POSITIVE PARITY STATES IN SOME ODD-A BISMUTH ISOTOPES

M. Alpsten^{*)} and G. Astner
CERN, Geneva, Switzerland.

ABSTRACT

The electron capture decays of $^{207,205,203,201}\text{Po}$ have been investigated. Several excited levels have been established in the bismuth daughters. Special attention is paid to a group of positive parity levels: at 1902 ($1/2^+$), 2060 ($3/2^+$), and 2405 keV ($5/2^+$) in ^{207}Bi ; at 1497 ($1/2^+$), 1709 ($3/2^+$), and 1969 keV ($5/2^+$) in ^{205}Bi ; at 1098 ($1/2^+$), 1313 ($3/2^+$) and 1488 keV ($5/2^+$) in ^{203}Bi ; at 846 keV ($1/2^+$) in ^{201}Bi . It is proposed that these states are due to holes in the $Z = 82$ proton shell, and some arguments supporting this interpretation are given.

RADIOACTIVITY $^{207,205,203,201}\text{Po}$, $^{201\text{m}}\text{Bi}$
[from $^{209}\text{Bi}(p,xn)$]; measured E_γ , I_γ , I_{ce} ,
 $\gamma\gamma$ -coinc, deduced cc. $^{207,205,203,201}\text{Bi}$
deduced levels, J, π . Ge(Li) Si(Li) detec-
tors, magnetic spectrometer, NaI(Tl) -
Ge(Li) coin.

(Submitted to Nuclear Physics)

*) Permanent address: Department of Physics, Chalmers University of Technology, Gothenburg, Sweden.

1. INTRODUCTION

Isotopes of bismuth have 83 protons. Hence one would expect that a proper description of the properties of their low-lying levels could be obtained in terms of coupling of one proton outside the $Z = 82$ closed shell with the neutrons (neutron holes) outside the $N = 126$ shell, and with possible collective excitations. Obviously, most low-lying excited states are of this type. In this work, however, we report on positive parity states in $(^{207}, ^{205}, ^{203}, ^{201}\text{Bi})$ which cannot be explained according to this model, and suggest an interpretation in terms of holes in the $Z = 82$ core.

So far the experimental information on excited levels in odd-A neutron deficient bismuth isotopes has been limited to data from alpha decay studies¹⁾ with one exception: the decay of ^{207}Po populating levels in ^{207}Bi has been studied^{2,3)}.

2. EXPERIMENTAL PROCEDURE

$^{201-205}\text{Po}$ were produced in $^{209}\text{Bi}(p, xn)$ -reactions using the CERN Synchro-cyclotron to irradiate a bismuth oxide powder target at a proton energy of approximately 110 MeV. Polonium was chemically separated using a technique described in detail elsewhere⁴⁾. After electromagnetic mass separation sources with a strength of about 10 μCi for $^{203}, ^{205}\text{Po}$ were obtained approximately 25 minutes after the end of the irradiation. In the case of ^{201}mBi , activity formed in the decay of ^{201}Po was studied.

Gamma and conversion electron spectra have been recorded using semiconductor detectors: A 10 cm^3 Ge(Li)-detector with a resolution of 4 keV FWHM at 1.33 MeV, a 1 cm^3 Ge(Li)-detector with 1.2 keV resolution at 122 keV, and a 2 mm thick Si(Li) electron detector with 3.5-4.0 keV resolution. For ^{201}mBi , gamma and conversion electron spectra were recorded simultaneously. The well-established 629 keV M4 transition⁵⁾ in

^{201}Pb is also seen in the decay from ^{201}Bi . This serves as an internal standard in the relative intensity calibration of the two detectors.

Important regions of the conversion electron spectra were also run in a double-focusing magnetic spectrometer⁶⁾ which permits a study at higher resolution and with less gamma background. Also, gamma-gamma coincidences have been measured using a Ge(Li) - NaI(Tl) - set-up.

Figure 1 shows parts of the gamma and conversion electron spectra from the decay of ^{205}Po recorded with Ge(Li)- and Si(Li)-detectors, whereas Fig. 2 shows a part of the ^{203}Po spectrum, with the conversion electron lines measured in the magnetic spectrometer.

3. RESULTS

3.1 ^{207}Po decay

The decay of ^{207}Po is described in detail elsewhere^{2,3)}. The data relevant for the present discussion are included in Fig. 7.

3.2 ^{205}Po and ^{203}Po decays

Tables 1 and 2 list the experimental information on the strongest transitions in the ^{205}Po and ^{203}Po decays, respectively. Only those with an intensity higher than 2% of that of the strongest transition, and a few weaker ones that are connected to the positive parity states, have been included in these tables. Many weak transitions are omitted, which have little influence on the discussion here. The relative gamma and internal conversion electron intensities have been combined to yield K-conversion coefficients. These are compared with the theoretical values of Sliv and Band⁷⁾ in Figs. 3 and 4. This information together with K/L-ratios and, in a few cases, $L_I + L_{II}/L_{III}$ -ratios have been used to deduce multipolarities of the transitions.

Figures 5 and 6 show those parts of the level schemes of ^{205}Bi and ^{203}Bi that are essential for the discussion of the positive parity states. More detailed arguments for these schemes will be given elsewhere⁸⁾. Suffice it here to say that they are well supported by energy sum relations, coincidence measurements and multipolarity assignments. The log ft values are deduced from total transition intensity balance, using $Q(p,n)$ -values from Mattauch et al.⁹⁾. Uncertainties in the intensities (mainly from unplaced weak transitions) and Q -values do not appreciably affect the log ft values.

3.3 $^{201\text{m}}\text{Bi}$ decay

A metastable state in ^{201}Bi ($T_{1/2} = 59$ min) is known from alpha decay studies^{10,11)}. We have observed a strongly converted transition with an energy of 846 keV. It decays with a half-life close to 60 min. The energy difference $E_Y - E_K = 846.3 - 755.7 = 90.6 \pm 1.0$ keV proves conversion in bismuth. Siivola et al.¹⁰⁾ conclude from binding energy systematics that the isomeric state should have an excitation energy around 900 keV. Hence it is most likely that this transition feeds the ground state directly. A multipolarity determination would therefore give information on spin and parity of the metastable state, as the spin of the ground state is measured¹²⁾ to be $9/2$, with negative parity according to systematics which interprets the bismuth ground states as $1h_{9/2}$. Our results, $\alpha_K = 0.13 \pm 0.04$ and $K/L = 2.3 \pm 0.4$ can be interpreted either as $M4 + (54 \pm 20)\% E5$ or $E4 + (26 \pm 11)\% M5$. From our information on other transitions in the $^{201\text{m}}\text{Bi}$ decay, one can estimate the isomeric transition branch to be smaller than 50%. Arguments for spin $1/2$ have been given earlier by Siivola et al.¹⁰⁾. If the transition is mainly $E4$ (retardation $> 10^5$) the level should be assigned negative parity. Peker and Kharitonov¹³⁾ have proposed a three-particle interpretation

if the parity is negative: $[P(h_{9/2})N(f_{5/2}^2)_4]_{1/2^-}$. In the light of the data for heavier isotopes we find the positive parity assignment more likely, but negative parity cannot, on the basis of the present information, be completely ruled out.

If, on the other hand, the transition is of M4 + E5 character, the M4 retardation is more than 1500 compared to the Moszkowski-Weisskopf single particle estimate¹⁴⁾. The retardation for the E5 admixture would be about 1. With the M4 + E5 interpretation, the isomer fits nicely into the systematics of the heavier isotopes. Hence we tentatively assign a level at 846 keV with spin and parity $1/2^+$.

4. DISCUSSION

Strong similarities between the decay schemes of $^{207,205,203}\text{Po}$ can be observed. In all cases only three states are strongly fed in the electron capture decay: two states around 1 MeV excitation that have been assigned spin and parity $7/2^-$, and one $3/2^+$ state, whose excitation energy decreases with decreasing mass number. The two $7/2^-$ states are readily interpreted as the $2f_{7/2}$ single proton state, its strength being split on essentially two levels. This is well borne out in ^{207}Bi by recent calculations by Blomqvist¹⁵⁾.

We limit our discussion here to the $1/2^+$, $3/2^+$, and $5/2^+$ levels, and suggest that they are due to one hole in the $Z = 82$ proton core, with two protons pairing off in the $h_{9/2}$ level. This idea was, on less evidence, put forward already by Arbman et al.²⁾ for ^{207}Bi . The arguments for the "core excitation" are the following:

1. (The discussion under this point is performed for mass number 207, but holds also for $A = 205, 203$ and slightly modified for $A = 201$ where the ^{201}Po ground state is $3/2^-$). The $\log ft$ value for the $5/2^- \rightarrow 3/2^+$ transition is 6.2, which is low for a first forbidden transition. This suggests an

interpretation in terms of a single particle transition between large parts of the initial and final wave functions. In the ^{207}Po ground state, which to a first approximation has the configuration $[P(h_{9/2}^2)N(p_{1/2}^{-2}f_{5/2}^{-1})]_{5/2^-}$ essentially only the $p_{1/2}$, $f_{5/2}$ and $p_{3/2}$ levels contain holes in the $82 < N < 126$ shell. If one limits the neutron excitation to this shell, only the following first forbidden non-unique single particle beta transitions will be possible:

$$P(s_{1/2}) \rightarrow N(p_{1/2}) \quad (1)$$

$$P(d_{3/2}) \rightarrow N(p_{1/2}) \quad (2)$$

$$P(s_{1/2}) \rightarrow N(p_{3/2}) \quad (3)$$

$$P(d_{3/2}) \rightarrow N(p_{3/2}) \quad (4)$$

$$P(d_{5/2}) \rightarrow N(p_{3/2}) \quad (5)$$

$$P(d_{3/2}) \rightarrow N(f_{5/2}) \quad (6)$$

$$P(d_{5/2}) \rightarrow N(f_{5/2}) \quad (7)$$

$$P(g_{7/2}) \rightarrow N(f_{5/2}). \quad (8)$$

The alternatives (1)-(5) will not make it possible to pair off the neutrons in the bismuth final states. Thus the excited state in bismuth created out of (6) will be considerably lower in energy than for (1)-(5). Hence we exclude those from the following discussion and also (8) because of its high excitation. However, as it is known from the $\text{Pb}(t, \alpha)$ pick-up reaction that the first $5/2^+$ state in odd-A thallium isotopes has an appreciable $d_{5/2}$ content¹⁶⁾, we keep (7). The two beta processes (6) and (7) lead to $[P(d_{3/2}^{-1}h_{9/2}^2)N(p_{1/2}^{-2})]_{3/2+}$ and $[P(d_{5/2}^{-1}h_{9/2}^2)N(p_{1/2}^{-2})]_{5/2+}$ states in ^{207}Bi respectively. We see that transitions to these two levels will occur without any essential retardation, if energetically allowed. They should then be completely analogous to the electron capture decay of the corresponding lead isotopes. The relevant data

are summarized in Table 3. One notices a remarkable agreement between the $\log ft$ values. The $5/2^- \rightarrow 5/2^+$ transition is to be understood as proceeding via the $d_{5/2}$ admixture to the $5/2^+$ state.

A priori there is no reason not to include also neutron excitations outside the $N = 126$ shell [e.g. $P(h_{9/2}) \rightarrow N(g_{9/2})$]. Here one will not have any gain in pairing energy, corresponding to that which occurs when two protons pair off in the $h_{9/2}$ level instead of in the $d_{3/2}$ level. It is also clear that the dependance on neutron number for states created in this way would be opposite to what is actually observed for the positive parity states.

It would seem natural to explain the lowest-lying positive parity states in, say, ^{207}Bi as a coupling of an $h_{9/2}$ proton to the lowest negative parity states in ^{206}Pb , which are well understood in the shell model¹⁷⁾. However they all involve one $i_{13/2}$ neutron hole and, using the above arguments, one sees that such states cannot be populated directly in the electron capture decay. Also, for the ^{207}Bi case, where the agreement between experiment and theory for one proton two neutron hole states is impressive¹⁵⁾, it seems impossible to get a $1/2^+$ state low enough, using only such configurations.

Another group of positive parity levels is generated from the coupling of the 3^- octupole vibration with the ground state $h_{9/2}$ proton. This gives rise to levels with positive parity and spins ranging from $3/2$ to $15/2$. These levels have recently been resolved¹⁸⁾ in the case of ^{209}Bi . They cannot, however, be populated in beta decay, because of the one particle character of the beta process.

2. To estimate at what excitation energy states of the suggested type would occur, we use a procedure applied by Blomqvist

and Wahlborn¹⁹⁾ to the 2.13 MeV $1/2^-$ state in ^{209}Pb . The excitation energy is taken as $B_p(^{208}\text{Po}) - B_p(^{206}\text{Pb})$ for the $1/2^+$ state in ^{207}Bi and corresponding expressions for the lighter isotopes. In this manner the difference in pairing energy between the two states is taken into account. Table 3 gives the result using binding energies from Mattauch et al.⁹⁾. The discrepancy between experiment and theory is rather large, about 0.6 MeV, but the *variation* with mass number from $A = 207$ to $A = 205$ is well reproduced. For lower mass numbers experimental binding energy data are missing, and it is hard to draw any conclusions from estimated values. It is clear that this type of estimate cannot be expected to be as accurate here as for ^{209}Pb , because the neutron core is not closed. Blomqvist²⁰⁾ has pointed out that the attractive Coulomb interaction between the proton hole and the proton pair should give about 0.4 MeV further lowering of the core-excited states. Some energy should also be gained via the proton particle-neutron core interaction.

3. The agreement with the properties of the ground and first excited states in corresponding thallium isotopes is rather striking (cf. Table 3). In particular the large E2/M1 mixing ratios for the $3/2^+ - 1/2^+$ transitions should be observed.

4. The large M4 hindrance (>1500) for the $1/2^+ \rightarrow 9/2^-$ transition in ^{201}Bi supports the $P(h_{9/2}^2 s_{1/2}^{-1})$ assignment for the $1/2^+$ state. A $h_{9/2} \rightarrow s_{1/2}$ ($\Delta l = 5$) M4 transition is ℓ -forbidden, whereas the E5 component should proceed unhindered.

To sum up: It seems impossible to describe the positive parity states in the framework of a ^{208}Pb core with one proton and several neutron holes outside it, even if octupole vibrations are included. The core excitation description is satisfactory, possibly with a reservation for the surprisingly low excitation energy (the $s_{1/2} - h_{9/2}$ splitting is 3.55 MeV in ^{208}Pb). It seems that it can be explained²⁰⁾ along the lines discussed

under point 2 above. Thus the pushing down of the proton hole states seems only partly to be due to the larger pairing gained in the $h_{9/2}$ level.

Siivola's alpha decay work¹⁾ has established isomerism in odd-A bismuth isotopes down to mass number 191. For $A = 195$, 193, and 191, the alpha decay of the ground states are also observed. If one assumes that the alpha branches from the isomeric states go to corresponding thallium ground states and that the bismuth ground states alpha decay to excited $9/2^-$ states at approximately 280, 210, and 160 keV in $^{191,189,187}\text{Tl}$ respectively²⁰⁾ [corresponding to $9/2^-$ states observed in heavier odd mass thallium isotopes²¹⁾], one gets the following excitation energies for the isomeric states in bismuth: 430, 380, and 410 keV, respectively. It seems reasonable to assume that the isomeric state is $1/2^+$ also in these cases, its excitation energy varying smoothly from ^{207}Bi to ^{191}Bi .

Acknowledgements

We appreciate the continuous support and encouragement of Prof. I. Bergström, Prof. G. Andersson and Dr. A. Kjelberg. Messrs. S. Sundell and G. Droz carried out the many mass separations and Miss I. Jarstorff helped with the chemical preparations. Their efforts are gratefully acknowledged. Discussions with Drs. J. Blomqvist and S. Wahlborn have been stimulating and clarifying. This work has been supported by the Swedish Atomic Research Council.

Table 1

Experimental information on transitions in ^{205}Bi

Energy (keV)	Relative gamma intensity	Relative K- conversion electron intensity	Total transition intensity ^{*)}	K/L ratio	K-conversion coefficient	Multipolarity assignment
128.8	2.4	13.4	18	6	5.6 ± 1.2	M1
150.2	0.7	2.0	3.0		3.0 ± 0.8	M1
151.2	2.7	8.3	13	6	3.1 ± 0.6	M1
211.8	8.0	2.0	11	2.0	0.25 ± 0.03	E2 + 15% M1
247.7	0.4	0.1	0.5		0.25 ± 0.15	(E2)
260.7	8.1	4.8	14	5.5	0.59 ± 0.06	M1
453.9		0.1	0.1			
473.1	2.2	0.07	2.3		0.031 ± 0.006	E2
599.9	6.5	0.09	6.6		0.014 ± 0.003	E2
614.3	4.0	0.26	4.3	5	0.065 ± 0.009	M1
624.8	2.5	0.37	2.9	4	0.15 ± 0.02	M2
714	3.1	0.10	3.2		0.032 ± 0.015	M1
836.5	53	0.18	53		0.0034 ± 0.0003	E1
849.5	69	1.4	70	6	0.020 ± 0.002	M1 + 8% E2
872.1	100	0.70	101	6	0.0070 ± 0.0007	E2
1001.0	83	1.0	84	6	0.012 ± 0.001	M1 + 7% E2
1183.0	2.9	0.032	2.9		0.011 ± 0.002	M1
1238.4	13	0.086	13		0.0066 ± 0.0010	M1 + E2
1335.9	3.4	0.007	3.4		0.002 ± 0.001	E1
1513.8	5.4		5.4			
1551.7	7.2		7.2			
1576.0	3.7		3.7			
1702.3	0.7		0.7			
1708.1	1.6		1.6			
1729.2	4.0		4.0			
1811.0	2.9		2.9			
2573.7	0.4		0.4			

*) Contributions due to internal conversion in the L-shell from theory⁷⁾. $I_{M+N} + \dots / I_{L=0.3}$ assumed.

Table 2

Experimental information on transitions in ^{203}Bi

Energy (keV)	Relative gamma intensity	Relative K- conversion electron intensity	Total transition intensity*)	K/L ratio	K-conversion coefficient	Multipolarity assignment
175.2	5.9	9.8	17.8	5	1.6 ± 0.1	M1
182.5	0.2	0.4	0.6		1.8 ± 0.3	M1
189.5	6.8	3.2	46	0.11	0.47 ± 0.04	E3
197.7	1.0	1.4	2.8		1.4 ± 0.1	M1
204.7	1.0	0.7	4.9	0.3	0.75 ± 0.08	E3 + 6% M2
214.8	29	5.2	39	1.2	0.18 ± 0.02	E2 + 5% M1
261.8	2.6		2.6			
389.6	2.2	0.08	2.3		0.034 ± 0.011	E2
419.3	4.5	0.04	4.6		0.008 ± 0.005	E1
486.1	4.2	0.09	4.3		0.022 ± 0.006	E2
647.6	3.6	0.14	3.7		0.04 ± 0.01	M1
742.8	1.2		1.2			
893.5	31	0.025	31	4.5	0.008 ± 0.001	E2
908.7	100	1.3	101	5	0.013 ± 0.001	M1 + 50% E2
918.6	0.7		0.7			
1090.9	34	0.37	34	6	0.011 ± 0.001	M1 + 25% E2
1123.8	2.8		2.8			
1132.5	0.6		0.6			
1242.2	8.1	0.01	8.1		0.0014 ± 0.0007	E1
1337.7	5.5		5.5			
1352.7	2.5		2.5			

*) Contributions due to internal conversion in the L-shell from theory⁷⁾. $I_{M+N} + \dots/I_L = 0.3$ assumed.

Table 3

Comparison between positive parity states in odd-A Bi and Tl isotones.
Experimental and estimated excitation energies for $1/2^+$ levels in Bi.

	N = 124		N = 122		N = 120		N = 118
	^{207}Bi	^{205}Tl	^{205}Bi	^{203}Tl	^{203}Bi	^{201}Tl	^{201}Bi
$\Delta E(3/2^- - 1/2^-)$, keV	158	205	212	279	214	331	
$\Delta E(5/2^- - 1/2^-)$, keV	503	615	473	680	389	692	
E2 admixture ($3/2^- \rightarrow 1/2^-$)	92%	-	85%	62%	95%	68%	
$\log ft$ ($5/2^- \rightarrow 3/2^+$)	6.2	-	6.6	6.5	6.6	6.5 ^{*)}	
$\log ft$ ($5/2^- \rightarrow 5/2^+$)	6.5	-	7.0	7.0	6.8	6.9 ^{*)}	
$\Delta E_{\text{exp}}(9/2^- - 1/2^+)$	1902		1497		1098		846
$\Delta E_{\text{est}}(9/2^- - 1/2^+)$	2589		2097		(2378)		(1160)

*) Calculated from existing data²¹⁾ and $Q(p,n)$ -values from Ref. 9.

REFERENCES

- 1) A. Siivola, Referenced in P. Eskola, Arkiv Fysik 36 477 (1967).
- 2) E. Arberman, J. Burde and T.R. Gerholm, Arkiv Fysik 13 501 (1958).
- 3) G. Astner and M. Alpsten, to be published in Nuclear Phys.
- 4) E. Tielsch, Nuclear Phys. A100, 425 (1967).
- 5) R. Stockendal, J.A. McDonell, M. Schmorak and I. Bergström, Arkiv Fysik 11, 165 (1956).
- 6) E. Arberman and N. Svartholm, Arkiv Fysik 10, 1 (1955).
- 7) L.A. Sliv and I.M. Band, Tables of Internal Conversion Coefficients in Alpha, Beta and Gamma Ray Spectroscopy (Ed. K. Siegbahn, North Holland Publ. Co., Amsterdam, 1965).
- 8) M. Alpsten and G. Astner, to be published.
- 9) J.H.E. Mattauch, W. Thiele and A.H. Wapstra, Nuclear Phys. 67, 1 (1965).
- 10) A. Siivola, P. Kauranen, B. Jung and J. Svedberg, Nuclear Phys. 52, 449 (1964).
- 11) I. Mahunka et al., Izvest. Akad. Nauk SSSR, Ser. Fiz. 30, 1375 (1966).
- 12) S. Axensten, C.M. Johansson and I. Lindgren, Arkiv Fysik 15, 463 (1959).
- 13) L.K. Peker and Yu. Kharitonov, Izv. Akad. Nauk SSSR, Ser. Fiz. 30, 144 (1966).
(Transl. Bull. Acad. Sci. USSR, Phys. Ser. USA, 30, 151, 1966.)
- 14) D.H. Wilkinson, in Nuclear Spectroscopy (Ed. F. Ajzenberg-Selove) (Academic Press, New York, 1960).
- 15) J. Blomqvist, to be published.
- 16) S. Hinds, R. Middleton, J.H. Bjerregaard, O. Hansen and O. Nathan, Nuclear Phys. 83, 17 (1966).
- 17) W.W. True, Phys. Rev. 168, 1388 (1968).

- 18) J.C. Hafele and R. Woods, Phys.Letters 23, 579 (1966).
R.M. Diamond, B. Elbek and P.O. Tjøm, to be published.
- 19) J. Blomqvist and S. Wahlborn, Arkiv Fysik 16, 545 (1960).
- 20) J. Blomqvist, private communication.
- 21) C.M. Lederer, J.M. Hollander and I. Perlman, Table of
Isotopes (John Wiley and Sons, New York, 1967).

Figure captions

- Fig. 1 : Spectra from the decay of ^{205}Po . The lower part of the figure shows a region of the gamma spectrum recorded with a 10 cm^3 Ge(Li)-detector, the upper part the corresponding conversion electron spectrum recorded with a 2 mm thick Si(Li)-detector.
- Fig. 2 : Spectra from the decay of ^{203}Po . The lower part of the figure shows a region of the gamma spectrum recorded with a 1 cm^3 Ge(Li)-detector. The upper part shows the corresponding K-conversion electron spectrum measured in a double-focusing beta spectrometer⁶⁾. The latter is not corrected for decay.
- Fig. 3 : K-conversion coefficients for transitions in ^{205}Bi . The points represent experimental values. The lines are theoretical values from Sliv and Band⁷⁾.
- Fig. 4 : K-conversion coefficients for transitions in ^{203}Bi . The points represent experimental values. The lines are theoretical values from Sliv and Band⁷⁾.
- Fig. 5 : Decay scheme of ^{205}Po . The 10.5 and 24.9 keV transitions have not been observed. Arguments for their existence will be given elsewhere⁸⁾.
- Fig. 6 : Decay scheme of ^{203}Po .
- Fig. 7 : Levels in odd mass bismuth isotopes.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7