EXCITED STATES IN ^{199}Bi, ^{201}Bi, ^{203}Bi ISOTOPES

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The β^{+}-EC decays of isomeric and ground states in ^{199,201,203}Po isotopes, produced in heavy ion reactions have been investigated. On the basis of the single γ-spectra, γ-γ coincidence and conversion electron measurements, the levels in ^{199,201,203}Bi isotopes are presented. The experimental data and the results of theoretical calculations are compared.

1. *Introduction*

The investigation of bismuth isotopes in the neighbourhood of the double magic nucleus ^{208}Pb is a good source of information on the nature of the effective nuclear forces in nuclei. Owing to their closeness to the double magic nucleus ^{208}Pb, bismuth isotopes present a region of particular interest.

The higher mass isotopes, situated not far from the double magic nucleus, have been the subject of numerous studies. Nevertheless, very little is still known about the nuclear energy levels of the more neutron-deficient isotopes of bismuth.

Levels in $^{199, 201, 203}$Bi isotopes may be populated by the β^{+}-EC decay of the $^{199, 201, 203}$Po isotopes. These isotopes were identified in alpha decay studies by Tielsch-Cassel [1] and Brun [2], who also established isomerism in $^{199, 201}$Po. However, at the beginning of our investigation the decay schemes of the $^{199, 201}$Po isotopes were unknown. The β^{+}-EC decay of the ground state of ^{203}Po isotope was investigated by the Swedish group [4].

Siivola [3] reported on isomerism in ^{201}Bi. Alpsten and Astner observed a strongly converted 846 keV gamma transitions with a half-life of $50 \div 60$ min. which was assigned to the decay of the ^{201m}Bi isomeric state.

In our previous work [5] we investigated β^{+}-EC decays of the isomeric states in $^{199, 201}$Po isotopes. Results of this investigation are included in our present work, but they are given with improved statistics and accuracy.

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2. *Experimental method*

The radioactive sources were obtained by irradiating a golden target in the external beam of the U-300 heavy ion cyclotron in the JINR Laboratory of Nuclear Reactions in Dubna. The nuclei ^{199}Po and ^{201}Po were produced in the reaction ^{197}Au(^{10}B, xn)$^{207-x}$Po. The ^{203}Po nuclei in the reactions: ^{197}Au(^{11}B, 5n)^{203}Po and ^{n}Pt (^{12}C, xn)^{203}Po. After irradiation the samples without chemical separation were transported to the detector

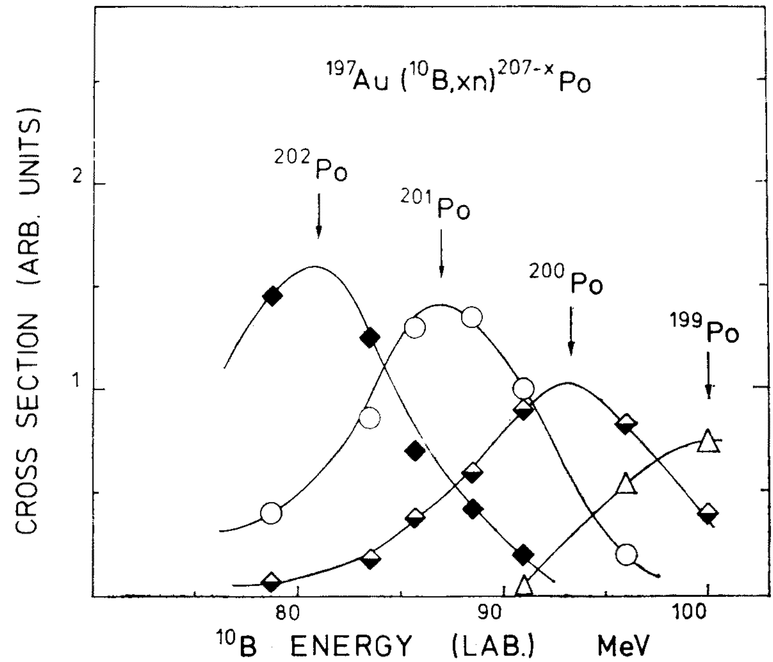

Fig. 1. The excitation functions for the $_{I}$e ^{7} $_{6}$Au(^{10}B, xn)$^{207-x}$Paction

system. The presence of the polonium isotopes in the samples was confirmed by their excitation functions and half-lives well established from alpha decay studies [1, 2, 6, 7]. Results of our measurements of the excitation functions for the reactions: ^{197}Au(^{10}B, xn) $^{207-x}$Po and ^{197}Au(^{11}B, xn)$^{208-x}$Po are shown in Figs 1, 2.

Two Ge(Li) detectors, one a 13 cm^3 planar crystal detector with resolution of 2 keV FWHM at 122 keV under ideal conditions, and the other of 37 cm^3 and resolution of 2.5 keV FWHM, were used for the measurements of gamma rays. Commercially available low noise amplifiers and associated electronic components, including a 4096-channel pulse height analyser, were employed.

Gamma-gamma coincidence spectra were obtained using a Ge(Li)–NaI(Tl) set up. The electronics used was of the standard slow-fast coincidence type. A time-to-amplitude converter and a single-channel analyser replaced the conventional slow circuit. Time pick-off units were employed for fast coincidence measurements. A gamma-gamma coincidence was achieved by means of $1^1/_2 \times 2''$ NaI(Tl) crystal as a gating detector and the 37 cm^3 coaxial Ge(Li) detector for analysis.

Conversion electron spectra were recorded using a 2.5 mm thick Si(Li) detector with the resolution of about 6 keV for all energies.

For the analysis of gamma spectra a CDC-1604A computer was used. The computer programme fitted the peak with a symmetrical Gaussian of a variable width and used

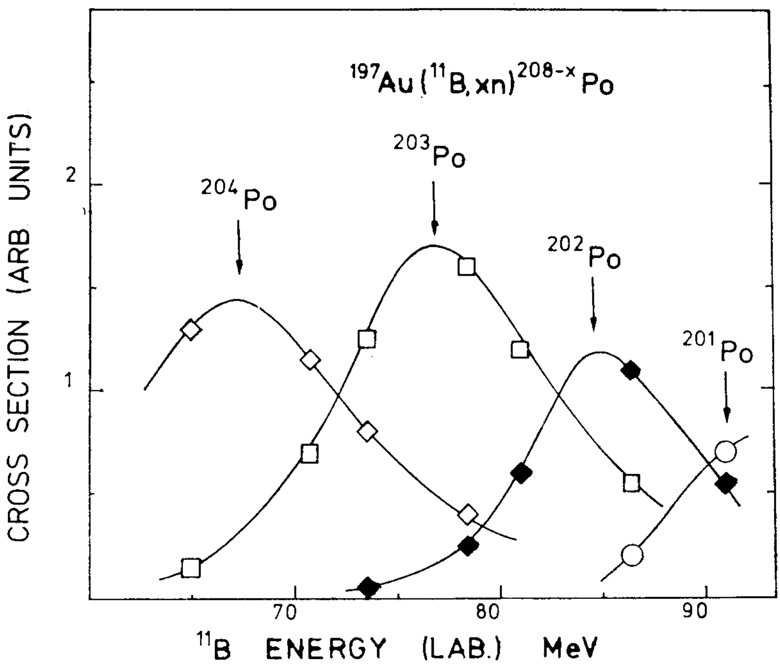

Fig. 2. The excitation functions for the $^{197}Au(^{11}B, xn)^{208-x}Po$ reaction

an exponential approximation for the background. The code employed contained many options, including an automatic peak searching and error analysis. The output consisted of printed plots of the fit along with tabulation of the results.

3. *Decays of the 13/2+ isomeric states in* $^{199, 201, 203}Po$ *isotopes*

In many odd isotopes of lead, polonium as well as in ^{207}Rn [9] isomeric states with spin 13/2+ were observed. Their existence depends on the presence of one-quasiparticle hole in the $1i13/2$ neutron shell. Fig. 3 shows the excitation energy of the 13/2+ isomeric states in the polonium and lead isotopes. The states may undergo alpha, β^+-EC decay, as well as radiation transition. In this chapter the β^+-EC decay of these isomeric states to levels in the respective bismuth isotopes has been studied.

Gippner et al. [22] carried out on-line measurements to investigate the decay of the short-lived isomeric states in the ^{199}Bi and ^{201}Bi isotopes. They observed the same gamma transitions in the cascade which decayed with the half-lives of 300ns $\leqslant T_{1/2} \leqslant$ 20μs and with the same energy within experimental accuracy.

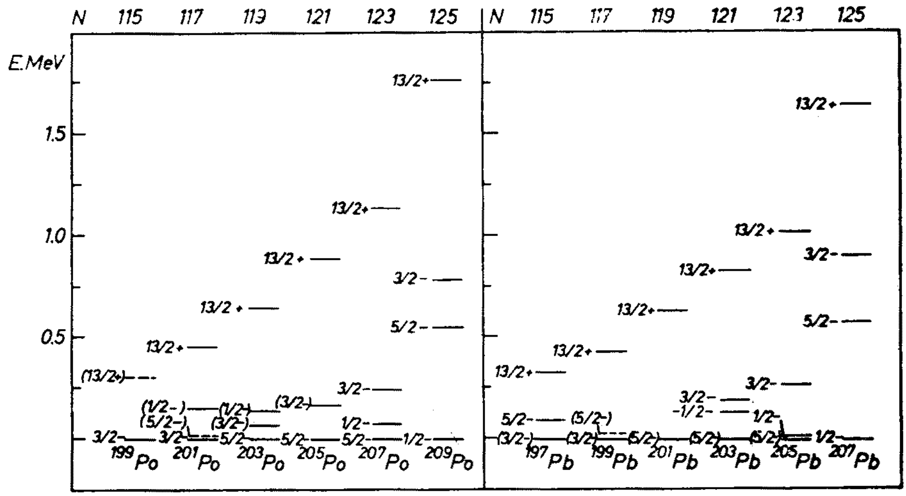

Fig. 3. Systematics of the 13/2+ isomeric state energy in the respective odd polonium and lead isotopes

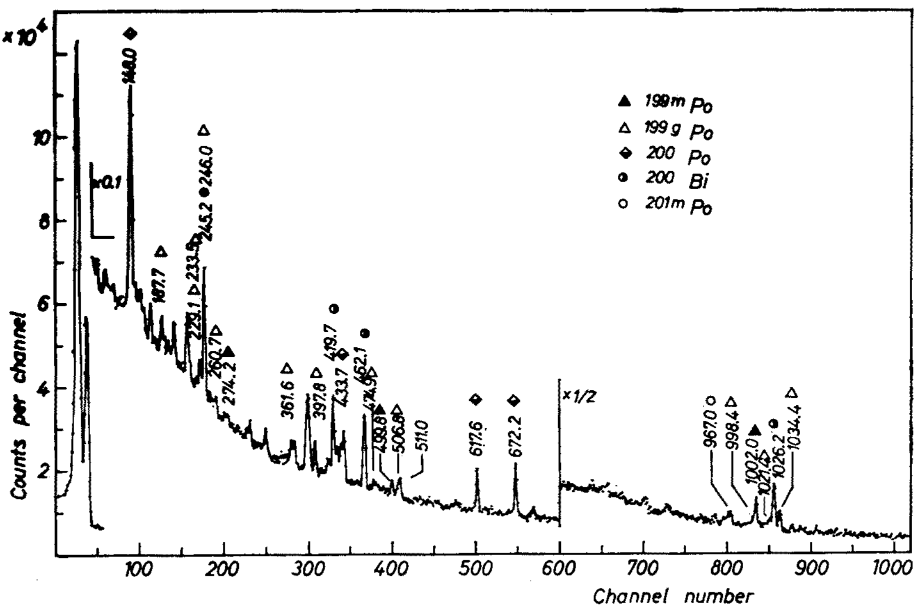

Fig. 4. The gamma-ray spectrum observed in the $^{197}Au(^{10}B, 8n)^{199}Po$ reaction

The ^{199m}Po isomeric state decay

The 4.2 min isomeric state in ^{199}Po isotope was established by Tielsch-Cassel [1] and Brun [2] in their alpha decay studies.

In present work the sources of the ^{199}Po isotope have been obtained in the reaction $^{197}Au(^{10}B, 8n)^{199}Po$ at the beam energy of 100 MeV, i.e. at the maximum energy of the ^{10}B. The single gamma ray spectrum of the ^{199}Po source, measured with the 13 cm^3 Ge(Li) detector is shown in Fig. 4. In the gamma ray spectrum we observed three gamma transitions with half-life of about 4 min and energies 1002.0, 499.8 and 274.2 keV, which were assigned to the β^+-EC decay of the 13/2+ isomeric state in the ^{199}Po isotope. Such an assignment of these transitions was made by means of the excitation function measurements. The half-life of the ^{199m}Po has been determined to be $T_{1/2} = 4.2 \pm 0.3$ min from the gamma measurements, what is in good agreement with the results obtained from the decay of the alpha group [1, 2, 6, 7]. The coincidence measurements showed that 1002.0, 499.8, and 274.2 keV gamma transitions form a cascade.

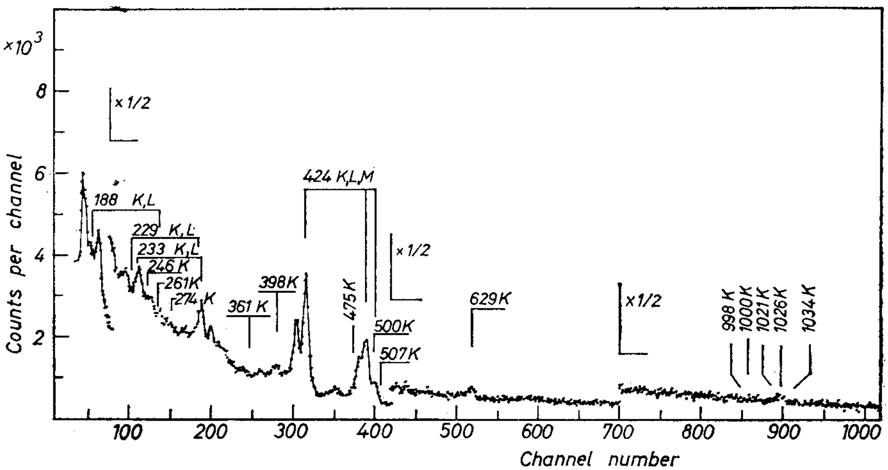

Fig. 5. Conversion electron spectrum observed in the ^{197}Au(^{10}B, 8n)^{199}Po reaction

In the conversion electron spectrum of the ^{199m}Po isomeric state decay we have not observed any strongly converted gamma transition with a half-life of about 4 min and energy $E > 100$ keV. No search has been carried out so far for low energy conversion electrons.

We observed though, the conversion electron lines appropriate to the gamma transitions with energy 1002.0, 499.8, and 274.2 keV (Fig.5). In order to normalize the observed simple gamma ray and electron conversion spectra it was assumed that the gamma transition with energy 499.8 keV has the nature of pure M1 type transition. This assumption was made on the basis of the conversion coefficients ratio [10] $(\alpha_K/\alpha_L)_{\rm exp} = 5 \pm 1$, while $(\alpha_K/\alpha_L)_{\rm th}^{\rm M1} = 5.9$. From this we found that the other two observed gamma ray transitions were of the M1 type.

The data on the ^{199m}Po isomeric state decay gamma lines obtained in the present investigation are listed in Table I.

The decay scheme of the ^{199m}Po isomeric state is shown in Fig. 9. The ground state spin value has been determined by Axensten and Olsmats [12] to be 9/2$^-$. The estimated Q values for ^{199}Po β^+-EC decay was obtained from Seeger's Table [11]. From this and the direct levels' feedings which we determined from intensity balance in this paper, the log ft values were calculated.

TABLE I

Transitions observed in the decay of the ^{199m}Po isomeric state*

Transition energy [keV]	Gamma intensity	Total transition intensity	K conversion coefficient	K/L ratio	Multipolarity assignment
274.2 ± 0.5	12.3	20.1	0.47 ± 0.30	~5	M1
499.8 ± 0.5	42.3	47.4	0.10	~5	M1
1002.0 ± 0.5	100	102	0.013 ± 0.006	—	M1

* The accuracy of the intensity measurements of the gamma transitions is about 5% for the strongest lines, about 10% for less intensive lines and about 30% for the weakest gamma transitions.

We would like to note that the 13/2+ isomeric states in even polonium isotopes can undergo alpha, β^+-EC decay, as well as they can decay by gamma transition. In havier bismuth isotopes with $A > 201$ gamma transitions are predominant, but as one moves away from the $N = 126$ neutron shell the possibility of the β^+-EC decay increases and may be expected to dominate in ^{199}Po isotope.

In papers [1, 2] two groups of alpha particles from isomeric and ground states decay were observed. If we assume that the decay is taking place to the ground state of ^{195}Pb, then the difference of energy between the alpha groups shows that the excitation energy of the isomeric state is $E(13/2) = 0.11$ MeV. If we assume, however, that the isomeric state alpha decay occurs to the unknown excited state in ^{195}Pb, then the problem of isomeric state excitation energy in ^{199}Po remains still open. From the systematics of the isomeric states energy in odd polonium and lead isotopes presented in Fig. 3 one may expect that the excitation energy of the isomeric state in ^{199}Po isotope is about 350 keV.

The ^{201m}Po isomeric state decay

The ^{201}Po isotope was obtained in the reaction $^{197}Au^{10}(B, 6n)^{201}Po$. The maximum cross section was found at the energy of 88 ± 3 MeV. The single gamma ray spectrum of the ^{201}Po source measured with 13 cm^3 Ge(Li) spectrometer is shown in Fig. 6.

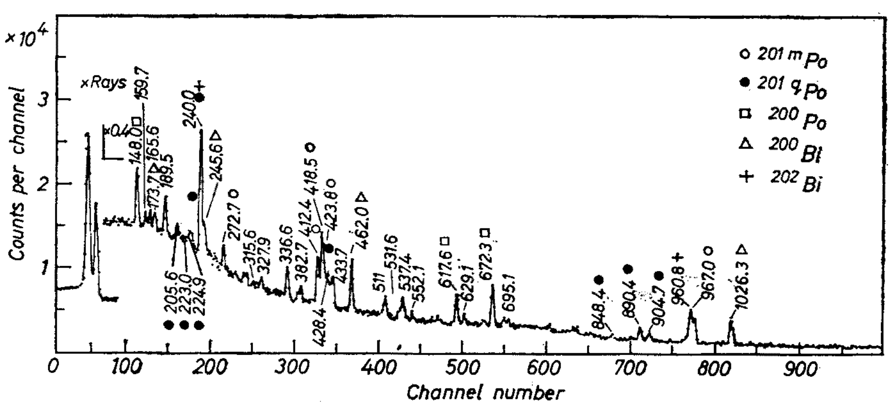

Fig. 6. The gamma-ray spectrum observed in the $^{197}Au(^{10}B, 6n)^{201}Po$ reaction

The presence of the ^{201}Po nuclei in the samples was confirmed by the excitation function and half-lives.

In the gamma-ray spectrum we observed four gamma transitions with half-life $T_{1/2} = 9.0 \pm 0.3$ min and energies 967.0, 418.5, 412.4, and 272.7 keV which were assigned to the decay of the 13/2+ isomeric state in the ^{201}Po isotope. In our coincidence measurements we found that the 967.0, 412.4, and 272.7 keV gamma transitions form a cascade.

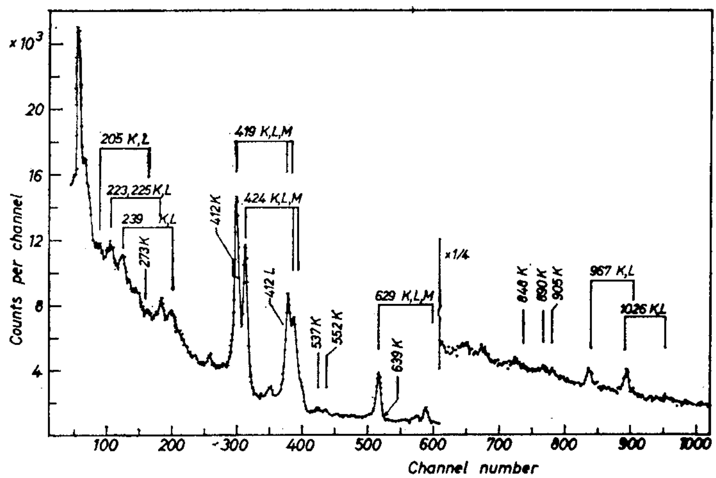

Fig. 7. Conversion electron spectrum observed in the ^{197}Au(^{10}B, 6n)^{201}Po reaction

From the conversion electron spectrum — Fig. 7, we found the relative conversion electron coefficient for these gamma transitions. We observed a very strongly converted gamma transition with the energy 418.5 keV. The normalization between the electron and gamma-ray intensities for the ^{201m}Po isotopes was done on the assumption of the 418.5 keV gamma transition to have a pure M4 character indicated by the α_K/α_L ratio of 2.0 ± 0.3. The theoretical value is: $(\alpha_K/\alpha_L)_{th}^{M4} = 1.9$ [10]. Under this assumption we have found the 967.0, 412.4, and 272.7 keV gamma transitions to be of an M1 character. The gamma and conversion electron data obtained are listed in Table II. The accuracy of the intensity measurement of the 418.5 keV gamma ray transition was not very good. In our gamma-ray

TABLE II

Transitions observed in the decay of the ^{201m}Po isomeric state*

Transition energy [keV]	Gamma intensity	Total transition intensity	K conversion coefficient	K/L ratio	Multipolarity assignment
272.7 ± 0.4	8.3	13.6	0.42 ± 0.30	5.7	M1
412.4 ± 0.5	44.8	54.0	0.22 ± 0.10	5.3	M1
418.5 ± 0.6	20.5	115.0	2.75	2.0	M4
967.0 ± 0.5	100	102.6	0.011 ± 0.005	6.3	M1

* See footnote for Table I.

spectra we observed intense 419.1 keV gamma transition from ^{200}Bi isotope decay. The β/γ branching ratio was found to be $\beta/\gamma = 1.15 \pm 0.2$. The decay scheme of the ^{201m}Po isomeric state is shown in Fig. 9. The $\log ft$ values were found in the same way as in the ^{199m}Po isomeric state decay.

From the energy balance for the alpha transitions from $^{201,\,201m}$Po and the isomeric transition in ^{197}Pb isotope Tielsch–Cassel [4] determined the excitation energy of the isomeric state in ^{201}Po isotope to be 425 ± 2 keV. One may expect that the M4 transition does not proceed directly to the ground state in ^{201}Po isotope, but to a state $5/2^-$ at the energy of about few keV. The ground state spin is measured [12] to be $3/2^-$. One may expect the same situation in ^{199}Pb isotope. The 424 keV gamma-ray transition may not proceed to the ground state of the ^{199}Pb isotope, but to an excited state with a low energy and spin $3/2^-$.

The ^{203m}Po isomeric state decay

The ^{203}Po nuclei were obtained in the reaction: ^{197}Au(^{11}B, 5n)^{203}Po and ^{n}Pt(^{12}C,xn) ^{203}Po. In gamma-ray spectrum of products of the reaction we can see quite distinctly a gamma line with energy 640.9 keV and short half-life and three other lines with the

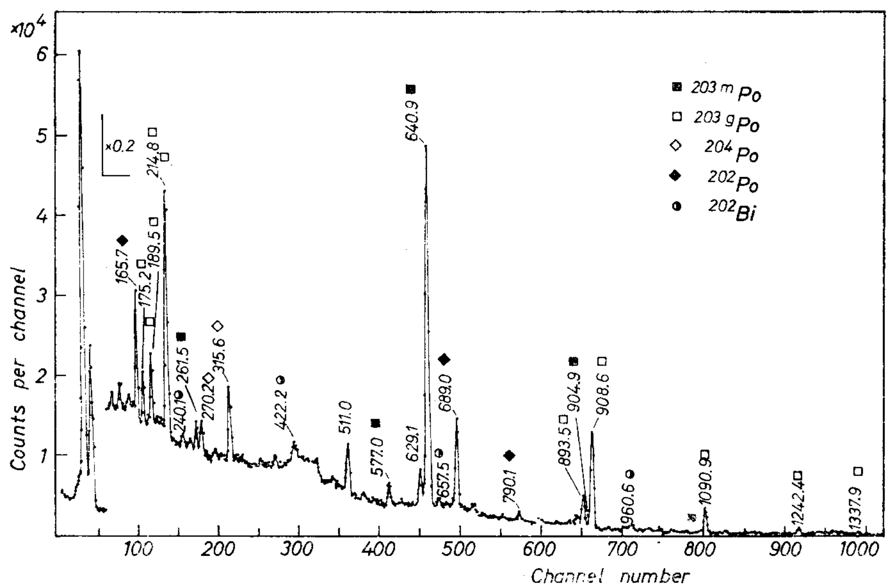

Fig. 8. The gamma-ray spectrum observed in the ^{n}Pt(^{12}C, xn)^{203}Po reaction

same half-life and much smaller intensity — Table III. The half-life of all the four lines is about 1 min, what is in good agreement with the results of measurements carried out by Morek [13], where the half-life of decay of the isomeric state in ^{203}Po was 1.2 ± 0.2 min. Conversion electrons spectrum measurements carried out with the use of the on-line heavy ion beta spectrometer [14] have shown that the gamma transition with energy 640.9 keV is of M4 type. That is in agreement with the previous papers [13, 15]. Other three gamma transitions with the same half-life were assigned to the ^{203m}Po beta decay

TABLE III

Transitions observed in the decay of the ^{203m}Po isomeric state*

Transition energy [keV]	Gamma intensity	Multipolarity assumption	Total transition intensity
261.5±0.4	12.0	(M1)	20.6
577.0±0.5	54.2	(M1)	58.8
640.9±0.5	1197	M4	2172
904.9±0.5	100	(M1)	102.5

* See footnote for Table I.

feeding the excitation levels in ^{203}Bi. The gamma-gamma coincidence and multipolarity measurements were not carried out due to small intensity and short half-life. The sequence of levels and their spin values were assumed on the basis of their intensity balance in analogy with lighter odd bismuth isotopes. From data presented above we can see that the isomeric

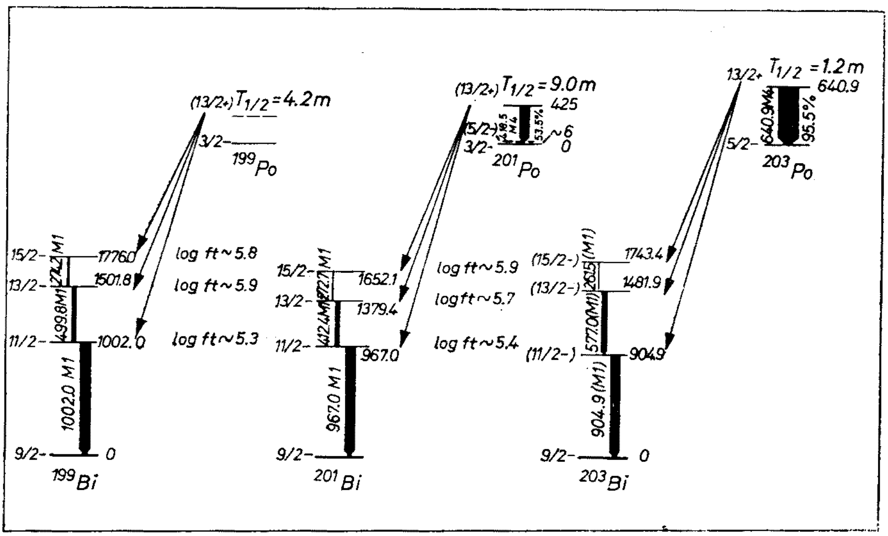

Fig. 9. The decay schemes of the ^{199m}Po, ^{201m} and ^{203m}Po isomeric states

state in ^{203m}Po in 95.5% decays through gamma transition of the M4 type to the ground state of ^{203}Po, and only in 4.5% through beta decay to the excitation levels in ^{203}Bi. The experimental data of the 13/2+ isomeric state in ^{203m}Po was presented in Fig. 9.

4. The decays of the ground states in $^{199, 201, 203}$Po isotopes

Decay of the ^{199g}Po isotope

In gamma ray spectrum of products of the reaction ^{197}Au(^{10}B, 8n) ^{199}Po we observed gamma transitions from decay of the isomeric state in ^{199}Po as well as the gamma transitions between levels fed in beta decay of the ground state ^{199g}Po. The half-life of these lines

TABLE IV

Experimental information on transitions observed in the decay of the ^{199g}Po ground state*

Transition energy [keV]	Gamma intensity	Total transition intensity	K conversion coefficient	K/L ratio	Multipolarity assignment
187.7±0.5	16.0	43.4	1.37±0.70	~6	M1
229.1±0.5	10.2	31.5	0.325	0.2	E3
233.5±0.5	11.8	22.9	0.71±0.40	~5	M1
246.0±0.6	9.0	14.9	0.52±0.30	~5	M1
260.7±0.5	8.5	14.5	0.53±0.30	~5	M1
361.6±0.5	47.0	50.3	0.04±0.03	~2	E2
397.8±0.5	9.0	11.0	0.15±0.10	—	M1
474.9±0.5	15.0	21.1	0.35±0.20	~5	M2
506.8±0.5	8.0	8.2	0.05±0.03	~4	E2
998.4±0.5	33.0	33.3	<0.01	—	E2
1021.4±0.6	51.8	52.8	0.02±0.01	—	M1
1034.4±0.5	100	101.7	0.013±0.007	—	M1

* The accuracy of the intensity measurements of the gamma transitions is about 5% for the strongest lines, about 10% for less intensive lines and 20–30% for the weakest gamma transitions.

was determined to be 5.2±0.3 min, which is in good agreement with the results of alpha ground state decay investigations in ^{199}Po. The list of the gamma lines from the ground state beta decay of ^{199}Po and their multipolarity is presented in Table IV. To obtain relative conversion electron coefficient values of the gamma lines we assumed that gamma transition with energy 229.1 keV is a pure E3 type. It was made on the basis of the characteristic conversion electron coefficients ratio (α_K/α_L)exp $= 0.22 \pm 0.10$, while the table value was found to be $(\alpha_K/\alpha_L)^{E3}_{th} = 0.232$ [10].

When we started to build the decay scheme of ^{199}Po we assumed that the 3 intense gamma transitions with energies 1034.4, 1021.4, and 998.4 keV correspond to the decay of the first three excitation levels with spin $5/2^-$, $7/2^-$ and $7/2^-$ and energy 998.4, 1021.4, and 1034.4 keV, respectively, directly to the ground state of ^{199}Bi. It was found out that the lines were not in coincidence with each other. From analysis of the obtained $\gamma-\gamma$ coincidence spectra it was found that the γ-lines 475+506 keV expose far better the gamma transition with energy 1021.4 keV than that with energy 1034.4 keV. This enabled us to deduce the existence of a level at an energy of 1496.5 keV. The sum of energy of gamma transitions 229.1 keV (E3) and 246.0 (M1) is close to the energy of the 474.9 keV transition. This made it possible to establish the level at energy 1250.5 keV and spin 1/2+. In gamma--gamma coincidence spectrum obtained for the gamma transition with energy 361.6 keV, we observed the increase of intensity of the gamma transition with energy 1034.4 keV. From this we constructed the level 3/2− at energy 1396.1 keV. Other gamma transitions were situated in the fragment of the decay scheme (Fig. 11) chosen on the basis of intensity balance, on the sum energy rules and multipolarity assignment for each gamma transition. One should remember that in the proposed decay scheme only intense gamma transitions were placed. We may expect, however, that there may exist other, less intense lines, which were not taken into account in our decay scheme.

Decay of the ^{201g}Po isotope

In the decay of ^{201g}Po isotope we have seen a similar situation as in the ^{199g}Po isotope decay. In the products of the reaction ^{197}Au(^{10}B, 6n)^{201}Po we observed gamma transitions from the decay of the 13/2+ isomeric state in ^{201}Po as well as those corresponding to the beta decay of the ground state of the ^{201}Po isotope. The attribution of the gamma

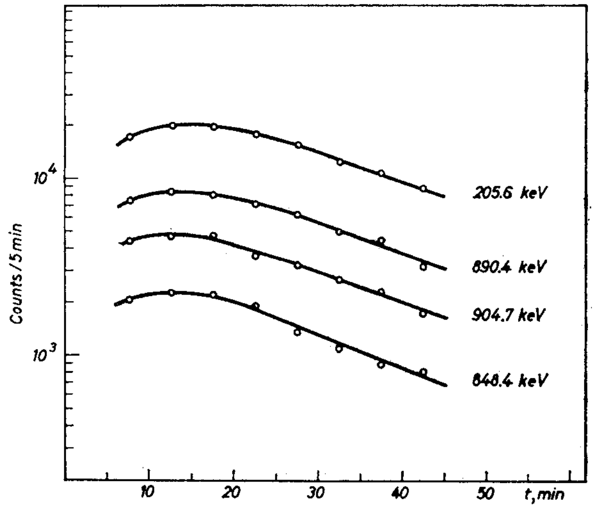

Fig. 10. The dacay curves of the gamma transitions assigned to the ^{201g}Po usotope decay

lines to the ground state decay of the ^{201}Po isotope was made in the same way as in other isotopes, i.e. it was supported by our excitation functions and half-lives measurements. In Fig. 10 we show the decay curves of the gamma transitions assigned to ^{201g}Po isotope decay. The time scale is in minutes from the end of irradiation. The curves are not linear. It seems to us that the observed shape of the decay curves is caused by feeding of the ^{201}Po ground state with 418.5 keV gamma transition from 13/2+ isomeric state decay. The observed curves, Fig. 10, we described by the equation:

$$N = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_{01}[\exp(-\lambda_1 t) - \exp(-\lambda_2 t)] + N_{02}\exp(-\lambda_2 t),$$

where λ_1 denotes constant of the isomeric state decay,

$\lambda_1 = \frac{\ln 2}{g_{min}} = 0.077$ 1/min, and λ_2 is the unknown constant of the ground state decay of ^{201}Po isotope. From our numerical calculation we got that the half-life of ^{201}Po ground state decay is $T_{1/2} = 14.5 \pm 1.0$ min.

Taking the 224.9 keV gamma transition to have pure E3 multipolarity as implied by its K/L ratio (α_K/α_L)exp $= 0.26 \pm 0.08$, $(\alpha_K/\alpha_L)^{E3}_{th} = 0.215$ [10], the relative electron conversion coefficients were calculated. The experimental data of the gamma ray and the obtained conversion electron coefficients are listed in Table V.

From the coincidence and intensity relations (similarly as in the ^{199g}Po isotope decay) one can deduce the first three excitation levels at 848.4, 890.4 and 904.7 keV and

TABLE V

Experimental information on transitions observed in the decay of the ^{201g}Po ground state*

Transition energy [keV]	Gamma intensity	Total transition intensity	K conversion coefficient	K/L ratio	Multipolarity assignment
205.6±0.4	14.9	30.1	0.80±0.40	5.7	M1+E2
223.0±0.5	10.2	21.4	1.00±0.50	4.0	M1
224.9±0.5	22.5	75.3	0.345	0.2	E3
239.0±0.5	15.2	26.1	0.55±0.25	6.0	M1(E2)
428.4±0.5	16.6	17.3	—	—	(E2)
537.4±0.5	10.3	11.4	0.05±0.03	3.0	M1(E3)
552.1±0.5	11.8	12.5	0.07±0.03	—	M1
639.1±0.5	10.0	10.0	<0.01	—	E1
848.4±0.6	25.3	27.3	<0.015	—	E2
890.4±0.5	100	102.6	0.030±0.015	—	M1
904.7±0.6	54.5	55.8	0.036±0.015	—	M1
1163.8±0.6	7.0	7.0	—	—	(E2)
1206.1±0.6	6.2	6.2	—	—	(M1)

* See footnote for Table IV.

spins 5/2−, 7/2−, 7/2−, respectively. The 428.4 keV transition is in clear coincidence with the 890.4 keV and 224.9 keV transitions and in weak coincidence with the 904.7 keV. From this we deduce levels at 1115.3 keV and 1543.9 keV and spin 1/2+ and 5/2+, respectively. The 239.0 keV transition seems to be in coincidence with those at 904.7 keV, but not in coincidence with 428.4 keV. Level at 1143.7 keV is thus implied, without any connections to the other excited levels, however. The energy sum of the 223.0, and 205.6 keV

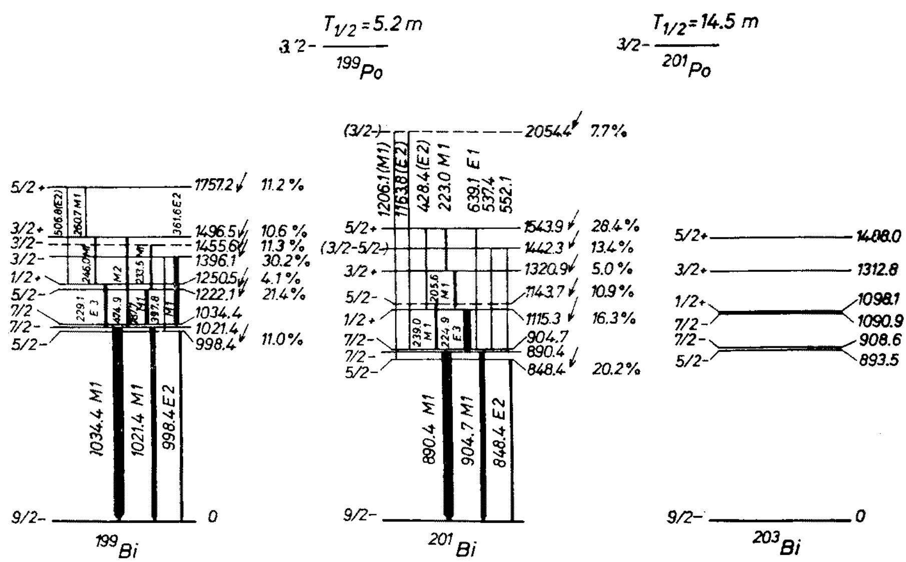

Fig. 11. The proposed decay schemes of ^{199g}Po and ^{201g}Po isotopes

transitions is close to the energy of the 428.4 keV transition. For the intensity reasons 205.6 keV transition can be placed below those of 223.0 keV, i.e. at the 1115.3 keV level. Positions of other levels are supported by energy sums, intensity relationships and multipolarity assignments. The proposed fragment of the decay scheme of the ^{201g}Po isotope was shown in Fig. 11.

Siivola et al [3] reported on the existence of alpha radioactive isomeric state in ^{201}Bi. The Swedish group [4] observed 846 keV gamma transition with multipolarity M4+E5 or E4+M5 (both results were possible) and with half-life of 50÷60 min. The authors assigned this transition to the decay of the 1/2+ or 1/2− state in ^{201}Bi isotope. In our work neither the 846 keV transition was seen, nor the transition with energy 700–1000 keV and considerable conversion electron coefficient value, which we could assign to the decay of the isomeric state in ^{201}Bi. It is more likely that the isomeric state could be fed directly in the reaction, e.g., ^{191,193}Ir (^{12}C, xn)^{201}Bi. In gamma-ray spectrum of products of this reaction we did not observe any gamma transition with energy of 846 keV and half-life longer than 2 min.

Decay of the ^{203g}Po isotope

In Figure 8 we have presented gamma-ray spectrum of products of the reaction ^{n}Pt(^{12}C, xn)^{203}Po. Gamma lines attributed to the beta decay of ^{203g}Po isotope were marked by plain square.

Beta decay of ^{203}Po ground state was investigated by the Swedish [4] and American [16] groups. The decay scheme of this isotope seems to be well known, so we did not repeat their investigations. In the present paper, for comparison, the results obtained by Alpsten et al. were employed.

We would like to add that during the first few minutes after the end of irradiation we observed an increase of intensity of gamma transitions assigned to the ^{203g}Po isotope decay. It can be explained by feeding the ground state of ^{203}Po in the isomeric state gamma decay. The half-life of the isomeric state is short and the mentioned above effect was missing in earlier works.

5. *Calculations*

The measurements performed in the present work show that the 5/2−, 7/2−, 11/2− and 13/2−, 15/2− levels in ^{199,201,203}Bi have energies close to the energies of the lowest 2+ and 4+ states, respectively, in the neighbouring ^{198,200,202}Pb isotopes. One may suppose that the 5/2−, 7/2−, 11/2− and 13/2−, 15/2− states in the bismuth isotopes are formed by coupling the single-proton motion with the respective 2+ one-phonon and 4+ two-phonon states of the core with $Z = 82$. The model which describes such a coupling is the intermediate coupling unified model [19, 20]. Thus we use this model to the interpretation of negative parity excited levels in the ^{199,201,203}Bi isotopes. The 2+ and 4+ states in the neighbouring lead isotopes are treated as one-phonon and two-phonon states of the core of ^{199,201,203}Bi isotopes. The single-proton is assumed to have available $h9/2$ and $f7/2$ states. The effective energy spacing $Ep = E(f7/2) - E(h9/2)$ and the nucleon surface coupling strength ξ are treated as parameters, fitted to experiment.

The measured energy spectra and the calculated energies of the negative-parity states of ^{199,201,203}Bi are presented in Figs 12, 13, 14. In these figures there are also shown the levels obtained in calculations in which the core harmonic vibrations up to three phonons are taken into account. In the last case the 13/2−, 15/2− doublets lay much higher than

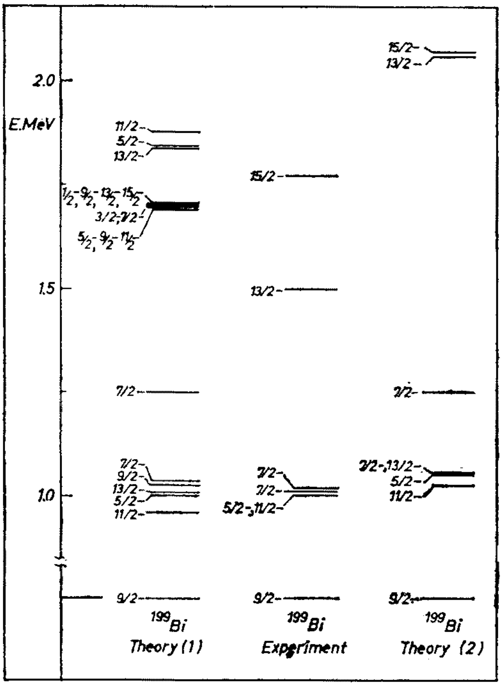

Fig. 12

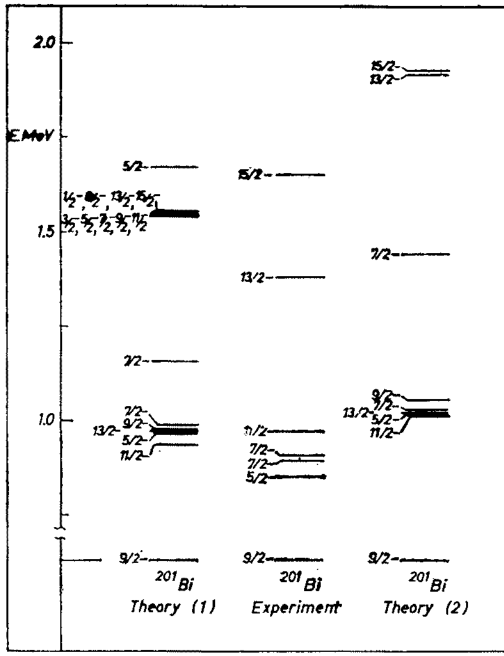

Fig. 13

Fig. 12. Comparison of the theoretical and experimental energy levels of the ^{199}Bi isotope. Theory 1 denotes the results of the calculations in which anharmonic oscillations of the core are taken into account. Theory 2 indicates the levels obtained in calculations in which the core harmonic oscillations up to the three phonons are taken into account

Fig. 13. Comparison of the theoretical and experimental energy levels of the ^{201}Bi isotope. Theory 1 denotes the results of the calculations in which anharmonic oscillations of the core are taken into account. Theory 2 indicates the levels obtained in calculations in which the core harmonic oscillations up to the three phonons are taken into account

the experimental ones. In calculations with the assumption that the two-phonon states have the same energies as the 4+ states in the lead isotopes, the position of the 13/2−, 15/2− levels is close to the experimental ones. The splitting of 13/2−, 15/2− is not obtained because only two phonons are taken into account. The splitting which results from the three phonon treatment is also too small. It is possible that it is connected with the splitting of 0+, 2+, 4+ states in the two-phonon triplets, but there is no experimental evidence about it. In all the considered isotopes the ground states have the spin 9/2− and are almost

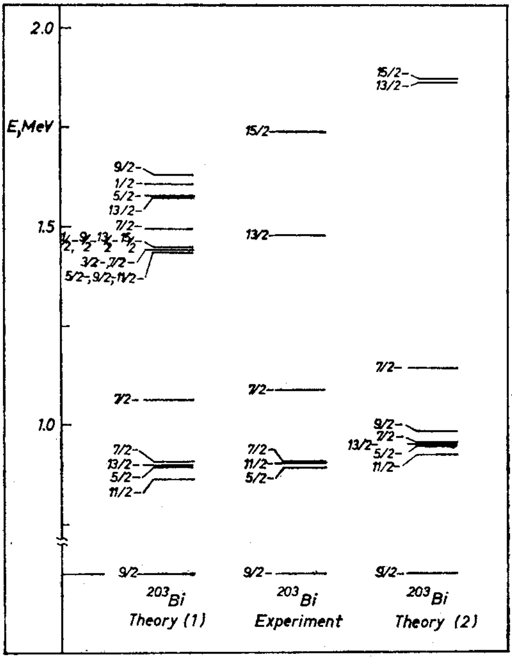

Fig. 14. Comparison of the theoretical and experimental energy levels of the ^{203}Bi isotope. Theory 1 denotes the results of the calculations in which anharmonic oscillations of the core are taken into account. Theory 2 indicates the levels obtained in calculations in which the core harmonic oscillations up to the three phonons are taken into account

pure single-proton $h9/2$ states. The lowest excited levels have the spin 5/2− and are formed mainly by the $h9/2$ proton state coupled to the one-phonon state of the core. Two 7/2− states are a mixture of the single-proton $f7/2$ state and the component formed by the $h9/2$ proton state coupled to the one-phonon state of the core. The observed splitting of the

TABLE VI

Isotope	Anharmonic oscillations of the core				Harmonic oscillations of the core		
	ξ	Ep	$E(2+)$	$E(4+)$	ξ	Ep	$\hbar\omega$
^{199}Bi	1.12	1.2	1.062	1.625	1.1	1.2	1.062
^{201}Bi	1.00	1.1	1.0263	1.4883	1.1	1.2	1.0263
^{203}Bi	1.06	1.0	0.961	1.383	1.1	1.1	0.961

two 7/2− states is of the order of a few keV in ^{199}Bi and ^{201}Bi isotopes and is about 100 keV in ^{203}Bi isotope. The calculated energy splitting of these levels is of the order of 001 keV for three $^{199, 201, 203}$Bi isotopes. The calculated position of the 5/2−, 7/2−, 11/2− 13/2− and 15/2− levels is in agreement with the experiment for the parameters listed in Table VI.

6. *Discussion*

In the preceding chapter the intermediate coupling unified model has been employed for the interpretation of the negative parity state structure in $^{199,201,203}Bi$ isotopes. The same model has been applied by Bradley and Meder [21] for calculation of excited states energy in heavier odd bismuth isotopes: $^{203-207}Bi$. Comparing the results obtained in the papers of theirs and of ours one can see that the employed model gives satisfactory agreement between theoretical and experimental excitation energy values for the levels with spin 5/2−, 7/2− and 7/2−. The theoretical energy splitting of the 7/2− levels in $^{203,205,207}Bi$ isotopes seems to be in better agreement with the experiment than in the lighter odd mass bismuth isotopes. In the $^{199,201}Bi$ the experimental energy splitting of the 7/2− levels are smaller than the theoretical ones.

The excitation energy of the 11/2− levels is in satisfactory agreement with the experiment only in ^{207}Bi isotope. For the lighter odd bismuth isotopes the calculated excited 11/2− levels are situated clearly below the experimental ones. In the calculated decay schemes the 11/2− levels form the first excited levels. One may suppose that limitations on the possible excitation energy for the 11/2− levels are due to the assumption that experimental values of the excitation energy of the 2+ levels in even neighbouring lead isotopes may be taken as for the one-phonon states. In the assumption mentioned above, it is difficult to obtain higher energies of the calculated 11/2− levels. The agreement of the experimental 13/2− and 15/2− levels with the calculated ones has been discussed in the chapter "Calculation".

In our previous paper [5] theoretical calculations were made for the other, less accurate parameter values than in the present work. Besides, the calculated excited energy values for the 11/2− levels in ^{199}, ^{201}Bi isotopes were wrong.

In the present paper the positive-parity states, feeding the ground state beta decay of the odd polonium isotopes were also observed. The bands of the positive parity levels 1/2+, 3/2+ and 5/2+ in $^{203,205,207}Bi$ isotopes were interpreted by Arbman [17] and Alpsten et al. [6] as the states connected with one proton excited out of the $Z = 82$ core. One proton pair coupled to zero angular momentum arises in this situation. The population of the positive parity states may arise from the conversion of one proton $d3/2$ or $d5/2$ subshell to $f5/2$ neutron. It seems that Arbman's interpretation, with some small modifications, could be applied to the description of population of positive parity states in $^{199,201}Po$ isotope beta decay. The ground state spin value in ^{199}Po and ^{201}Po isotopes was measured to be 3/2−. The 1/2+ levels could then also be directly populated in beta decay of $^{199,201}Po$ isotopes. Excitation energy of the positive parity states regularly decreases as one moves away from the $N = 126$ neutron shell, but in ^{199}Bi isotope excitation energy of these states is clearly increasing. One can see that the levels are always situated above the 5/2− and 7/2− levels.

Analogical positive parity states were observed in odd thallium isotopes where the 1/2+ states were the ground states, and the 3/2+ and 5/2+ states were the low-lying excited states. We also observed the positive-parity states in odd astatine isotopes [18] with similar excitation energy as in bismuth isotopes.

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