UCRL 3808

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

BERKELEY, CALIFORNIA

DISCLAIMER

UCRL-3808

UNIVERSITY OF CALIFORNIA

Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

RADIATIONS FROM DECAY OF BISMUTH-203, BISMUTH-204, LEAD-204m, AND BISMUTH-205

Arnold R. Fritsch and Jack M. Hollander

June, 1957

Printed for the U. S. Atomic Energy Commission

RADIATIONS FROM DECAY OF

BISMUTH-203, BISMUTH-204, LEAD-204m, AND BISMUTH-205

Contents

RADIATIONS FROM DECAY OF BISMUTH-203, BISMUTH-204, LEAD-204m, AND BISMUTH-205

Arnold R. Fritsch and Jack M. Hollander

Radiation Laboratory and Department of Chemistry
University of California, Berkeley, California

June, 1957

ABSTRACT

A study has been made of the radiations from the neutron-deficient isotopes Bi^{203}, Bi^{204}, Bi^{205}, and Pb^{204m}, principally by conversion electron spectroscopy with four 180^{o} electron spectrographs of the permanent-magnet type. The decay schemes of the bismuth isotopes are found to be very complex, and in spite of high-resolution studies and some coincidence work unique level schemes cannot be given in any case. A new transition in the decay of the 1-hour Pb^{204} isomer has been identified at 289.5 kev, and this is interpreted as arising from a 4+ state of Pb^{204} at 1563 kev. A comparison is given of the results of the present study of Bi^{205} decay with those of other recent spectroscopic studies of the Pb^{205} levels.

RADIATIONS FROM DECAY OF BISMUTH-203, BISMUTH-204, LEAD-204m, AND BISMUTH-205

Arnold R. Fritsch* and Jack M. Hollander

Radiation Laboratory and Department of Chemistry
University of California, Berkeley, California

June, 1957

INTRODUCTION

Studies of the electron-capture decays of the neutron-deficient bismuth isotopes have been of interest because they provide a means of observing the energy levels of corresponding lead isotopes that differ from the double-closed shell by only one or more neutrons and hence are describable in terms of the extreme single-particle model.

The decay of Bi^{207} populates levels of Pb^{207}, levels of a single neutron (hole) in the 126 shell. These levels are, in order of increasing energy: $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $i_{13/2}$, and $f_{7/2}$.

The levels of a neutron pair manifest themselves in Pb^{206}, and have been studied from the electron-capture decay of Bi^{206} by Alburger and Pryce.[1] Their results indicate a marked increase in complexity of the Pb^{206} levels over those of Pb^{207} as evidenced by the twenty-six transitions and twelve states that are reported. An approximate theoretical treatment of the two neutron holes, originally developed by Pryce,[2] was applied with considerable success in the interpretation and understanding of the experimental Pb^{206} results.

This work had as its objective the study of the decays of Bi^{203}, Bi^{204}, and Bi^{205} by methods of high-resolution beta spectroscopy. Subsequent to its completion, we became aware of the detailed study of Bi^{205} by Schmorak, Stockendal, McDonell, Bergström, and Gerholm.[3] For the most part, the transition data of the two investigations of Bi^{205} are in good agreement although the electron-electron coincidence work

*Present address: Westinghouse Electric Corporation, Pittsburgh, Pa.

by Schmorak et al. leads them to a different conclusion regarding the first excited state of Pb^{205} from that we have reached from consideration of Po^{209} alpha-decay data. We shall not present here our data on Bi^{205} in detail, but only point out areas where further work seems necessary. A more complete description of this work is to be found in the thesis by one of us (A.R.F.).[4]

The present results on Bi^{203} and Bi^{204} are in no sense complete or even satisfactory. However, as further work is not being carried on presently in this laboratory on this problem, we believed that a brief summary of our experimental data would be of value even though unique decay schemes cannot be given. Indeed, Bi^{204} decay, with 67 transitions identified, may continue to challenge nuclear spectroscopists for some time.

BOMBARDMENTS AND CHEMISTRY PROCEDURES

The bismuth activities were produced by means of alpha-particle bombardments ~~upon~~ enriched samples of Tl^{203} (80% Tl^{203}, 20% Tl^{205}), using the Crocker 60-inch cyclotron. The energies of the alpha particles were chosen in such a manner that a distinction could be made between the nuclides. To obtain the 14-day Bi^{205}, bombardments were carried out at 28 Mev, which is below the α,3n threshold and yet allows the full α,2n yield to be obtained. Bi^{204} and Bi^{203} are not produced at this energy, and contamination by Bi^{206} is held to a minimum. For study of 12-hour Bi^{204}, bombardments of Tl^{203} were made at 38 Mev; at this energy Bi^{203} is not produced but much Bi^{206} is formed from the α,n reaction on Tl^{203} and the α,3n reaction on Tl^{205}. Bi^{206} and Bi^{204} are relatively easy to differentiate, however, because of the large difference in their half lives. The 12-hour Bi^{203} was obtained by full-energy alpha bombardments at 45 Mev. Approximately equal amounts of 12-hour Bi^{203} and 12-hour Bi^{204} are formed at this energy, hence the assignment of transitions to Bi^{203} could be made only after Bi^{204} had been studied separately.

The target material, Tl_2O_3, was dissolved immediately after bombardment in a minimum volume of concentrated hydrochloric acid. Recovery of the thallium was effected by extractions with diethyl ether saturated with concentrated hydrochloric acid. The activity was adsorbed on a Dowex-1 anion-exchange column, following which the lead fraction was removed by elution with 20 ml of 0.1<u>N</u> HCl. The bismuth activity was then stripped from the column with 1N H_2SO_4, evaporated to dryness, dissolved in dilute HCl, and subsequently electroplated upon 5-mil platinum wires.

EXPERIMENTAL METHODS

Photon spectra of these isotopes were obtained by use of a NaI(Tl) scintillation detector coupled to a 50-channel analyzer. Conversion-electron spectra were examined with four permanent-magnet beta spectrographs ranging in field strength from 50 gauss to 340 gauss and operating at ~0.1% momentum resolution.[5] Some gamma-gamma coincidence experiments have also been performed.

I. Bismuth-203

Half Life

The half life of Bi^{203} was measured by following the decay of the K-conversion line of the 825-kev transition in the double-focusing spectrometer with the result: $t_{1/2} = 11.5 \pm 1.0$ hours.

Scintillation Spectrum

Because of the complexity of the spectrum and because of the presence of Bi^{204} in the samples, the photon spectrum revealed clearly only the strong transition at 825 kev, and hence was of little value in providing information about the many other transitions from Bi^{203} decay.

Electron Spectrum

A summary of the Bi^{203} transitions observed from the electron spectrum is given in Table I. Eight transitions have been identified with a moderate degree of certainty by the observation of at least three conversion lines of each; seven other transitions are assigned from observation only of K lines. Because our samples of Bi^{203} were weaker than the corresponding Bi^{204} and Bi^{205} samples, we feel that the Bi^{203} spectrum reported here is incomplete, and that with stronger sources many more transitions will probably appear.

A multipolarity assignment can definitely be made for the 126.4-kev transition, which is identified by its L-subshell conversion pattern

Table I.

Transitions observed from Bi^{203} electron spectrum

Transition energy (kev)	K	L_I	L_{II}	L_{III}	M_I	M_{II}	M_{III}	N	Probable multipole order
	Relative electron line intensities[a]								
60.1		VW			d			W	M1 ?
117.7	W[b]	VW			VVW?			VVW	M1 ?
126.4	VW	[illegible]	300	230		100	60	VVW	E2
186.5	1040	200			170			VW	M1, M2
264.0	770	180			VW				M1, M2
819.7	100	VVW							
824.9	1000	250			150				M4
1033.7	35	VVW							
381.5[c]	100								
465.4	VVW								
606.1	50								
625.0	VW								
708.4	75								
722.1	30								
1536.4	60								

a. Where lines were too weak for densitometry, visual estimates of line blackness are given. W = weak, V = very.

b. Unresolved from Bi^{204} 105.5-kev gamma M_I line.

c. The seven assignments below are tentative; only the K lines have been observed.

d. M_I line masked by $K - L_I - L_{II}$ Auger line.

as an E2 transition. The 60.1, 117.7, 186.5, and 264.0-kev transitions are shown to be predominantly magnetic by their high L_I conversion, but either M1 or M2 is possible. The 824.9-kev isomeric transition has been identified as M4, from its half life and its K-conversion coefficient.[6]

Pb^{203} Isomer

This lead isomer was discovered by Hopkins,[7] who measured its half life as 5.6 seconds and assigned it to Pb^{202m}. The later assignment to Pb^{203m} was made by Fischer.[8] In order to strengthen this mass assignment, we have verified the genetic relationship between this isomer and its Bi^{203} parent by a chemical "milking" experiment. The Bi^{203} activity was placed upon an ion-exchange column containing Dowex-1 anion resin, and Pb^{203} was stripped rapidly from the column with a small volume of 0.1N HCl and then placed into a counter. The entire procedure consumed about 5 seconds. The "best" value of the half-life obtained from 22 such experiments was 7.1 ± 0.5 seconds.

A continuous-flow system was also assembled so that the photon spectrum of the isomer could be examined with the scintillation spectrometer. Only one photopeak was seen, with an energy 826 ± 5 kev; this is presumably the previously identified[6] M4 isomeric transition of Pb^{203m}. In a gamma-gamma coincidence experiment, essentially zero coincidences were observed with this photon, indicating that the isomer decays directly to the ground state. A more precise value of the transition energy, measured from the Bi^{203} electron spectrum, is 824.9 ± 1.0 kev.

Transition Sums

Although a level scheme will not be presented for Pb^{203}, a few transition-energy sums can be noted that may be of help in establishing this scheme. These are given in Table II, and are based upon an acceptance criterion of agreement within 0.1%. The significance of sums of the transitions based on K-line assignments alone is of course questionable.

Conclusions---Bi^{203}

A possible similarity between the Pb^{203} and Pb^{205} energy levels is indicated by a comparison of the energies of a number of the stronger transitions of these nuclides as follows:

Pb^{203}	Pb^{205}
126.4	112.2
264.0	260.5
381.5	383.0
625.0	626.2
708.4	703.3
1033.7	1043.5

That there are fewer reported transitions of Bi^{203} than of Bi^{205} may be due merely to the experimental difficulty in producing Bi^{203} in quantities comparable to Bi^{204} and Bi^{205}, because the thick targets that were employed have the effect of reducing the α,4n yields relative to those of the α,3n and α,2n reactions.

Table II

Transition-energy summs of Bi^{203} decay		
60.1 + 126.4	=	186.5
Crossover	=	186.5
186.5 + 819.7	=	1006.2
381.5 + 625.0	=	1006.5
264.0 + 824.9	=	1088.9
381.5 + 708.4	=	1089.9
606.1 + 824.9	=	1431.0
708.4 + 722.1	=	1430.5

Bismuth-204 and Lead-204m

Half Life

A Bi^{204} sample was followed for one week in a G-M counter, and a half-life value of 11.0 ± 0.5 hours was obtained. The main contaminant in the sample was 6.4-day Bi^{206} to the extent of 10% of the initial counting rate. The bombardment had been made below the α,4n threshold to avoid the production of Bi^{203}, and its absence was verified by the conversion-electron spectrum obtained with another part of the sample.

Photon Spectrum

The photon spectrum of Bi^{204} was obtained with the scintillation spectrometer, and a comparison was made of this spectrum with that of the 68-minute Pb^{204m} isomer. The two spectra are shown in Fig. 1. The spectrum of Pb^{204m} is known to consist only of a 375-kev photon and a pair of unresolved photons at ~900 kev. That of Bi^{204} is evidently more complex, but the only additional photon that is easily identified is the peak at 670 kev.

Electron Spectrum--Bi^{204}

The high resolution (0.1 %) of the permanent-magnet spectrographs was essential to a study of the extremely complex spectrum of Bi^{204} and the associated isotopes Bi^{205}, Bi^{206}, and Bi^{207}. Figure 2 shows a portion of the densitometer tracing obtained from a photographic plate of Bi^{204} and Bi^{206} in the energy region from 770 to 840 kev. Two of the photographic plates are reproduced in Fig. 3.

A listing of the transitions associated with Bi^{204} decay is given in Table III. These are divided into three rather subjective groups which correspond to decreasing levels of confidence in the assignments. The first and second groups contain transitions with two or more conversion lines assigned, but those in the second group are weaker or contain possible ambiguities. In the third group only one line per transition has been observed, but in at least two independent experiments. The numerical relative intensities of the stronger conversion lines have been obtained from densitometer tracings of the photographic spectra. The absolute accuracy of the transition energies should be better than 0.2%. Relative conversion-line intensities are probably good to ± 50%.

Electron Spectrum--Pb^{204m}

In an attempt to construct a decay scheme for Bi^{204} one can utilize as a basic framework the simple Pb^{204m} decay scheme. This isomer is known to de-excite by three cascade gamma rays of energies 911, 375, and 899 kev, which define levels in Pb^{204} at 0, 899, 1274, and 2185 kev of spins and parities 0+, 2+, 4+, and 9-, respectively. We have examined the conversion-electron spectrum of Pb^{204m} and have found a new level in Pb^{204} which we

Table III

Bi^{204} Transitions

E_γ	Conversion lines observed	K-line intensity
78.62	$L_{II}L_{III}M_{I}M_{II}M_{III}N_{III}$	3080 (L_{II})
80.21	$L_{I}L_{II}M_{I}N_{I}$	2090 (L_{I})
100.4	$L_{I}L_{II}M_{I}$	270 (L_{I})
119.8	K L_{I}	W
140.9	K $L_{I}M_{I}$	1230
144.5	K $L_{I}M_{I}N_{I}$	M
170.0	K $L_{I}M_{I}$	1820
212.7	K L_{I}	90
216.2	K $L_{I}M_{I}$	1630
219.5	K $L_{II}L_{III}M_{II}M_{III}N_{II}$	500
222.5	K $L_{I}M_{I}N_{I}$	940
227.1	K L_{I}	80
240.7	K $L_{I}M_{I}$	290
249.1	K $L_{I}M_{I}N_{I}$	1820
289.5	K L_{I}	1440
291.0	K L_{I}	570
330.9	K L_{I}	170
375.0	K $L_{I}L_{II}L_{III}M_{I}N_{I}$	3970
405.5	K L_{I}	130
412.4	K L_{I}	120
421.8	K L_{I}	320
438.8	K L_{I}	230
501.8	K L_{I}	150
522.2	K $L_{II}L_{III}M_{II}$	120
532.6	K L_{I}	260

Table III - (continued)

E_γ	Conversion lines observed	K-line intensity
661.5	K L_I	210
663.4	K $L_I L_{II}$	80
671.0	K $L_I L_{III} M_I N_I$	810
710.4	K L_I	120
725.3	K L_I	50
791.9	K L_I	90
899.2	K $L_I L_{III} N_I$	1000
911.5	K $L_{II} L_{III} M_{II} N_{II}$	1330
918.4	K $L_I M_I$	110
<u>2nd Confidence Group</u>		
109.1	$L_I L_{II} M_{II}$	VW (L_I)
164.9	K L_I	W
184.9	$L_I L_{II}$	90 (L_I)
213.5	K L_{II}	170
252.4	K L_I	80
440.2	K L_I	50
<u>3rd Confidence Group</u>		
105.5	L_I	VVW
168.8	K	340
209.1	K	W
332.1	K	110
340.6	K	70
376.8	K	210
468.3	K	120
542.2	K	40
545.7	K	30

Table III - (continued)

E_γ	Conversion lines observed	K-line intensity
548.8	K	W
585.4	K	W
615.2	K	W
621.7	K	VW
646.4	K	VVW
684.3	K	VVW
718.5	K	50
745.2	K	VW
748.5	K	110
765.4	K	VW
832.3	K	40
834.3	K	50
844.1	K	100
933.6	K	VW
1056.7	K	30
1139.8	K	VVW
1203.9	K	VW
1211.5	K	VW

believe lies at 1563 kev; the same conclusion has also been reached independently by Herrlander, Stockendal, McDonell, and Bergström in their recent study of this isomer.[9]

The conversion electron data of Pb^{204m} are given in Table IV. In addition to the previously known transitions, a very weak line appears which we have assigned as the K line of a 289.5-kev transition; the basis for this assignment lies largely in the fact that a strong 289.5-kev transition has been identified from Bi^{204} decay (See Table III). Since it is not expected that there will be a new level in Pb^{204} below the 4+ level at 1274 kev it seems reasonable that this new level lies between the 4+ level and the 2185-kev 9- level. We were unable to find in the Pb^{204m} spectrum lines of a second transition corresponding to the difference between 911.5 and 289.5, i.e., 622.0 kev, but such a transition was identified in the Bi^{204} spectrum. The 289.5-kev transition is shown to be lower in the level scheme than the 622-kev transition by two arguments:

(a) The 289.5-kev transition has a high K/L ratio (as observed in the Bi^{204} spectrum) and hence is of low multipole order, probably dipole. Its prominent L conversion in the L_I subshell indicates that it is an M1 or an M2 transition, and hence it could not arise from the isomeric state, which de-excites mainly by the 911.5-kev E5 transition.

(b) In the Bi^{204} spectrum, the 289.5-kev transition is extremely weak. It is likely, therefore, that the 289.5-kev transition lies lower in the cascade, since the alternative explanation would require that there be a very strong transition in Bi^{204} decay that is parallel to the 622-kev transition; such a parallel transition has not been observed.

The spin of the new level, as suggested by the probable magnetic dipole character of the 289.5-kev transition, may be 3+, 4+, or 5+. Analogy with the known Pb^{206} level scheme[1] suggests an assignment of 4+; the 622.0-kev transition would then be an E5, as is the 911.5-kev transition. Further demonstration of the E5 character of the 622.0-kev transition has been given by Herrlander <u>et al.</u>,[9] who find a K/L ratio of 0.74 ± 0.09, in reasonable agreement with Rose's theoretical ratio for an E5 transition, 0.84.[10]

From the Pb^{204m} spectrum, we measure the ratio of the intensity of the K line of the 289.5-kev transition to that of the 375.0-kev transition as 0.027. By use of Sliv's theoretical K-conversion coefficient[11] for a 289.5-kev M1 transition (0.36), and the experimental K-conversion coefficient of the 375.0-kev E2 transition measured by Herrlander *et al.*[9] (0.044), we obtain a transition ratio (290/375) of 0.004. Herrlander *et al.* report a transition ratio (622/912) of 0.0027. Since the 622- and 290-kev transition intensities should be about equal, as well as the 912- and 375-kev intensities, these two ratios should be roughly equal. This branching may be compared with that expected theoretically from a strict $E2 \Delta I+1$ dependence. The calculated ratio is 622/912 = 0.013, as compared with the experimental average value 622/912 = 0.003, indicating that the 622-kev transition is slower by a factor of about four (relative to the 912-kev transition) than would be predicted from the energy dependence alone.

TABLE IV

Conversion Lines Observed From Pb^{204m} Decay

Electron Energy (kev)	Visual Intensity	Assignment
201.7	VW	289.5 K
287.7	VS	375.0 K
359.7	M	375.0 L_{II}
362.2	VW-W	375.0 L_{III}
371.6	W	375.0 M_{II}
374.1	VW	375.0 N_{II}
811.9	VW	899.2 K
824.0	MS	911.5 K
896.3	M	911.5 L_{II}
899.8	VW-VVW	911.5 L_{III}
908.9	W	911.5 M_{II}
911.6	VW	911.5 N_{II}

Transition Sums--Bi^{204}

To build further upon the energy-level framework provided by Pb^{204m}, we have examined the transition-sum relationships of Bi^{204} decay. Since there are several thousand sums obtained from the 67 transitions, many accidental coincidences of sums of two transitions with other sums of two transitions will occur, even at a precision of 0.1%. We have listed in Table V, therefore, only sums of two compared with single transitions (agreement within 0.1%); 111 such sums are found.

It is significant that from this list of sums the energy of the E5 isomeric transition, 911.5-kev, occurs as a crossover transition six times. The probability that this number of sums would occur by chance is only 1 in 10,000, hence at least some of these cascade relationships must be significant. The six sums to 911.5 ± 0.9 kev are:

$$
\begin{aligned}
832.3 + 78.6 &= 910.9\\
791.9 + 119.8 &= 911.7\\
671.0 + 240.7 &= 911.7\\
661.5 + 249.1 &= 910.6\\
684.0 + 227.1 &= 911.1\\
621.7 + 289.5 &= 911.2
\end{aligned}
$$

Only one of these six pairs of cascade transitions has actually been observed in the electron spectrum of the isomer itself (by Herrlander et al.[9]), therefore one must account for the absence of the other cascades on intensity grounds if the sums are to be considered valid.

Two sums that can clearly be rejected in this way are those of the 240.7-571.0 pair and the 661.5-249.1 pair, because the K lines of all these transitions are much too intense in the Bi^{204} spectrum to have been unobserved in the Pb^{204m} spectrum. The status of the other three Bi^{204} sums remains in question because at least one of each pair is sufficiently weak relative to the 911.5 that it could have been missed in the Pb^{204m} spectrum. It would be desirable to re-examine the Pb^{204m} spectrum with stronger sources to search for these weak competing isomeric transitions.

Conclusions--Bi^{204}

A Pb^{204} level scheme cannot be constructed on the basis of the numerical sum relationships alone; the complexity is such that a precision greater than 0.1% would be required. Electron-electron coincidence work at fairly high resolution could also help to decide the true or accidental nature of some of the transition sums.

Table V

Energy Sums of Pb^{204} Transitions

Cross-over	Cascade sum		Cross-over	Cascade sum	
219.5	78.62	140.9	646.4	100.4	540.7
249.1	80.21	168.8	646.4	144.5	501.0
289.5	80.21	209.1	646.4	240.7	405.5
330.9	78.62	252.4	661.5	119.8	542.2
405.5	164.9	240.7	661.5	222.5	438.8
412.4	80.21	332.1	661.5	249.1	412.4
412.4	184.9	227.1	663.4	78.62	585.4
421.8	209.1	212.7	663.4	140.9	522.2
438.8	216.1	222.5	663.4	330.9	332.1
440.2	109.1	330.9	671.0	168.8	501.8
440.2	212.7	227.1	671.0	249.1	421.8
440.2	213.5	227.1	671.0	330.9	340.6
468.3	216.2	252.4	684.0	216.2	468.3
468.3	219.5	249.1	710.4	164.9	545.7
501.8	80.21	421.8	710.4	168.8	542.2
501.8	170.0	332.1	710.4	209.1	501.8
501.8	212.7	289.5	718.5	170.0	548.0
501.8	249.1	252.4	718.5	176.2	542.2
522.2	100.4	421.8	718.5	216.2	501.8
532.6	119.8	412.4	725.3	78.62	646.4
542.2	164.9	376.8	728.3	176.2	548.8
542.2	252.4	289.5	745.2	212.7	532.6
545.7	168.8	376.8	745.2	222.5	522.2
545.7	213.5	332.1	745.2	332.1	412.4
548.8	80.21	468.3	748.5	216.2	532.6
548.8	109.1	440.2	765.4	216.2	548.8
548.8	216.2	332.1	765.4	219.5	548.7
585.4	209.1	376.8	765.4	222.5	542.2
615.2	176.2	438.8	791.9	176.2	615.2
615.2	209.1	405.5	791.9	249.1	542.2
615.2	240.7	375.0	791.9	289.5	501.8

Table V (continued)

Cross-over	Cascade sum		Cross-over	Cascade sum	
832.3	168.8	663.1	1056.7	213.5	844.1
832.3	170.0	661.5	1056.7	222.5	834.3
832.3	289.5	548.2	1056.7	291.0	765.4
832.3	330.9	501.8	1056.7	330.9	728.3
834.3	412.4	421.8	1056.7	332.1	725.3
834.3	109.1	728.3	1056.7	144.5	911.5
834.3	219.5	615.2	1056.7	212.7	844.1
834.3	249.1	585.4	1139.8	222.5	918.4
834.3	332.1	501.8	1139.8	240.7	899.2
844.1	78.62	765.4	1139.8	375.0	765.4
844.1	375.0	468.3	1139.8	421.8	718.5
844.1	405.5	438.8	1139.8	460.3	671.0
899.2	252.4	646.4	1203.9	412.4	791.9
899.2	376.8	522.2	1203.9	438.8	765.4
911.5	78.62	832.3	1203.9	532.6	671.0
911.5	119.8	791.9	1203.9	542.2	661.5
911.5	240.7	671.0	1211.5	376.8	834.3
911.5	249.1	661.5	1211.5	501.8	710.4
911.5	684.0	227.1	1211.5	548.8	661.5
911.5	289.5	621.7	1211.5	548.8	663.4
918.4	170.0	748.5			
918.4	332.1	585.4			
918.4	326.8	542.2			
933.6	100.4	832.3			
933.6	140.9	791.9			
933.6	168.8	765.4			
933.6	184.9	748.5			
933.6	209.1	725.3			
933.6	222.5	710.4			

Bismuth-205

Half Life

A sample of Bi^{205} was followed for more than seven half lives with a G-M counter to obtain a value for the Bi^{205} half life of 15.3 ± 0.7 days. Approximately 80% of the initial counting rate of the sample was Bi^{205}; the other 20% was 6-day Bi^{206} with a very small amount of 8-year Bi^{207}.

Scintillation Spectrum

The gamma-ray scintillation spectrum of Bi^{205} was examined for a measure of the relative intensities of the more intense photons; the results are given in Table VI.

Electron Spectrum

The transitions assigned to Bi^{205} decay from this work, and from the work of Schmorak *et al.*,[3] are given in Table VII. Also given are the measured intensities of various prominent lines relative to the K-line of the 703.3-kev transition. The agreement of the transition energies with those reported by Schmorak *et al.*[3] is for the stronger transitions very good.

Table VI

Bi^{205} Photon Spectrum

Energy of gamma ray (kev)	Relative intensity
570	0.35
700	1.00
1000	0.62
1770	2.0

Gamma-Gamma Coincidences

Because of the complexity of the Bi^{205} spectrum, little information was gained from gamma-gamma coincidence experiments. The only certain results were that the 570-kev transition is in coincidence with the 1044-kev transition and that the 703-kev transition is in coincidence with radiation of energy greater than 1750 kev.

A search was also conducted for delayed states in Bi^{205} decay. By gating with the K x-rays and comparing the resulting coincidence spectrum with the singles spectrum one was able to discern that none of the more

Table VII

Transitions observed in Bi^{205} decay

E_γ (kev) This work	E_γ (kev) Schmorak et al.	I (K-line) This work	I (K-line) Schmorak et al.
112.2	---	11.5 (L)	---
---	115.2	---	10 (L)
131.2	---	---	---
149.0	---	---	---
192.6	---	---	---
---	235.9	---	8
260.5	260.5	83	110
282.4	282.3	33	41
284.0	284.2	116	160
349.3	349.4	29	28
383.3	383.2	---	6
493.5	493.6	11	11
511.7	511.7	16	22
526.0	---	---	---
531.1	---	---	---
550.3	550.0	---	6.3
570.7	571.0	77	74
573.7	---	---	---
579.7	580.0	26	24
626.2	626.5	---	6.7
---	688.9	---	1
703.3	703.3	100.0	100.0
744.6	745.0	---	2.1
758.6	758.3	---	3.1
---	761.0	---	2.0

Table VII (continued)

E_γ (kev) This work	Schmorak *et al.*	I (K-line) This work	Schmorak *et al.*
910.7	910.8	---	9.8
987.5	987.8	21	27.5
---	1002.7	---	2.1
1014.0	1014.2	---	4.9
1043.5	1043.7	22	32.5
1073.3	---	---	---
1190.1	1190.3	---	7.6
~1346	1337	---	0.3
---	1351.5	---	1.1
---	1502.5	---	0.4
---	1552.0	---	0.8
~1617	1614.6	---	3.1
---	1766.4	---	43.6
---	1777.4	---	5.2
---	1863.3	---	2.0
---	1906.5	---	0.6
---	~2600	---	< 0.5

intense transitions was delayed, since both spectra were almost identical. By gating on the K x-rays and inserting appropriate delays into the coincidence circuit, an upper limit of about 5×10^{-9} sec was set on the half life of the 703-kev E2 gamma ray. A similar limit was set for the other transitions.

Search for Isomeric State in Pb^{205}

Since isomers of the M4 type are known to occur in Pb^{201}, Pb^{203}, and Pb^{207}, it has been expected that Pb^{205} should also have such an isomer. Further, the Pb^{203} and Pb^{207} isomers are directly populated to a considerable extent from the decay of Bi^{203} and Bi^{207}, respectively; hence it was natural to search for the Pb^{205} isomer from the decay of Bi^{205}.

From the known half lives of Pb^{207m} (0.8 sec) and Pb^{203m} (7 sec), one predicts a half life of from 1.5 to 2 seconds for a similar M4 isomer in Pb^{205}. Also an interpolation of the energies of the Pb^{207} and Pb^{203} isomeric transitions leads to a prediction of an energy of 900 to 1000 kev for the Pb^{205} isomer.

We have searched for this isomer, in two separate experiments, with negative results. The experimental method was the following: Sources of fairly pure Bi^{205} were produced by alpha-particle bombardment of Tl^{203} well below the α,3n threshold. The regular chemical procedure was followed, except that in the final step the bismuth activity was allowed to remain upon the anion-exchange column. A continuous-flow system with 0.1N HCl as eluant was then used to remove the lead daughter activity continuously and pass it along a glass tube at a known flow rate. By means of a single-channel scintillation spectrometer the activity could be measured as a function of distance along the glass tube, and hence the half life determined.

The experiment yielded a half life of 0.7 sec, which agrees with the known half life of Pb^{207m} (0.8 sec). Further proof that this activity was Pb^{207m} was obtained by identification in the gamma spectrum of the 570-kev gamma ray of Pb^{207m}.

It is possible from these experiments to set an upper limit to the population of such a Pb^{205} isomer by the decay of Bi^{205}, using the figure of 90% for the population of Pb^{207m} by Bi^{207} decay and the known half lives of Bi^{207} (8 years) and Bi^{205} (15.3 days). Assuming that the $Tl^{203}(\alpha,2n)Bi^{205}$ cross-section is about the same as the $Tl^{205}(\alpha,2n)Bi^{207}$ cross section, and knowing the isotopic enrichment of the thallium target material, one calculates that the population of an isomeric state in Pb^{205} by decay of Bi^{205} is less than 0.1%. This limit, of course, is valid only for an isomer similar to that of Pb^{203m} and Pb^{207m}; an isomer with half life less than 0.3 sec is not ruled out by these experiments.

Transition-Energy Sums and Level Scheme

On the basis of transition-energy sums and coincidence information, Schmorak et al.[3] present a level scheme of Pb^{205} in which ten levels are considered to be "well established." Because of the close agreement of our transition energies with theirs, most of the sum relations are also in accord. However, there are several inconsistencies within their level scheme that would seem to require further clarification. It is fairly certain that the 703.3-kev transition proceeds to the ground state, both because of its high intensity and because it is not in coincidence with any of the other strong transitions. But the level scheme of Schmorak et al. places the strong 260.5-kev transition in a position high in the scheme, where decay would proceed to ground via a cascade through the 703.3-kev transition; such a position seems to contradict the experimental data cited in Table IV and in Table VI of their paper,[3] which indicate that these two radiations are not in coincidence. Further, the alpha- and gamma-ray data of Asaro and Perlman[12] on the decay of Po^{209} (populating the same daughter nucleus) show that the first excited state of Pb^{205} has an energy of 260 ± 5 kev, not 282.3 kev as postulated by Schmorak et al. However, the alternative proposal that the 260.5-kev transition be assigned to the first excited state of Pb^{205} also contradicts the Bi^{205} coincidence data, since coincidences are found between the 571.0- and 260.5-kev transitions, yet there are found no transitions with the proper energies to connect the 1043.7- and 260.5-kev levels. The same contradiction holds for the information that the 284.2-kev gamma is in coincidence with the 282.3-kev gamma; a transition of 421.0 kev, which would then be necessary to connect the 703.3-kev and 282.3-kev levels, is not found either by Schmorak et al.[3] or in this work. It seems clear from the Po^{209} alpha-decay data that the first excited state of Pb^{205} lies at 260 kev, although it has not been proved that the M1 transition that de-excites this state is identical to the 260.5-kev transition observed from Bi^{205} decay. Further coincidence experiments with Bi^{205} at fairly high resolution will be necessary for the clarification of the Pb^{205} level scheme.

Conclusions--Bi^{205}

Because of the large number of transitions found in Bi^{205} decay it is interesting to observe from a statistical plot of transition energies whether or not any correlations can be made with the known energies of single-neutron transitions in this region. In Figure 4 we give such a plot, which shows the following maxima and a possible interpretation.

Maximum (kev)	Single-neutron transition in Pb^{207} (kev)	
125	- - - - - - - - - - - - -	
280	$p_{3/2} \longrightarrow f_{5/2}$	300
560	$f_{5/2} \longrightarrow p_{1/2}$	570
750	$p_{3/2} \longrightarrow p_{1/2}$	870
1025	$i_{13/2} \longrightarrow f_{5/2}$	1063

Apparently in the "three-hole" nucleus Pb^{205} manifestations of odd-nucleon transitions remain, superimposed upon the various excitations of the other nucleon pair.

This work was done under the auspices of the U. S. Atomic Energy Commission.

REFERENCES

1. D. E. Alburger and M. H. L. Pryce, Phys. Rev. 95, 1482 (1954).

2. M. H. L. Pryce, Proc. Phys. Soc. (London) A65, 773 (1952).

3. Schmorak, Stockendal, McDonell, Bergström, and Gerholm, Nucl. Phys. to be published (1957).

4. A. R. Fritsch, UCRL-3452 (Thesis) June, 1956.

5. W. G. Smith and J. M. Hollander, Phys. Rev. 101, 746 (1955).

6. Stockendal, McDonell, Schmorak, and Bergström, Arkiv Fysik 11, 165 (1956).

7. H. J. Hopkins, Phys. Rev. 88, 680 (1952).

8. V. K. Fischer, Phys. Rev. 99, 764 (1955).

9. Herrlander, Stockendal, McDonell, and Bergström, Nucl. Phys. 1, 643 (1956).

10. M. E. Rose, privately circulated tables of relativistic, screened conversion coefficients for point nuclei.

11. L. A. Sliv, privately circulated tables of relativistic, screened K-conversion coefficients for nuclei of finite size.

12. Frank Asaro and I. Perlman, private communication.