the present data; its rate is at least 390 times less than the Weisskopf single particle estimate.

I. INTRODUCTION

There has been considerable interest in recent years in the study of nuclei very far from stability but within one or two protons of a closed proton shell. This interest has resulted in the discovery of the onset of deformation in the light Hg isotopes, first observed[1] through anomalous isotope shifts in $^{183,185}Hg$. Later extensive level scheme studies[2–4] showed the coexistence of nearly spherical and deformed states in the nuclei, $^{184,186,188}Hg$. The onset of deformation was probed further by several studies of odd-A Tl isotopes,[5–8] studies which revealed bands of regularly spaced levels consisting of $h_{9/2}$ and $i_{13/2}$ protons strongly coupled to the Hg core. The band structure exhibits the same sort of spacings as the yrast bands of $^{188-196}Hg$. Conversely, the $^{193,195}Tl$ $h_{11/2}$ band has spacings representative of a spherical core, corresponding to a hole in a closed shell Pb nucleus. Also of interest is the fact that the $h_{9/2}$ and $i_{13/2}$ states intrude from above the $Z=82$ closed shell but actually fall to quite low excitation in the light Tl nuclei.[9]

The present work was initiated to search for similar effects in the region above the $Z=82$ closed shell. It is expected that the odd-A Bi isotopes will contain $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$ particle states coupled to Pb cores and $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ holes in Po cores. The relative spacing of these levels as one moves away from stability, as well as a detailed study of the bands built on the single particle levels, is of interest in investigating the role of the closed shell and the possible onset of deformation as one moves away from stability.

The EC-β^+ decay of ^{199}Po was studied previously, but without the benefit of mass or chemical separation.[10] Because of this lack of specificity, many of their results appear to be inconsistent as will be demonstrated. The present work is part of a systematic study of the odd-A Bi isotopes. The presence of $\frac{1}{2}^+$ isomers in $^{199,201}Bi$ has already been discussed in a separate publication,[11] and a detailed report on the decay of ^{201}Po will appear elsewhere.[12]

II. EXPERIMENTAL DETAILS

The ^{199}Po sources were prepared by bombarding natural iridium foils in the ion source of the university isotope separator (UNISOR) with 115 MeV $^{14}N^{4+}$ ions from the Oak Ridge isochronous cyclotron. The atoms, ionized in the high temperature ion source,[13] were separated by mass in the Scandanavian-type isotope separator. The mass 199 beam was selected with a slit and was imbedded in an aluminized Mylar tape which was periodically advanced under computer control to position the freshly collected source in front of the detectors.

Two cyclotron runs occurred. During the first, γ-γ-time coincidence list data and γ-ray multiscaled histogram data were acquired through high efficiency Ge(Li) detectors. In the second, γ-ray and conversion electron multiscaled spectra and γ-e$^-$ coincidence data were acquired. In both runs the multiscaled spectra were taken in the core of the controlling computer through an 8192-channel analog-to-digital converter (ADC) and were stored by time plane on a magnetic disk. The multiscaled spectra were subsequently processed by various techniques with the majority of the peak fitting being accomplished through the use of the computer code SAMPO (Ref. 14), which has been adapted for use on the University of Tennessee DEC-10 computer. The γ-γ-time and γ-e$^-$ coincidence data were stored simultaneously in a list which was transferred to magnetic tape for later analysis.

The relative efficiencies of the Ge(Li) detectors were measued with a National Bureau of Standards (NBS) calibration source containing several radioactive standards. The γ-ray relative intensities, energies, and half-lives associated with each transition were determined from the multiscaled spectra. While the half-lives essentially determined the transitions belonging to the decay of ^{199}Po, the γ-γ and γ-x ray coincidences aided in making assignments and made possible the construction of a decay scheme. Conversion electrons were detected with a Si(Li) detector cooled to liquid nitrogen temperature. The Si(Li) detector was calibrated by using a mixed ^{207}Bi and ^{133}Ba source of known strength. However, in the final analysis small corrections to the electron counter efficiency were made by using known transitions following the decay of daughter nuclei in the actual experimental spectra.

III. EXPERIMENTAL RESULTS

The γ-ray singles data were collected in ten spectra, each of which was incremented for a 1.5 min segment of the first 15 min following a fresh ^{199}Po source collection. The spectrum resulting from summing all ten multiscaled spectra is shown in Fig. 1. Initial γ-ray identification was made through half-life analysis of each peak in the ten spectra. The half-life for a given peak was determined by a weighted least squares fit of the intensity by an exponential function of time. Some typical decay curves are shown in Fig. 2 and represent various combinations of decay from $^{199}Po^{m}$ (4.17 min) and $^{199}Po^{g}$ (5.2 min). Since the half-life of the shortest lived daughter of ^{199}Po is

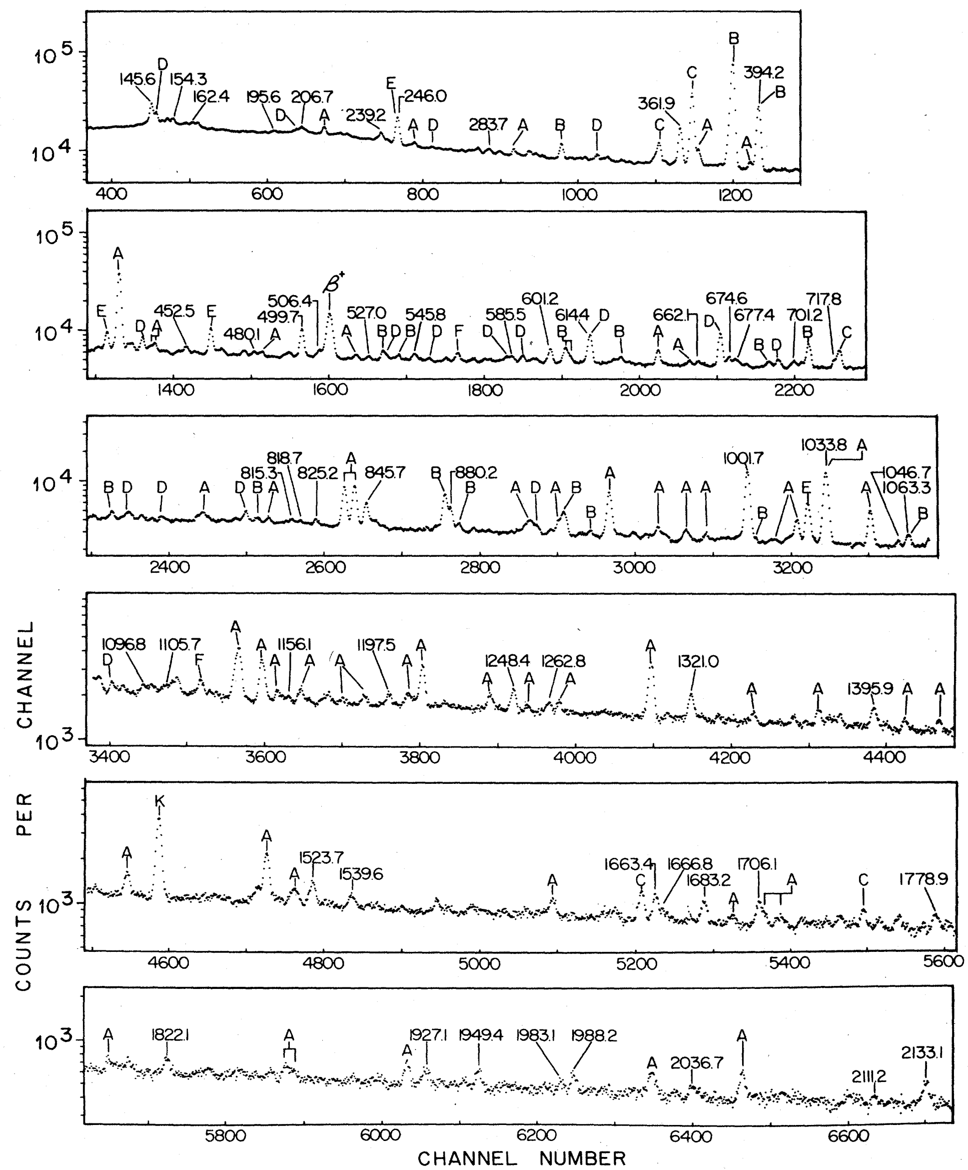

FIG. 1. The γ-ray spectrum from ^{199}Po decay. Energies of peaks in ^{199}Po decay are labeled. Peaks resulting from decay products or contaminants are indicated as $A={}^{199}Bi$, $B={}^{195}Pb$, $C={}^{199}Pb$, $D={}^{200}Po$, $E={}^{200}Bi$, $F={}^{195}Tl$, and $K={}^{40}K$.

greater than three times as large, the identification by half-life was very effective. However, in a few cases other close lying levels could not be resolved. One such case was the 1034 keV line shown in Fig. 2, which contains a transition following the decay of ^{199}Bi, a daughter activity in our source. By adding a Bi decay curve of previously reported relative intensity[15] to a decay curve equal to 83% of the 1002 keV curve, the fit shown in Fig. 2 was obtained. The decay curves for the 500 and 1002 keV peaks yield half-lives close to the value of 4.17 min obtained from a weighted average of various α-decay results.[16] Since these transitions are shown to come from relatively high spin states in ^{199}Bi, it is clear that the 4.17 min half-life belongs to the $\frac{13}{2}^+$ isomer of ^{199}Po. The 880 keV transition may represent a mixture of the 4.17 and 5.2 min activities. The half-life for the 246 keV level appears to be somewhat larger than 5.2 min but this results from a buildup of the $\frac{3}{2}^-$ ground state of ^{199}Po by an isomeric transition from the $\frac{13}{2}^+$ isomer. Similar decay analyses were made for all the strong transitions. For the very small peaks, the first five and the last five time-plane spectra were summed and compared. A comparison of these sum planes clearly showed a much greater decrease in the area of those peaks associated with ^{199}Po decay than in the area of any other peaks present. Additional identification of the EC parent was obtained from the determination of the energies and intensities of x rays in coincidence with a given γ ray.

The values of the energy, peak area, and relative intensity were obtained from the sum spectrum (Fig. 1). Ener-

TABLE I. The energies and relative intensities of γ rays observed in the decay of ^{199}Po in comparison with previous results.

Current study		Korman *et al.*[a]		Jonson *et al.*[b]		Current study		Korman *et al.*[a]		Jonson *et al.*[b]	
E_γ	I_γ	E_γ	I_γ	E_γ	I_γ	E_γ	I_γ	E_γ	I_γ	E_γ	I_γ
145.6	19.4			145.8	14.1	701.2	4.9				
				152.1	5.0	717.8	6.1				
154.3	4.2			154.7	4.1					737.9	41.6
162.4	1.6					815.3	2.3				
		187.7	16.0			818.7	1.5				
195.5	1.2					825.2	3.6				
				204.4	5.0	845.7	19.8			845.8	30.0
206.7	4.3			206.6	9.0	880.2	15.2			880.4	40.7
		229.1	10.2					998.4	33.0		
		233.5	11.8			1001.7	100	1002.0	100[c]	1002.0	85.7
239.3	7.5							1021.4	51.8		
246.0	23.9	246.0	9.0	245.9	47.6	1033.8	83	1034.4	100	1034.0	100
		260.7	8.5			1046.7	1.2				
		274.2	12.3[c]			1096.8	1.9				
283.7	3.3					1105.7	1.8				
361.9	36.6	361.6	47.0	361.6	23.1	1063.3					
				390.3	8.1	1156.1	1.2				
394.2						1197.5	4.2				
		397.8	9.0			1248.4	8.7				
				416.9	14.3	1262.8	3.2				
452.5	3.4					1320.1	10.0				
480.1	2.7					1395.9	7.3				
				487.3	6.0	1523.6	6.8				
499.7	21.9	499.8	42.3[c]			1539.6	4.5				
506.4		506.8	8.0			1663.4	7.5				
527.0	2.3					1666.8	2.0				
				531.9	18.2	1683.2	6.3				
545.8	3.9					1706.2	6.5				
585.5	3.4					1778.9	4.2				
601.2	10.9					1822.1	4.0				
				608.8	20.4	1927.1	1.8				
616.4	1.3					1949.4	3.3				
				639.3	96.6	1983.1	2.1				
				641.4	53.1	1988.2	3.7				
				656.2	29.6	2036.7	1.7				
662.0	2.8					2111.2	1.5				
674.6	7.7					2133.1	3.4				
677.4	5.8										

[a]Data from Ref. 10.
[b]Data from Ref. 17 which includes transitions in ^{203}At.
[c]Assigned as following decay of the $\frac{13}{2}^+$ isomer in ^{199}Po and normalized separately (Ref. 10).

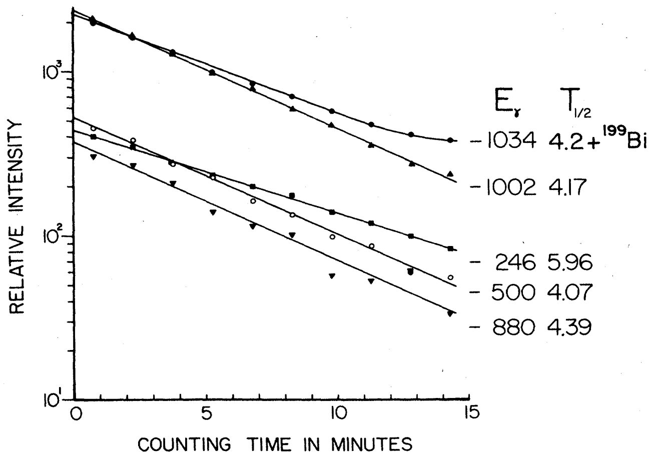

FIG. 2. Selected decay curves for ^{199}Po decay. The half-lives for the lines are given in minutes. Energies of the lines are given in keV. The 1034 keV curve also contains a component from a transition of the same energy in the ^{199}Bi decay (see the text).

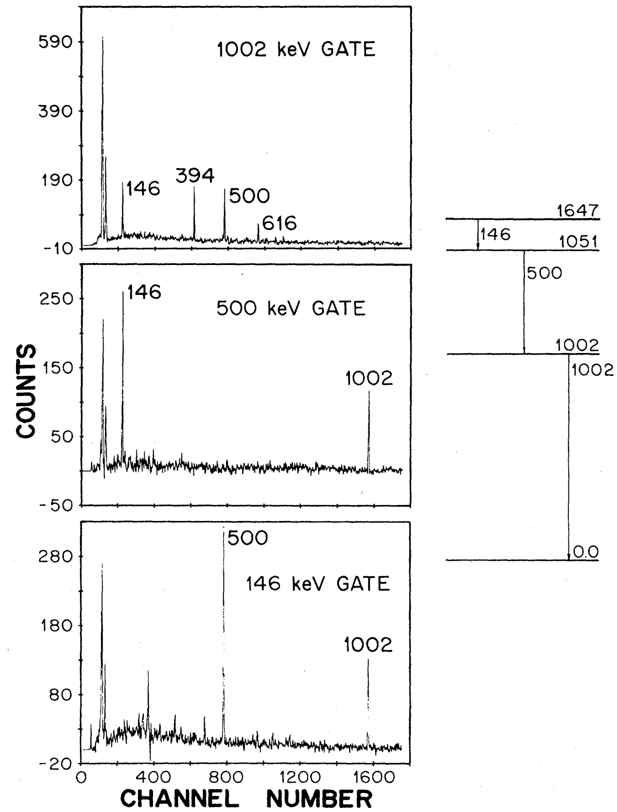

FIG. 3. Coincidence spectra for 1002, 500, and 146 keV transitions in ^{199}Po decay.

gies and intensities of those γ rays resulting from ^{199}Po decay, hence representing transitions between levels in ^{199}Bi, are listed in Table I along with the results of Korman *et al.*[10] for ^{199}Po decay and of Jonson *et al.*[17] for the decay of short-lived daughters of ^{203}Rn. While Jonson *et al.* attributed the transitions listed to the decay of ^{203}At, it is obvious that most of the results obtained were from ^{199}Po decay. The alpha decay of ^{203}Rn no doubt populates the low-spin ($\frac{3}{2}^-$) ground state of ^{199}Po more heavily than the high-spin ($\frac{13}{2}^+$) isomer, just the converse of population trends from Ir(^{14}N,xn) used in the present work. Thus, somewhat higher relative intensities were observed by Jonson *et al.* for transitions resulting primarily from the $\frac{3}{2}^-$ ground state decay. Particularly notable are the large relative intensities observed by Jonson *et al.* for the 207, 246, and 880 keV transitions and a moderately high value for the 846 keV transition. This evidence tends to confirm our assignment of these transitions, taken up later in this paper, to depopulation of low-spin states.

Since many of the results of Korman *et al.*[10] are inconsistent, a few remarks describing the principal discrepancies are in order. The gamma rays reported in Ref. 10 were separated into two groups, believed to come separately from the two isomers of ^{199}Po, and were normalized separately. A γ-ray cascade with energies of 1002, 500, and 274 keV was assigned to the decay of the $\frac{13}{2}^+$ isomeric state. The conversion coefficients for these levels were based on taking the 500 keV transition as $M1$ on the basis of a K to L ratio. In comparison, this study revealed no 274 keV γ ray in ^{199}Po decay, and even with the use of a higher resolution electron detector, the 500 keV K line was not separated from the L lines of the 424 keV transition in ^{195}Pb. In fact, as shown in the following, we assign an $E2$ multipolarity to the 500 keV transition based on its total L conversion coefficient. Of the 12 transitions assigned by Korman *et al.* to the ^{199}Po ground state decay, only five were observed in this study. Of the five which were observed, the 1021 keV line follows ^{199}Bi decay. Furthermore, the 229 keV transition, which Korman *et al.* used to calibrate the conversion coefficients for the 12 transitions reported, was not observed in this study.

Several samples of the spectra obtained from the second

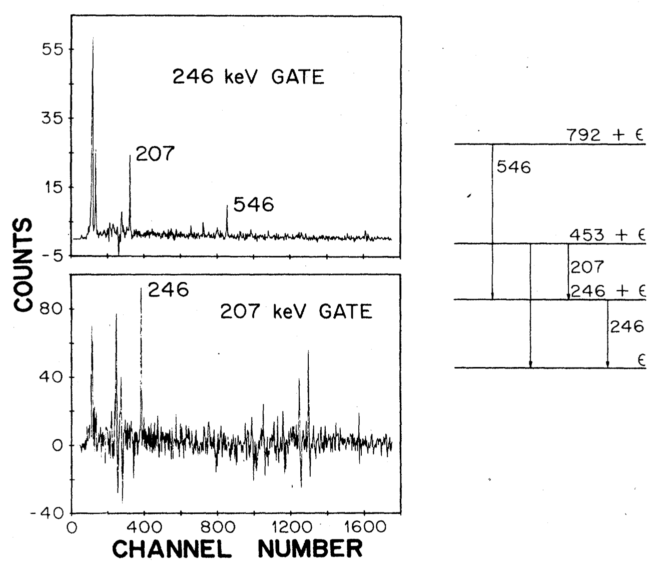

FIG. 4. Coincidence spectra for the 246 and 207 keV transitions in ^{199}Po decay.

TABLE II. Observed coincident transitions with relative coincidence intensity given as s=strong, m=medium, w=weak.

Transition energy (keV)	Observed coincident transitions (by energy in keV)				
146	500(s)	1002(s)			
207	246(s)				
239	362(m)	394(m)			
246	207(s)	545(m)			
362	239(m)	1034(s)			
395	239(w)	1002(s)			
500	146(s)	195(w)	1002(s)		
601	1034(m)				
616	1002(m)				
675	1034(m)				
677	1002(w)				
1002	146(s)	394(s)	500(s)	517(m)	677(w)
1034	362(s)	601(m)	675(m)		

Ge(Li) detector in coincidence with certain discrete lines from the first detector are shown in Figs. 3 and 4. Similar gated spectra were obtained for every known γ ray originating from ^{199}Po decay; the results are listed in Table II.

Conversion electron (ce) and γ-ray data were obtained in the multiscale spectra mode along with ce-γ coincidence data in the second cyclotron run. Some features of the electron spectra obtained are visible in the sample shown in Fig. 5. The full width at half maximum of the K lines near 1 MeV is typically 3.5 keV. The dominance of the 99 keV $E3$ transition in ^{195}Tl and the 424 keV $M4$ transition in ^{199}Pb is apparent. These two transitions and the 384 keV $M1+E2$ transition in ^{195}Pb were used for final calibration of the e$^-$ detector. The K conversion coefficients for the transitions in ^{199}Bi following ^{199}Po decay are given in Table III along with some theoretical values taken from the tables of Hager and Seltzer.[18] The last column gives the multipolarity assignment made from

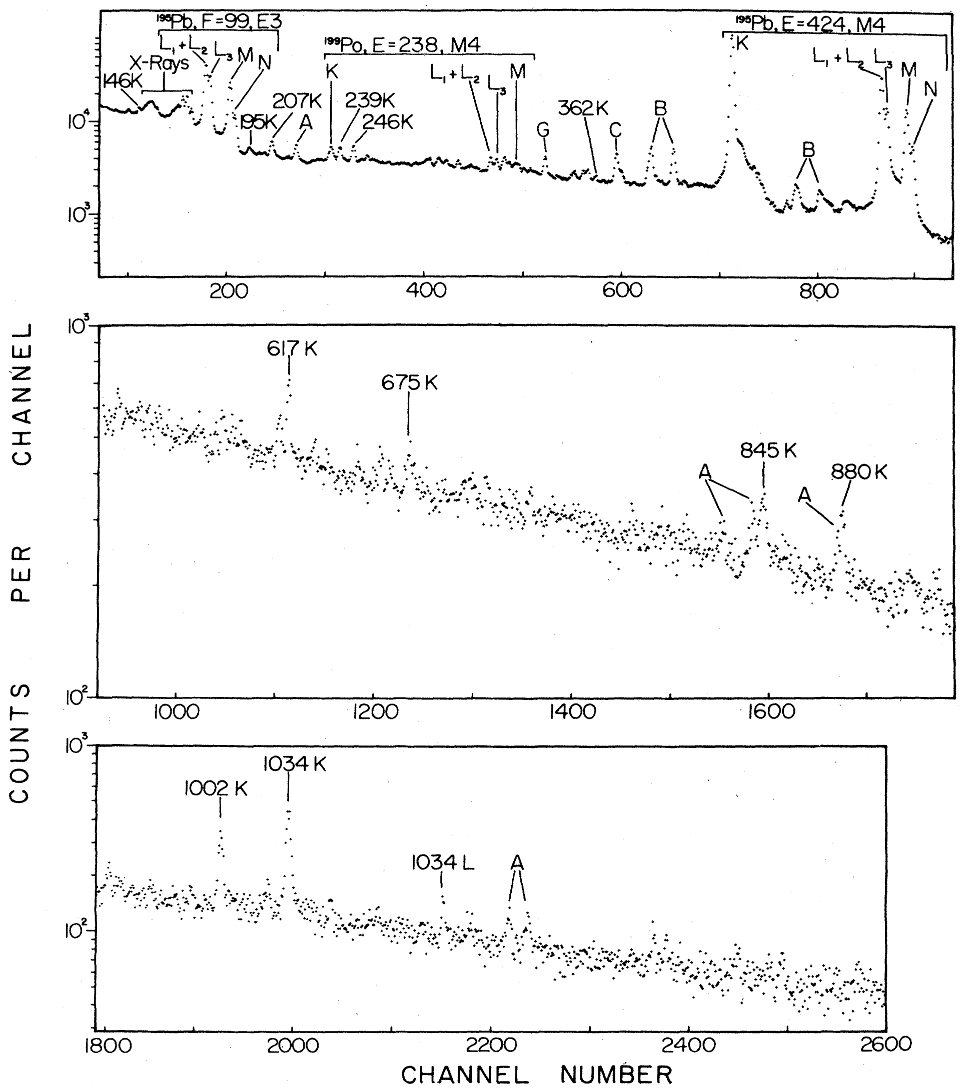

FIG. 5. The electron spectrum from ^{199}Po decay. Some peaks of decay products or contaminants are indicated as $A={}^{199}$Bi, $B={}^{195}$Pb, $C={}^{199}$Pb, and G=unidentified Pb.

TABLE III. A comparison of experimental and theoretical coefficients with resulting probable multipolarities of observed transitions.

E_γ	E_e	α_k (expt.)	Error	Theory[a]	Designation
146	55	0.037	0.019	$E1$, 0.15 $E2$, 0.34	$E1$
196	105	1.8	0.3	$M1$, 1.4	$M1$
207	117	0.91	0.13	$M1$, 1.1	$M1(+E2)$
239	150	0.37	0.05	$M1$, 0.72	$E2+M1$
246	156	0.21	0.03	$M1$, 0.69 $E2$, 0.11	$E2+M1$
362	272	0.019	0.005	$E2$, 0.045	$E1$
500	485L	$\alpha_l=0.0081$	0.0027	$E2$, 0.007	($E2$)
546	455	0.053	0.015	$E2$, 0.018 $M1$, 0.068	$M1$
602	511	0.0079	0.0033	$E1$, 0.0056 $E2$, 0.015	$E1$
675	584	≤ 0.083	0.017	$M1$, 0.046 $E2$, 0.012	$M1$
717	627	0.015	0.011	$E2$, 0.011 $M1$, 0.039	($E2$,$M1$)
825	735	0.027	0.010	$M1$, 0.027	$M1$
845	754	0.013	0.077	$E2$, 0.0076 $E1$, 0.0030 $M1$, 0.026	($E2$,$M1$)
880	790	0.024	0.003	$M1$, 0.023	$M1$
1002	912	0.058	0.007	$E2$, 0.0056	$E2$
1034	944	0.012	0.0014	$M1$, 0.015 $E2$, 0.0053	$M1+E2$
1248	1158	0.006	0.003	$E2$, 0.0037 $M1$, 0.0096	($E2$,$M1$)
1321	1230	0.0039	0.0014	$E1$, 0.0014 $E2$, 0.0033 $M1$, 0.0081	($E2$)
1396	1305	≤ 0.0053	0.0017	$M1$, 0.0070 $M2$, 0.016 $E3$, 0.0062	($E3$,$M2$)

[a]Theoretical values from Ref. 18.

these data. Since the K line for the 500 keV transition was not resolved from the L lines for the strong 424 keV transition, the internal-conversion coefficient (ICC) for the unresolved L lines of the 500 keV transition is listed and compared with theory.

The $\frac{13}{2}^+$ state in ^{199}Po was known to be isomeric from α-decay studies.[19,20] The isomeric transition has not been observed before, but the conversion electrons correspond-

TABLE IV. A comparison of experimental and theoretical K to L and K to M ratios for the $\frac{13}{2}^+ - \frac{5}{2}^-$ isomeric transition in ^{199}Po. Theoretical values for other multipolarities are not close to the experimental value.

Ratios	Experimental values	Theoretical values[a] $M4$	$M3$
$\frac{K}{L_1+L_2}$	1.53±0.22	1.27	2.27
$\frac{K}{L_3}$	1.81±0.29	1.94	5.48
$\frac{K}{M}$	1.90±0.32	2.16	2.66

[a]From Ref. 18.

ing to a 238 keV transition in Po are apparent in Fig. 5. The measured half-life for these lines is 4.3±0.2 min, which agrees with the half-life of the $\frac{13}{2}^+$ isomer (4.17 min) observed in α decay.[16] A coincidence gate set on the K electron peak showed Po x rays in coincidence, confirming it to be a transition in Po. Additionally, a γ-ray peak of about 72 keV was observed in the coincidence spectrum. A quantitative comparison of experimental and theoretical values of K to L and K to M ratios is shown in Table IV. It is clear that the 238 keV transition in ^{199}Po has $M4$ multipolarity.

IV. DISCUSSION

A. ^{199}Po decay scheme and systematics

The ^{199}Po decay scheme, shown in Fig. 6, was constructed through use of the coincidence results and accurate energy sums. The energy and relative intensity for each transition were taken from Table I, while the suggested multipolarities are from the results of the conversion electron measurements (Table III). The spin-parity assignments are based on the experimental multipolarities, but in ambiguous determinations some choices were made based on systematics in the heavier bismuth isotopes. A simple core coupling model (see the following) was also considered as a guide in determining what states should be present.

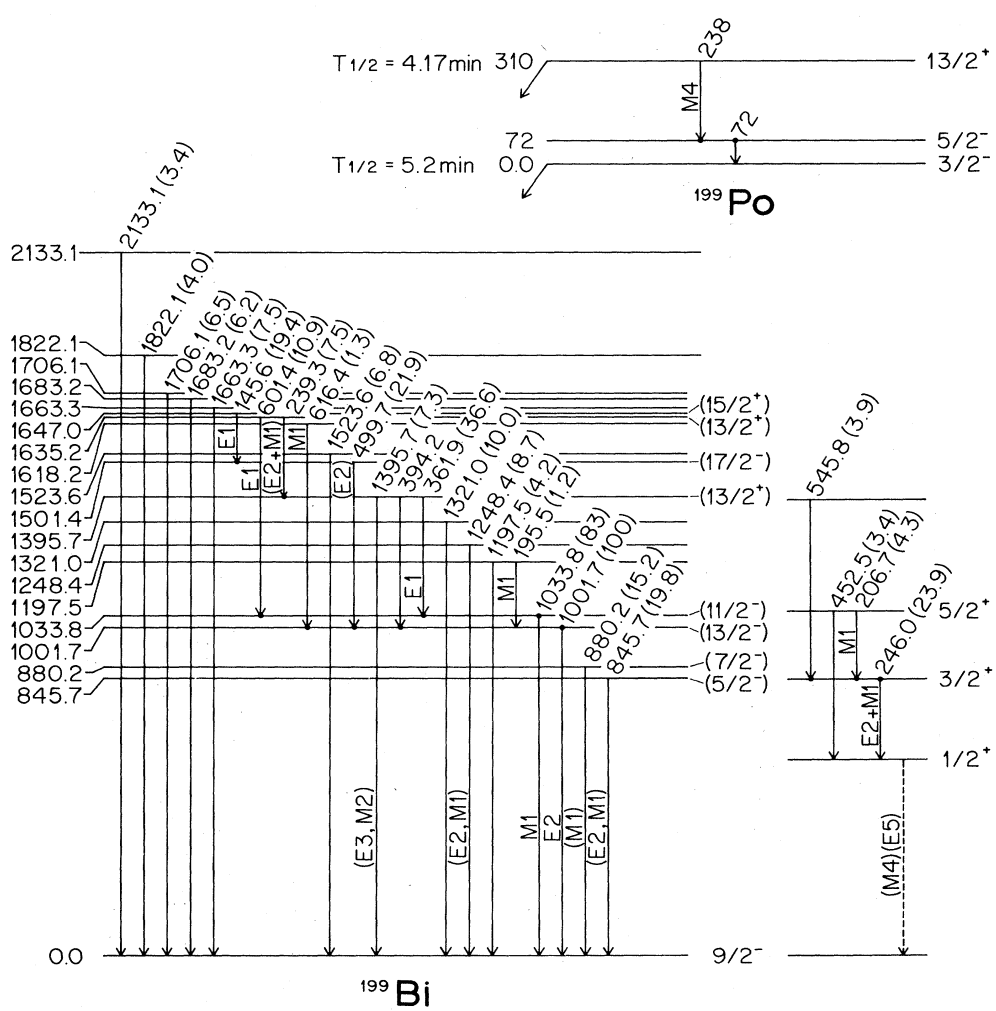

FIG. 6. The decay schemes of ^{199}Po. The energy in keV and the relative intensity are given for each transition. The levels on the right-hand side were separated from the others because of no coincidence relationships with the principal transitions (see the text).

The ground state of ^{199}Bi has been shown through atomic beam measurements[21] to have a spin of $\frac{9}{2}$ and may be considered as an $h_{9/2}$ proton coupled to a ^{198}Pb ground state core. Since the first 2^+ state in ^{198}Pb is at 1064 keV, in a weak coupling model one would expect core excited states with spins and parities of $\frac{5}{2}^-$, $\frac{7}{2}^-$, $\frac{9}{2}^-$, $\frac{11}{2}^-$, and $\frac{13}{2}^-$ near 1 MeV excitation in ^{199}Bi. Because the (^{14}N,xn) reaction utilized here strongly favors the population of the $\frac{13}{2}^+$ isomer in ^{199}Po and since the isomeric transition from this state is weak, the EC-β^+ decay is dominated by the isomer. Thus, the $\frac{13}{2}^-$ level in ^{199}Bi should be strongly populated by the $\frac{13}{2}^+$ isomer in ^{199}Po and should decay directly to the ground state by an $E2$ transition. The very strong $E2$ transition at 1002 keV is the logical choice to depopulate the $\frac{13}{2}^-$ state. The $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states would be more weakly populated, primarily by the $\frac{3}{2}^-$ ground state of ^{199}Po, and would decay by $E2$ and $M1$ transitions, respectively, to the $\frac{9}{2}^-$ ground state. The 846 and 880 keV levels are the most likely prospects for these states. The strong $M1$ transition from the 1034 keV level to the ground state suggests that it is one of the remaining members; it is assigned as $\frac{11}{2}^-$ since a strong population of the $\frac{9}{2}^-$ state is not expected. Other weakly excited states in the decay scheme are, of course, candidates for the $\frac{9}{2}^-$ state. The states thus assigned are seen to compare systematically with similarly assigned states in the heavier bismuth isotopes in Fig. 7.

The intensity of the 500 keV transition is accounted for almost entirely by the feeding of the 146 keV transition, indicating no direct feeding of the 1051 keV level from EC-β^+ decay. This lack of feeding indicates that its spin differs from $\frac{13}{2}^+$ and $\frac{3}{2}^-$ by two or more units. Thus, the most likely spins are $\frac{9}{2}^-$ or $\frac{17}{2}^-$, and since a $\frac{9}{2}^-$ would feed other states as well as the 1002, the 1501 keV level is most likely a $\frac{17}{2}^-$ state.

The three levels at 1396, 1635, and 1647 keV decay to

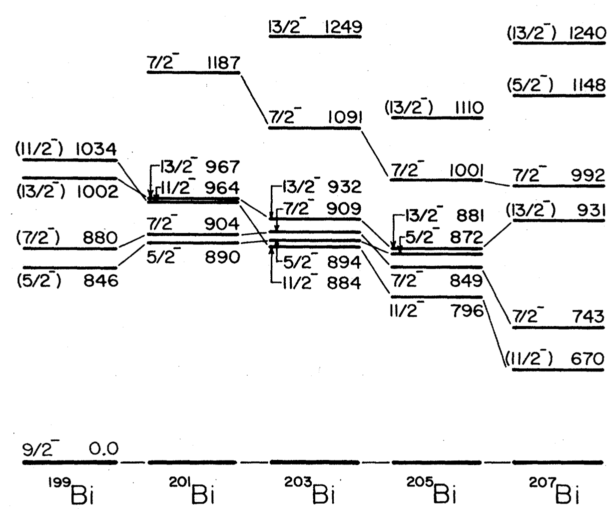

FIG. 7. Systematics of negative parity states in odd-A Bi isotopes, $A = 199-207$. Data for $^{201-207}$Bi from Refs. 12 and 22–25.

negative parity states by $E1$ transitions and hence must be positive parity states. The level at 1647 keV is strongly fed by direct EC-β^+ feeding from the $\frac{13}{2}^+$ isomer in ^{199}Po and decays by an $E1$ transition to the $\frac{17}{2}^-$ state; thus, it is probably a $\frac{15}{2}^+$ state. The level at 1396 keV decays by $E1$ to the $\frac{11}{2}^-$ state and by most likely $E3$ to the $\frac{9}{2}^-$ ground state. Since it is also strongly fed by EC-β^+, its most likely spin is $\frac{13}{2}^+$. The 1635 keV level decays by $E1$ to the $\frac{11}{2}^-$ state and by $E2+M1$ to the 1396 keV level, and might then be either a $\frac{11}{2}^+$ or $\frac{13}{2}^+$ level.

In terms of the simple particle-core coupling model discussed previously, the $\frac{15}{2}^+$ level at 1647 keV and one of the $\frac{13}{2}^+$ levels at 1396 or 1635 keV may be explained by coupling the $h_{9/2}$ proton to the 5^- core state which occurs in ^{198}Pb at 1824 keV. Also, the $\frac{17}{2}^-$ state at 1501 keV is an excellent choice for one of the states resulting from the coupling of the $h_{9/2}$ proton with the 4^+ level in ^{198}Pb at 1626 keV. The large $E1$ transition between the 1647 and 1501 keV levels in ^{198}Bi is then closely related to the $E1$ transition between the ^{198}Pb 5^- and 4^+ states at 1824 and 1626 keV. Other low-lying particle states, besides the $h_{9/2}$, can be deduced from the level scheme of ^{209}Bi; the $f_{7/2}$ and $i_{13/2}$ levels are at energies of 896 and 1608 keV, respectively. The second $\frac{13}{2}^+$ level suggested in the ^{199}Bi level scheme (Fig. 6) could be the $i_{13/2}$ particle state, while levels at 1321, 1248, and 1263 keV are probable candidates for the $f_{7/2}$ particle states. These energies would be consistent with the systematic trend of the second $\frac{7}{2}^-$ state shown in Fig. 7.

The group of transitions on the right-hand side of Fig.6 showed coincidence relations with each other but not with any of the principal transitions in the spectrum (see Fig. 4). Similar level and transition patterns have been observed in the heavier odd-A Bi nuclei and each corresponds to a structure built on an $s_{1/2}$ hole state as shown in Fig. 8. On this basis the spins of these levels were suggested and are consistent with the multipolarities of the interconnecting transitions. Another piece of evidence confirming this assignment is the relatively large intensity observed for the 246 and 206 keV transitions by Jonson *et al.*[17] (see Table I). Since the lines observed by Jonson *et al.* followed the α decay of ^{203}Rn, it is apparent that their source had a larger relative abundance of the $\frac{3}{2}^-$ ground state of ^{199}Po, and thus, the population of these low-spin states in ^{199}Bi was enhanced. Note that the energy of the $\frac{1}{2}^+$ state, which is shown below the bottom line for each isotope in Fig. 8, is rapidly dropping with mass number in these nuclei. In ^{201}Bi the $\frac{1}{2}^+$ level has become the first excited state at 846 keV and decays isomerically to the $\frac{9}{2}^-$ ground state with a half-life of 59 min.[11,22] If the same steady rate of decrease in the energy of the $\frac{1}{2}^+$ state with decreasing A is assumed to continue to $A = 199$, the energy of the $\frac{1}{2}^+$ state in ^{199}Bi would be near 600 keV as indicated in Fig. 8. It is apparent that the $\frac{1}{2}^+$ state in ^{199}Bi would be isomeric also.

Actually, a low-spin isomer of ^{199}Bi has been observed to α decay to the ground state of ^{195}Tl in several previous experiments[26–29] with an adopted half-life and energy of 24.7 min and 5484 keV.[16] Combining the α-decay Q

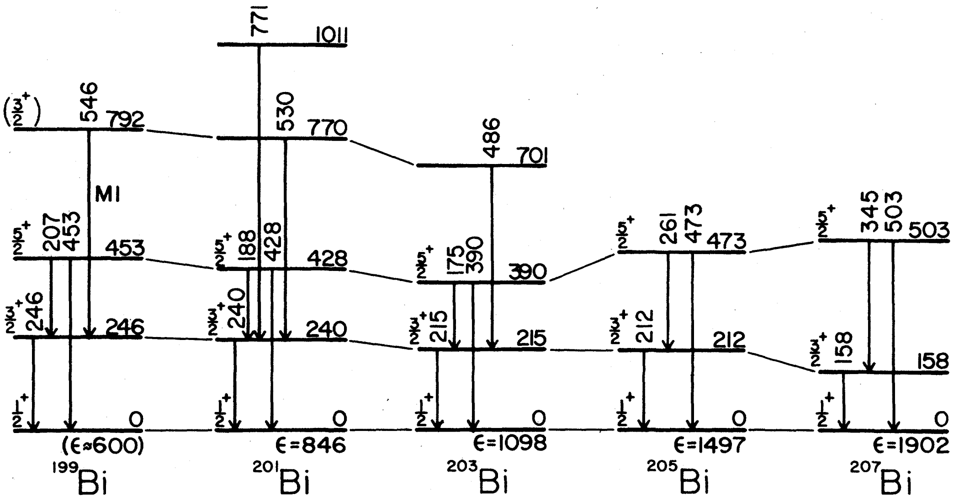

FIG. 8. Relative positions of the $\frac{5}{2}^+$ and $\frac{3}{2}^+$ states with respect to the $\frac{1}{2}^+$ state in odd-A Bi isotopes, $A=199$—207. ϵ is the excitation energy of the $\frac{1}{2}^+$ level above the ground state. Data for $^{201-207}$Bi are from Refs. 12 and 22—25.

value (5596 keV) with the Q value estimated from mass systematics[16] for the $h_{9/2}$ ground state ($\sim$4820 keV) we obtain another estimate (776 keV) for the excitation energy of the $\frac{1}{2}^+$ isomer in ^{199}Bi.

The isomeric decay of this $\frac{1}{2}^+$ state was not observed in this experiment. The upper limits set on the intensity of this transition by our spectra and some deductions concerning the retardation of this isomeric decay were reported previously[11] and are discussed in Sec. IV C 2.

Several other transitions in ^{199}Bi were observed and placed in the ^{199}Po decay scheme (Fig. 6) but were too weak to permit firm assignments of the spins or, in some cases, the energies. The less certain levels were omitted from Fig. 6.

Also shown in Fig. 6 is the isomeric decay of ^{199}Po^m. The $\sim$72 keV gamma ray in coincidence with the K conversion electron line establishes the presence of two levels below the $\frac{13}{2}^+$ isomer, and the $M4$ multipolarity of the isomeric transition and systematics establishes $\frac{5}{2}^-$ as the spin of the higher of these two levels. The assignment of $\frac{3}{2}^-$ to the ground state follows from systematics in the odd-A Po isotopes, shown in Fig. 9.

B. $\frac{13}{2}^+$ level in ^{195}Pb

The establishment of the energy of the $\frac{13}{2}^+$ isomer in ^{199}Po permits the placement of the same isomer in ^{195}Pb as shown in Fig. 10. Alpha decay studies[16,29,30] of the $\frac{13}{2}^+$ isomer yield a weighted average Q value of 6138

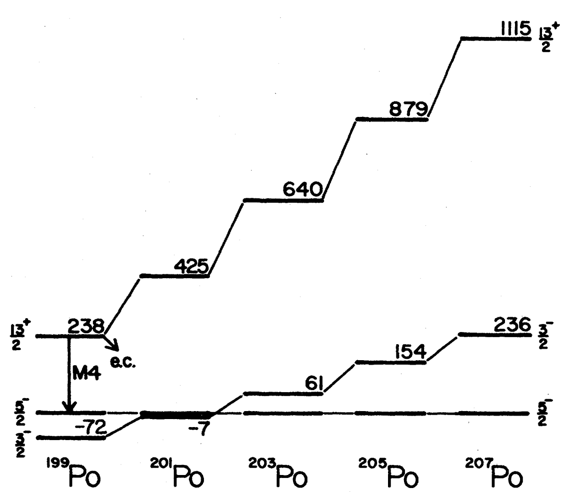

FIG. 9. Systematics of the low-lying $\frac{5}{2}^-$, $\frac{3}{2}^-$, and $\frac{13}{2}^+$ states in the odd-A Po isotopes, $A=199$—207. Data for $^{201-207}$Po are taken from Ref. 30.

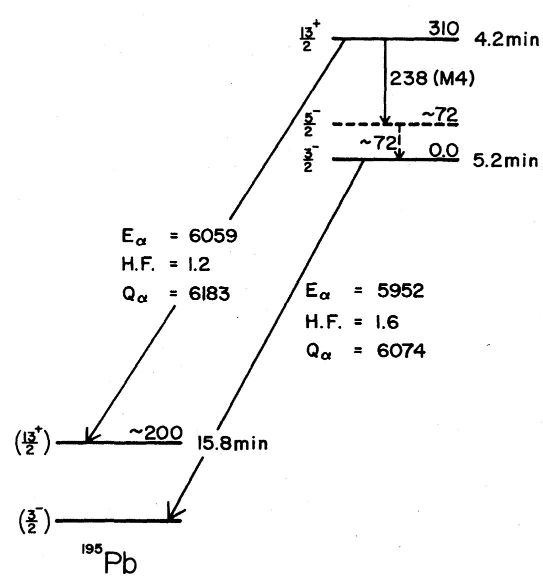

FIG. 10. Location of the $\frac{13}{2}^+$ state in ^{195}Pb.

keV, while the study[31] of the ground state decay yields a Q value of 6074 keV. Since the excitation energy of the $\frac{13}{2}^+$ state in ^{199}Po is 310 keV, the excitation energy of the $\frac{13}{2}^+$ state in ^{195}Pb is $\sim$200 keV.

C. Isomeric transition rates

1. The $\frac{13}{2}^+ \rightarrow \frac{5}{2}^-$ transition in ^{199}Po

By comparing the isomeric transition intensity in ^{199}Po to the total EC-β^+ feeding of high-spin states in ^{199}Bi, the branching ratio for the $M4$ transition from the $\frac{13}{2}^+$ state in Po can be estimated. By using known $M4$ conversion coefficients[18] the total intensity of the isomeric transition was calculated from the intensities of the K, L, and M electron peaks. The intensity of the EC-β^+ decay of the isomeric state is somewhat more uncertain due to the fact that both the isomer and ground state decay to ^{199}Bi. We have assumed that the total population of the $\frac{1}{2}^+$ isomer and the $\frac{5}{2}^-$ state in ^{199}Bi was from the $\frac{3}{2}^-$ ^{199}Po ground state decay and that the remaining states were populated by the decay of the $\frac{13}{2}^+$ isomer of ^{199}Po. Since about 70% of the γ-ray intensity assumed to come from the EC-β^+ decay of the $\frac{13}{2}^+$ isomer comes from assigned high-spin states in ^{199}Bi, it is clear that the assumed intensity cannot be grossly in error. These intensities were also corrected for conversion electron contributions. The relative strength of the isomeric transition to the EC-β^+ decay was thus found to be $9.38/280=0.034$. Considering that the α-decay branching ratio[16] is 39%, the branching ratio for the isomeric transition is 2.1%, while that for EC-β^+ decay is 59%.

The transition rate for the isomeric transition may also be calculated. The probability for isomeric γ-ray decay is found to be 8.5×10^{-7} s^{-1} which can be compared with the Weisskopf single-particle rate[32] of 3.2×10^{-7} s^{-1}. The experimental transition rate is thus equal to 2.6 W.u. (Weisskopf units) or the transition has a retardation factor of 0.38. This value is similar to the retardation factors for many other $M4$ transitions in odd-A nuclei as illustrated by several examples in Table V.

2. The $\frac{1}{2}^+$ to $\frac{9}{2}^-$ transition in ^{199}Bi

Although a group of transitions feeding the $\frac{1}{2}^+$ state in ^{199}Bi have been observed, the expected isomeric transition of this state to the $\frac{9}{2}^-$ ground state was not observed. Estimates of the energy of this state (Sec. IV A) ranged from about 600 to 800 keV. A very thorough search for a $M4$ transition was conducted over the range of transition energies from 500—1000 keV. No likely candidate was found. Nevertheless, the largest possible unexplained K electron line was determined; it corresponds to a bismuth transition energy of 667 keV and yields a total intensity (correcting for other conversion lines and the unobserved gamma line) of 0.41 u. The resulting upper limit then on the γ-ray intensity from this state is 0.25 u, well below our threshold for observation. The feeding of the $\frac{1}{2}^+$ level was assumed to be entirely due to the 246 and 453 keV transitions; this estimate is clearly a lower limit of the feeding since the $\frac{3}{2}^-$ ground state of ^{199}Po may decay directly to the $\frac{1}{2}^+$ isomer. A correction factor to account for the finite counting time in relation to the half-lives of the ^{199}Po and ^{199}Bi^m was made. The result was an upper limit on the isomeric transition branching ratio for the $\frac{1}{2}^+$ state of 3.2%.

Taking internal conversion into account and using the measured 24.7 min half-life, an upper limit to the γ-ray transition rate of 8.74×10^{-6} s^{-1} was deduced. The Weisskopf single particle $M4$ γ-ray transition rate is given by $T_{\rm sp}=3.3\times10^{-6}A^2E^9=3.41\times10^{-3}$ s^{-1}. Thus the $M4$ isomeric transition is retarded by a factor of at least 390. This lower limit is about 1000 times larger than typical retardation factors for $M4$ transition in odd-A nuclei (see Table V). This is probably related to the fact that the $\frac{1}{2}^+$ state is predominantly an $s_{1/2}$ proton hole coupled to a ^{200}Po core, while the $\frac{9}{2}^-$ state is an $h_{9/2}$ proton particle coupled to a ^{198}Pb core. The transition could be retarded because of the l selection rule for transitions between single-particle states, thus indicating that these states are extremely pure shell model states. Considered as an $E5$ transition, the retardation would be less extreme. Nevertheless, the corresponding $\frac{1}{2}^+-\frac{9}{2}^-$ isomeric transition was actually observed[11] in ^{201}Bi and was shown to be an almost pure $M4$ transition with a retardation factor of nearly 2000. This would indicate that the retardation is not merely due to l forbiddenness, but that other factors related to the different cores for the particle and hole states are involved.

TABLE V. A comparison of $M4$ retardation factors in Weisskopf units for ^{199}Po and other odd-A nuclei (source: Refs. 16, 31, and 33).

Isomer	Transition energy (keV)	Retardation factor
^{197}Hg^m	165	0.5
^{197}Pb^m	319	0.33
^{195}Hg^m	123	0.33
^{195}Pt^m	130	0.76
^{199}Hg^m	374	0.48
^{199}Pb^m	424	0.31
^{199}Po^m	238	0.38

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