ALPHA DECAY OF THE Bi^{210m} *ISOMER*

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The long-lived α active isomer Bi^{210m} has been studied. Lines with energies of 4930 ± 10 kev (60%), 4890 ± 10 kev (34%), 4590 ± 10 kev (5%), and 4480 ± 15 kev (~0.5%) have been detected in the α spectrum. Gamma radiation from the daughter nucleus Tl^{206} has been detected and studied. Gamma rays of energies 262, 301, 340, and 610 kev have been found. The existence of the coincidences α4930 — γ262, α4890 — γ301, α4590 — γ610, and α4590 — γ340 kev has been established. The γ-transition multipolarities were determined from the internal-conversion electron spectrum and were found to be E2 for 262 kev and M1 for 301 kev. The measured lifetimes of the Tl^{206} levels are τ(262 kev) = 1.7×10^{-9} sec and τ(301 kev) = 4.6×10^{-9} sec. A decay scheme for Bi^{210m} is constructed on the basis of the experimental data. It is shown that RaE is the ground state of Bi^{210} and the long-lived Bi^{210m} is its excited state (250 kev) with a partial half-life of ~ 5×10^{10} years relative to the isomeric transition. The experimental data are compared with the theoretical calculations of the energy states of the Tl^{206} and Bi^{210} nuclei.

1. INTRODUCTION

THE long-lived α active isomer Bi^{210} was first detected in 1950.[1] Hughes and Palevsky[2] estimated its half-life to be $T_{1/2} = (2.6 \pm 0.8) \times 10^6$ years from the difference in the thermal neutron absorption cross section of the Bi^{209} nucleus and the Bi^{210}(RaE) production cross section. Levy and Perlman[3] confirmed the correctness of assigning the mass number 210 to the α-active bismuth nucleus by means of electromagnetic separation of the isotopes and determined the α-particle energy as $E_\alpha = 4935 \pm 20$ kev. In their measurements, Levy and Perlman used a pulse ionization chamber and a long-lived Bi^{210} sample with a specific α activity of 140 min^{-1} mg^{-1}.

The study of the energy levels in the odd-odd nuclei ${}_{83}Bi^{210}_{127}$ and ${}_{81}Tl^{206}_{125}$ is of considerable interest. In addition to the filled shells, the Bi^{210} nucleus has one proton and one neutron and the Tl^{206} nucleus has one proton and one neutron "hole." The levels of these nuclei can be calculated on the basis of the nuclear shell model with allowance for the interaction with the core and the pair interaction. Up to the present time, however, there is practically no experimental data on the excited states of these nuclei. Thus, for the Bi^{210} nucleus, only the 47-kev level (from RaD β decay) has been determined, while the position of the isomeric level remained unknown; excited states of the Tl^{206} nucleus have not been observed in general.

The aim of the present work was to establish the successive levels in the Bi^{210} and Tl^{206} nuclei and to determine their quantum characteristics. Preliminary results have been published earlier.[4,5]

2. EXPERIMENTAL METHOD

The Bi^{210m} decay was studied with the aid of a pulse ionization chamber with a grid, scintillation γ spectrometer, multi-channel time analyzer, and a thin line magnetic β spectrometer.

The Bi^{210m} sample was obtained from the (n, γ) reaction by lengthy irradiation of Bi^{209} in a reactor. Produced alongside with the long-lived Bi^{210m} (σ = 14 ± 3 mb) is the five-day Bi^{210}(RaE), with approximately the same cross section (σ = 19 ± 2 mb); the Bi^{210} decays into Po^{210}. Since Po^{210} has a half-life of 138 days, and Bi^{210m} has a half-life of 2.6×10^6 years, the α radiation of the polonium will be considerably more intense (10^5 — 10^6 times as great) than the Bi^{210m} α radiation. Therefore the sample underwent careful chemical treatment to remove the Po^{210} and other radioactive contamination.[6] Moreover, the sample was enriched with the Bi^{210} isotope by the electromagnetic method. As a result, we obtained a source with a specific α activity of ~ 14 000 min^{-1} mg^{-1}.

*Deceased.

For the study of the Bi^{210m} α radiation, we used a pulse ionization chamber with a grid and a geometry of $\sim 2\pi$. The geometrical and electric parameters of the chamber were calculated by the method of Bunemann and Cranshaw.[7] The source was deposited on a stainless steel disk; its area was 25 cm^2 and active layer thickness 10 $\mu g/cm^2$. The chamber was filled with a mixture of Ar (90%) + CH_4 (10%) at atmospheric pressure. The addition of methane decreased the collection time of the electrons on the collector. We chose the differentiation and integration constants of the amplifier to correspond to the minimum noise and weakest dependence of the pulse amplitudes on the α-particle angle of flight: $\tau_{dif} = \tau_{int} = 5$ μsec. During operation, the gas mixture was continuously purified to remove electro-negative impurities, chiefly oxygen, by heated calcium chips. The chamber design allowed the rapid replacement of the samples without disturbance of the mixture composition.

The amplitude of the pulses from the electrode on which the sample was placed depends on the angle of flight of the α particle with respect to the chamber axis. These pulses were used to control the gating circuit for the analyzed pulses from the collector. In this way, we achieved the electron collimation described by Bochagov et al.[8]

The resolving power of the chamber was 28 kev for the U^{233} 4816-kev α line. A NaI(Tl) crystal with an FÉU-S photomultiplier was used as the detector. The spectrometer resolving power for the Cs^{137} (661-kev) line was 8%.

We studied the $\alpha\gamma$ coincidences with this spectrometer and the ionization chamber described above. The chamber design made it possible to place the scintillation detector in the direct vicinity of the chamber source.

The lifetimes of the excited states of the Tl^{206} nucleus were measured on a multi-channel time analyzer of 10^{-9}-sec range whose operation was based on the principle of transformation of the delay time between two pulses into an amplitude.[9]

The γ rays were recorded by a stilbene crystal and the α particles, by a thin plastic scintillator (a solution of terphenyl and polystyrene). An FÉU-33 photomultiplier was used. The half-width of the prompt coincidence curve (resolving time of the circuit), measured with a Co^{60} source, was $2\tau = 10^{-9}$ sec.

The study of the internal conversion electron spectrum was made on an air-core magnetic β spectrometer with a thin lens and ring focus.[10] The Bi^{210m} sample was deposited on a platinum foil 50 μ thick (platinum was used as a base because of the special nature of a deposit of an active substance). The source had a diameter of 10 mm and an active layer thickness of about 1 mg/cm^2. The spectrometer resolving power with such a source was $\Delta H\rho/H\rho = 6\%$ and the transmission was 1%.

With the source activity of 4000 $(2\pi)^{-1}$ min^{-1}, the detector background (G-M end-window counter) was greater than the number of recorded electrons on the most intense conversion line. Since all conversion electrons are in coincidence

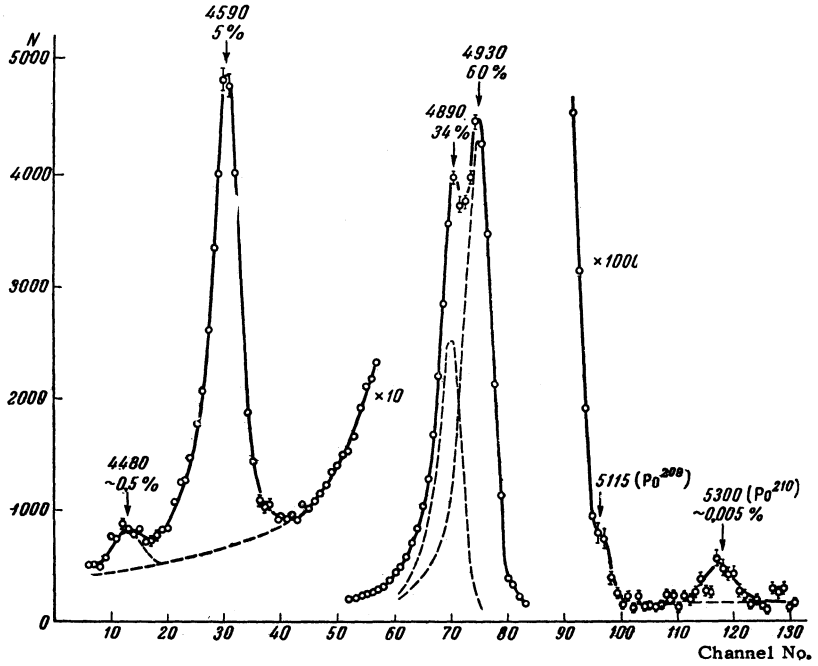

FIG. 1. α spectrum of Bi^{210m} (the resolved components of the spectrum are shown dotted).

with α particles of bismuth, we used the method of αe^- coincidences to reduce the background. We placed a scintillation counter, which recorded α particles, close to the source in the spectrometer. This counter consisted of a plastic scintillator (made in the shape of a thin hollow cone and placed on the side of the active layer), a light pipe, and an FÉU-1B photomultiplier shielded from the magnetic field of the spectrometer. The pulses from this counter and the pulses from the electron detector were applied to a coincidence circuit with a resolving time of 10^{-6} sec. In this case, the random-coincidence background due to cosmic radiation and radioactive contamination of the spectrometer material was approximately 10 pulses per 30 hours, and the number of αe^- coincidences on the most intense line was 400 pulses during the same time.

RESULTS OF THE MEASUREMENTS

α spectrum. The Bi^{210m} sample available to us had a specific activity 100 times that of the sample used by Levy and Perlman.[3] This made it possible to observe weak α groups with a comparatively high energy resolution.

Two well-separated intense lines 4930 ± 10 kev (60%) and 4890 ± 10 kev (34%) stand out in the α spectrum (Fig. 1). Also seen are α lines of 4590 ± 10 kev (5%) and 4480 ± 15 kev (~ 0.5%). These four lines should be assigned to the Bi^{210m} nucleus for the following reasons: 1) the sample emits β particles with E_{max} = 1500 ± 30 kev, which corresponds to the known[11] limiting energy of the β spectrum of the daughter nucleus Tl^{206} (the β particles were recorded by a scintillation counter); 2) the probability of an impurity is small, since the sample underwent careful chemical purification, and the isotope was separated by the electromagnetic method; 3) no lines with such (or close) energies are observed among the known α emitters.

Apart from the transitions already cited, two α transitions of low intensity and energies of 5115 ± 15 and 5300 ± 15 kev (~ 0.005%) were also observed. As will be shown below, an α transition to the Tl^{206} ground state would have an energy of 5185 kev. If it is assumed that the 5115-kev α transition belongs to Bi^{210m}, then there should exist in the Tl^{206} nucleus a 70-kev level from which the γ transition to the ground state is strongly converted. The range of the conversion electrons (of energy ~ 60 kev) would lie entirely in the gap between the high-voltage electrode and the grid of the ionization chamber. One would then observe in the α spectrum two maxima of approximately equal intensity: one at an energy of ~ 5180 kev, when the α particle and the conversion electron in coincidence with it produce the ionization in the chamber; the second at an energy of 5115 kev, when the conversion electron stops in the base. However, there are no maxima on the α-spectrum curve in the energy interval 5140 — 5260 kev, within the limits of experimental error (10^{-3}% in intensity). Consequently, the 5115 ± 15 kev transition should be attributed to some impurity. Calculations indicate that the observed intensity of the 5115-kev line can be explained by the presence of a contamination of 10^{-16} g of Po^{208} ($T_{1/2}$ = 2.93 years).

The 5300-kev line belongs to Po^{210}. Its intensity was checked over three half-life periods of polonium ($T_{1/2}$ = 138 days) and proved to be constant at ~ 0.005%. Hence, the presence of Po^{210} in the sample is due not to a contamination, but to the isomeric transition $Bi^{210m} \xrightarrow{\gamma, e^-} Bi^{210}$ (RaE) with a subsequent β decay RaE $\xrightarrow{\beta^-} Po^{210}$. Knowing the half-life of Bi^{210m} (2.6×10^6 years) and the amount of Po^{210} in equilibrium, we can calculate that the partial half-life of the isomeric state relative to the Bi^{210m} γ, e^- RaE transition is ~ 5×10^{10} years.

In the measurement of the α-transition energies, we used as references: Th^{230} (E_α = 4682 kev), U^{233} (E_α = 4816 kev), Pu^{239} (E_α = 5147 kev), and Am^{241} (E_α = 5480 kev).

γ spectrum and $\alpha\gamma$ coincidences. The present experiment was the first in which the γ radiation of the Tl^{206} nucleus following the α decay of Bi^{210m} was detected and studied. Lines corresponding to transitions of 262 ± 10 and 301 ± 10 kev, whose intensities are in the ratio 1 : 0.45, can be seen clearly in the γ spectrum. Also observed are the characteristic 72-kev x-ray line of Tl.

In order to establish the decay scheme of Bi^{210m}, we investigated the $\alpha\gamma$ coincidences. Gamma lines of 262 and 301 kev are observed in the spectrum of coincidences with the two most intense α groups 4890 and 4930 kev. Only the 262-kev γ line appears in the spectrum of coincidences with the 4930-kev group; the 310-kev line is not present. Consequently, the 301-kev γ transition is in coincidence with the 4890-kev α group, and the 262-kev γ transition, with the 4930-kev α group, i.e., the 4930-kev α transition goes to an excited state of Tl^{206} and not to the ground state, as had been suggested earlier.[3]

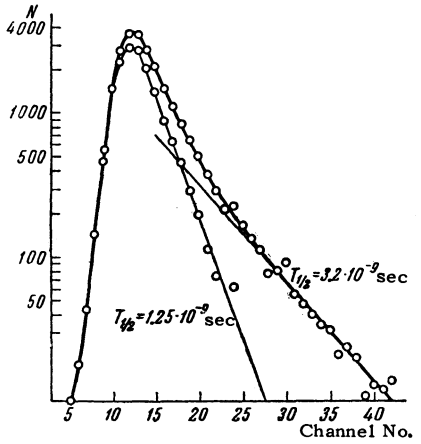

FIG. 2. $\alpha\gamma$ delayed coincidence curve for Bi^{210m}.

Observed in coincidence with the 4590-kev α group are 340 ± 15 and 610 ± 20 kev γ transitions, which were not noted in the singles γ spectrum, owing to the considerable background from the scintillation counter (α-source activity of 7000 $(4\pi)^{-1}$ min^{-1}). The presence of the 610-kev peak in the spectrum cannot be explained by the simultaneous recording in the scintillator of 262-kev and 340-kev γ quanta in cascade, in view of the small solid angle of the γ counter (~ 0.05 of 4π).

Lifetimes of excited states of the Tl^{206} nucleus. We carried out measurements of the lifetimes of the excited states of the Tl^{206} nucleus in the range of 5×10^{-10} to 2×10^{-8} sec by the delayed $\alpha\gamma$-coincidence method by means of a multichannel time analyzer. The obtained curve is shown in Fig. 2. It corresponds to coincidences between the most intense α transitions, i.e., 4930 and 4890 kev, with 262- and 301-kev γ quanta; the contribution from the 4480- and 4590-kev α transitions was slight, owing to their low intensity. In this case, there was no energy selection in the α channel or in the γ channel.

The experimental curve was resolved into two components, one with $T_{1/2} = (1.25 \pm 0.2) \times 10^{-9}$ sec (mean lifetime $\tau_1 = 1.7 \times 10^{-9}$ sec) and the other with $T_{1/2} = (3.2 \pm 0.3) \times 10^{-9}$ sec ($\tau_2 = 4.6 \times 10^{-9}$ sec). They were identified from the ratio of intensities. The relative intensity of the prompt component was 60 — 70% and of the delayed component, 30 — 40%. Such an intensity ratio also occurs for the 4930- and 4890-kev α transitions and for the 262- and 301-kev β transitions in coincidence with them. Therefore the lifetime $\tau_1 = 1.7 \times 10^{-9}$ sec should be assigned to the level to which the 4930-kev α transition goes, and the lifetime $\tau_2 = 4.6 \times 10^{-9}$ sec, to the level to which the 4890-kev α transitions goes.

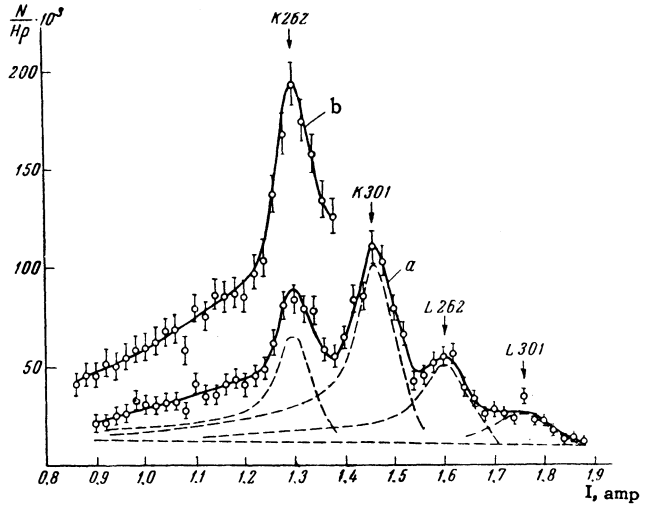

FIG. 3. Conversion electron spectrum of Tl^{206} (I is the spectrometer coil current in amperes). The resolved components of the spectrum are shown dotted.

Conversion electron spectrum of Tl^{206}. We investigated the internal conversion electron spectrum of the daughter nucleus Tl^{206} in the region between 80 and 330 kev. The lower limit of the measured energies was set by the source thickness ~ 1 gm/cm^2; a thinner source could not be used since its activity would be too low.

The conversion electron spectrum measured with a thin line magnetic β spectrometer is shown in Fig. 3. The background was reduced by the αe^- coincidence method (see Sec. 2).

Four internal conversion electron lines with energies of 176 ± 5, 215 ± 5, 250 ± 5, and 292 ± 5 kev were observed in the spectrum (curve a was measured over a time of 700 hours). Their intensity ratio was 0.6 : 1.0 : 0.4 : 0.16. The first two lines were identified as K lines of γ transitions at 262 ± 5 and 301 ± 5 kev; the last two lines were identified as the L lines of the same transitions. Curve b of Fig. 3 represents part of the same spectrum between 80 and 200 kev measured with larger statistics.

The spectrometer was calibrated with the ThB conversion line of energy 148.05 kev. The shape of this line was used to resolve the spectrum into the individual components. In order to take into account the distortion of the line shape due to backscattering of the electrons, the ThB source, as well as the Bi^{210} source, were deposited on a platinum foil.

4. DISCUSSION OF THE RESULTS

On the basis of the obtained data, we constructed the Bi^{210} decay scheme (Fig. 4).

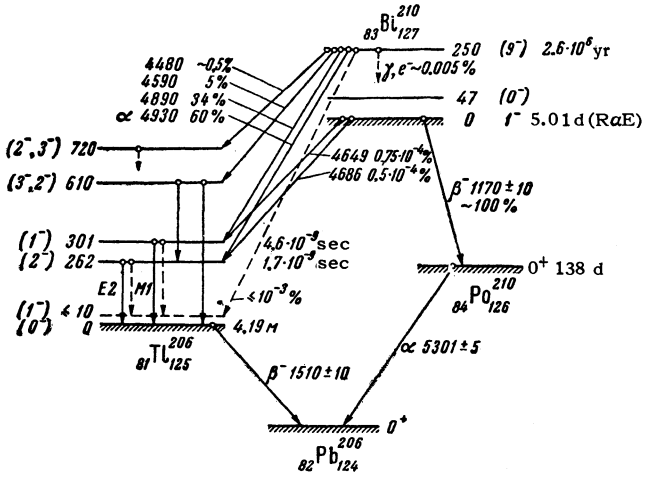

FIG. 4. Decay scheme of Bi^{210m}.

The levels of the Tl^{206} nucleus are determined from the α spectrum and the $\alpha\gamma$ coincidences. It is improbable that the 262- and 301-kev transitions do not go to the Tl^{206} ground state, since no γ lines of large energy (direct transitions) or γ lines corresponding to cascade transitions are observed. From the presence of the coincidences α4930 — γ262 and α4890 — γ301 kev, it therefore follows that the Tl^{206} nucleus has levels of 262 and 301 kev. Then the 4590- and 4480-kev α transitions go to the 610- and 720-kev levels, respectively. The existence of the 610-kev level is also confirmed by the coincidences α4590 — γ610 kev. The existence of a Tl^{206} level of about 60 kev, which was proposed by us earlier,[5] was not confirmed.

The multipolarities of the 262- and 301-kev γ transitions were established by comparison of the experimental values of the internal conversion coefficients α_K and the ratios K/L with their theoretical values (Table I). The internal conversion coefficients α_K were determined from the spectra of $\alpha\gamma$ coincidences by the ratio of the number of x-ray quanta accompanying the conversion to the number of nonconversion γ quanta. The large error was due to the approximate character of the corrections for the dependence of the γ spectrometer efficiency on the quantum energy and the error in the graphical resolution of the γ spectrum. The ratio K/L for the 262- and 301-kev transitions was determined from the internal conversion electron spectrum (Fig. 3).

From the data of Table I it is possible to conclude that the 262-kev transition is of the E2 type and the 301-kev transition is of the M1 type. Analysis of the Tl^{206} β spectrum leads to the value 0^- for the spin and parity of the ground state of thallium.[11] Then, from our determinations of the multipolarities of the γ transitions, we can fix the spins and parities as 2^- for the 262-kev level and 1^- for the 301-kev level.

According to the nuclear shell model, the ground and first excited state of the Tl^{206} nucleus should correspond to the configurations $(s_{1/2})_p^{-1}(p_{1/2})_n^{-1}$, $(d_{3/2})_p^{-1}(p_{1/2})_n^{-1}$, and $(s_{1/2})_p^{-1}(f_{5/2})_n^{-1}$. For each of these configurations, the residual interaction of the nucleons leads to doublet splitting and a level shift. Sliv et al.[13] calculated the splitting and level shift arising as a result of pair interactions of the outer nucleons and the interaction with the core surface. The results of the calculations are in good agreement with experiment. The 262-kev (2^-) and 301-kev (1^-) levels correspond primarily to the configuration $(d_{3/2})_p^{-1}(p_{1/2})_n^{-1}$. The 610- and 720-kev levels apparently belong to the configuration $(s_{1/2})_p^{-1}(f_{5/2})_n^{-1}$, where one of these levels (although this does not follow from the calculations) has a spin and parity of 2^- and the other 3^-.

The amount of splitting calculated for the configuration $(s_{1/2})_p^{-1}(p_{1/2})_n^{-1}$ proved to be small, only 5 — 10 kev. Hence, it is suggested that there is an excited level of energy 5 — 10 kev, spin and parity 1^- close to the Tl^{206} ground state, and the γ transitions from the 262- and 301-kev levels should go not only to the ground state, but also to this level. However, there is still no direct experimental proof of the existence of the 5 — 10 kev level. On the basis of the resolving power of our β spec-

TABLE I. Determination of the Nature of the 262- and 301-kev Transitions

Transition energy, kev	Compared quantities	Exptl. value	Theoretical values[12]						Possible type of transition
			*E*1	*E*2	*E*3	*M*1	*M*2	*M*3	
262	*K*/*L*	1.5±0.3	5.8	1.37	0.35	5.7	3.8	2.0	*E*2, *M*3
	α_K	0.15±0.06	0.0345	0.094	0.25	0.5	1.9	5.52	*E*2, *E*3
301	*K*/*L*	6.3±1.0	5.5	1.8	0.59	5.6	4.2	1.8	*E*1, *M*1
	α_K	0.26±0.1	0.023	0.06	0.165	0.30	1.05	2.90	*E*3, *M*1

trometer, we can only say that the energy of the low-lying excited level (if it exists) is not more than 10 kev. From the size of the experimental error in the determination of K/L, it follows that the possible mixture of M1 radiation in the transition from the 262-kev level does not exceed 7% and the mixture of E2 radiation in the transition from the 301-kev level does not exceed 20%. Such mixtures could be the result of transitions from these levels to the level at 5 — 10 kev.

The transition from the 301-kev level (M1, $1 \rightarrow 0$) should be l-forbidden ($d_{3/2} \rightarrow s_{1/2}$, $\Delta l = 2$). In fact, $\tau_{exptl}(301\ kev)/\tau_{theoret}(301\ kev) \approx 10^4$, where $\tau_{theoret}$ is the lifetime calculated from Moszkowski's formula.[14] The large value of l-forbiddenness is, perhaps, evidence of the fact that the mixture of neighboring configurations with $(d_{3/2})_p^{-1}(p_{1/2})_n^{-1}$ is small. As regards the 262-kev transition (E2, $2 \rightarrow 0$), we find $\tau_{exptl}/\tau_{theoret} \approx 0.5$.

If no assumption is made as to the existence of the 1^- level close to the Tl^{206} ground state, then the ground state 0^- and the 301-kev (2^-) level should be assigned to the configuration $(s_{1/2})_p^{-1}(p_{1/2})_n^{-1}$ and the 262-kev (2^-) level, to the configuration $(d_{3/2})_p^{-1}(p_{1/2})_n^{-1}$. The transition from 301 kev (M1, $1 \rightarrow 0$) will take place between the levels of one doublet. In this case, its experimental probability is approximately 10^{-3} times the theoretical value calculated by Varshalovich's method.[15] This strong forbiddenness cannot be satisfactorily explained. Therefore the variant of the Tl^{206} level scheme with the introduction of the low-lying 5 — 10 kev level is preferable, since it attributes the disparity between the experimental and theoretical probabilities for the 301-kev transition to l-forbiddenness.

The position of the isomeric level of Bi^{210} with $T_{1/2} = 2.6 \times 10^6$ years can be established from the energy balance of the decay branches:

$$Bi^{210m} \xrightarrow{\alpha} Tl^{206} \xrightarrow{\beta^-} Pb^{206}, \qquad Bi^{210}(RaE) \xrightarrow{\beta^-} Po^{210} \xrightarrow{\alpha} Pb^{206}.$$

For the first branch

$$Q_\alpha(Bi^{210m}) + E_\beta(Tl^{206}) = 6796 \pm 15\ kev;$$

for the second branch

$$E_\beta(RaE) + Q_\alpha(Po^{210}) = 6574 \pm 15\ kev.$$

The energy of the isomeric state Bi^{210m} is determined from the equality of these quantities and is equal to 222 ± 20 kev. Walen and Bastin-Scoffier[16] studied the decay $RaE \xrightarrow{\alpha} Tl^{206}$ on a magnetic α spectrometer. They observed α transitions of energies 4649 and 4686 kev going to the 301- and 262-kev levels of the daughter nucleus. This made it possible to determine more accurately the energy of the excited isomeric level:

$$Q_\alpha(Bi^{210m}) - Q_\alpha(RaE) = 250 \pm 10\ kev$$

According to the calculations of Sliv et al., the lowest levels of Bi^{210} belong mainly to a mixture of two configurations $(h_{9/2})_p(g_{9/2})_n$ and $(h_{9/2})_p(i_{11/2})_n$ and have spins and parities 1^- (ground state, i.e. RaE), 0^- (47-kev level[17] appearing in the β decay of RaD), 1^- (not observed experimentally), and 9^-. From a comparison of the partial half-life of the isomeric state ($\sim 5 \times 10^{10}$ years) with the theoretical estimates from Weisskopf's formula,[18] it follows that the spin of the isomer Bi^{210m} is not less than 7. The theoretical value of the spin and parity 9^- is shown on the decay scheme.

TABLE II. Reduced Forbiddenness Factors for α Transitions of the Bi^{210} Nucleus

	E_α, kev	ΔL	Reduced forbiddenness factors
Bi^{210m}	4930	8	$5{,}5 \cdot 10^3$
	4890	8	$6{,}1 \cdot 10^3$
	4590	8	$5{,}3 \cdot 10^2$
		or 6	$7 \cdot 10^3$
	4480	6	$1{,}4 \cdot 10^4$
		or 8	$1 \cdot 10^3$
	5180	8	$4 \cdot 10^9$
RaE	4686	2	$3 \cdot 10^2$
	4649	0	$2{,}1 \cdot 10^2$

The isomer decays mainly by the emission of α particles. Table II gives the reduced forbiddenness factors for the α transitions to the Tl^{206} levels. It is of interest that the forbiddenness coefficients for the α transitions going to the levels of a single doublet (262 and 301 kev) are close to each other in the case of Bi^{210m} (E_α = 4930 and 4890 kev) and in the case of RaE (E_α = 4686 and 4649 kev). The strong forbiddenness for the α transitions of Bi^{210} are connected with the difficulty of forming α particles in the nucleus from nucleons in different shells. The forbiddenness coefficient for the 5180-kev transition to the proposed 5 — 10 kev level (1^-) is not less than 10^9.

In conclusion, the authors consider it their duty to express their gratitude to L. A. Sliv and D. A. Varshalovich for discussions of the results, to N. B. Abel'skaya, E. G. Gracheva, V. V. Maslovskaya, and L. Ya. Rudaya for chemical purification of the samples to remove radioactive contamination and for the preparation of the samples, to V. S. Eletskii and A. E. Nevskii who took part in the construction and setting up of the equipment.

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