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September 1967

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Abstract

The electron-capture decay of 8.3-hr ^{210}At to levels in ^{210}Po has been studied with high-resolution germanium and silicon spectrometers and an anti-Compton germanium spectrometer. Fifty transitions among levels in polonium have been observed, and the K-conversion coefficients of nine of these have been measured with a solid-state conversion-coefficient spectrometer. The new data account for most of the weak, unassigned conversion-electron lines reported in previous studies. A decay scheme is presented that incorporates forty transitions, and the ^{210}Po levels are discussed in terms of recent theoretical calculations.

1. Introduction

The study of energy levels of nuclei in the vicinity of the double closed shell at $^{210}_{82}Pb$ continues to be an effective means for observing the single-particle aspects of nuclear structure. In the case of $^{210}_{84}Po$, one expects the composition of the low-lying excited states to be dominated by the coupling of the 83rd and 84th proton orbitals immediately beyond the 82-proton configuration, and thus a fairly simple description of this nucleus would seem to be possible. Although the ^{210}Po energy levels had been the subject of several experimental and theoretical investigations, only a few excited states have been identified with certainty, and many weak transitions have remained unassigned.

The ^{210}Po levels have been studied mainly from the electron-capture decay of $^{210}_{85}At$. Data obtained by Mihelich et al.[1]) and by Hoff and Hollander[2]) are in agreement with respect to the most intense transitions, and these are summarized in the decay scheme of figure 1. The transition multipolarities were derived in their work from K-conversion coefficient and L-subshell conversion ratio measurements. Directional correlation measurements by Schima et al.[3]) substantiated the spin assignments shown in the decay scheme with the exception of that of the 3024-keV level (see Section 4.2). The lifetimes of the 4^+ and 6^+ members of the ground-state band were measured by Funk et al.[4]). Not shown in the figure are a large number of weak transitions whose positions in the level scheme were uncertain. In addition Hoff and Hollander[2]) and Mihelich et al.[1]) also observed many weak lines in the conversion electron spectrum which, although unassigned, were considered to belong definitely to ^{210}At decay.

In this paper we report on a reinvestigation of the decay of ^{210}At with high-resolution solid-state detectors. In this study, the energies and intensities of fifty γ-ray transitions were measured with a Compton-rejection germanium γ-ray spectrometer, and the K-conversion coefficients of the stronger transitions were determined with a conversion-coefficient spectrometer. A lithium-drifted silicon detector was also used, to study the low-energy electron and gamma-ray spectra. From these data, a new level scheme of ^{210}Po has been constructed incorporating forty of the observed transitions, and this scheme is discussed with reference to the theoretical level schemes of Kim and Rasmussen[5]) and Redlich[6]).

2. Experimental Procedure

2.1 SOURCE PREPARATION

Astatine-210 was produced by the (α, 3n) reaction on ^{209}Bi targets in the Berkeley 88-inch cyclotron. The bismuth targets were prepared by vacuum evaporation of the metal onto 0.25 mm. aluminum discs, which produced target thicknesses of 25-30 mg/cm^2. Initial bombardments at beam energies of 41 MeV resulted in appreciable production of ^{209}At from the (α, 4n) reaction (evidenced by the presence of gamma-rays of 545 and 780 keV decaying with a 5-hour half life) and therefore the beam energy was reduced to 38 MeV in subsequent irradiations, which greatly diminished the yield of ^{209}At. This observation is consistent with excitation functions measured by Kelly and Segrè[7]) and Ramler et al.[8]), which indicate that the relative yields of ^{209}At and ^{211}At are minimized at this energy. The major radiations of ^{211}At, 62 and 671 keV, were in fact not observed in our spectrum.

As a check on the radiochemical purity of the astatine sources, two chemical separation techniques were employed. In the first, the irradiated target was heated to the melting point of bismuth, and the volatilized astatine was collected on a cooled metal foil[9]). In the second procedure, the bismuth target was dissolved in nitric acid and astatine was extracted into isopropyl ether from a nitric acid-hydrochloric acid mixture[10]). The gamma-ray spectra of sources prepared by the two techniques were found to be identical. With the exception of very weak lines, all gamma-rays were observed to decay with a half-life of about 8 hours; no prominent gamma-rays of half-life shorter than eight hours, or other extraneous lines, were observed. Spectra taken after several days showed the presence of ^{206}Bi from the weak alpha branching of ^{210}At [11]).

3. Experimental Results

3.1 GAMMA-RAY SPECTRUM

Initial measurements of the ^{210}At gamma-ray spectrum made with a 6 cm^3 Ge(Li) detector showed, besides the well-known lines reported previously[1,2,3]), a number of very weak lines that were only poorly resolved from the intense Compton background. In order to study these transitions with an improved signal-to-background ratio, a Compton rejection Ge(Li) system constructed by D. C. Camp[12]) was employed. The detector elements of this system consist of a 7 cm^3 germanium diode mounted between two NaI(Tl) cylinders of dimensions 22.9 cm (dia) × 11.4 cm (thickness). Source radiations are collimated by a 1.27 cm (dia) hole in a 10.1 cm (thickness) lead shield. In our measurements

a source-to-detector distance of 18 cm was used. The gamma-ray spectrum of ^{210}At obtained with this device in the energy range 100-2400 keV is shown in figs. 2 and 3. The reduction in continuous background afforded by the anti-Compton spectrometer amounted to a factor of six in the region of the Compton edge of the 1180.4-keV transition. This device also provided so large a reduction in the intensities of "single-escape" and "double-escape" peaks (loss of annihilation radiation following pair production in the detector) that only one single-escape peak was observed (that of the 1599.0 gamma-ray, at 1087.9 keV).†

The low-energy part of the spectrum (E<150 keV) was recorded with a lithium-drifted silicon detector of dimensions 5 mm (dia) by 3 mm (thickness), and a teflon absorber was used to distinguish between gamma-rays and conversion electrons. The spectra obtained with and without the absorber are shown in fig. 4. (The weak indium X-rays apparent in the gamma-ray spectrum arise from interaction of radiation with part of the detector mounting material.)

Energy calibration of the γ-ray spectrometers in the range 50-2400 keV was made by using sources of ^{241}Am, ^{57}Co, ^{203}Hg, ^{137}Cs, ^{60}Co, ^{22}Na, ^{88}Y, ^{24}Na, and ^{54}Mn, with reference to the energy data compiled by Haverfield[13]).

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†The observed intensity ratio (I_{1088}/I_{1599}) was $(3.06 \pm 0.25) \times 10^{-2}$, whereas the expected intensity ratio (single-escape peak/full energy peak) for a 1599-keV gamma-ray was estimated, experimentally, to be $1.6_0 \times 10^{-2}$. Therefore, at least 48% of the intensity of the 1088-keV photopeak must be due to a real gamma ray of this energy.

In the low-energy range, calibration for conversion-electron and gamma-ray spectra was based on energies of the polonium X-rays and the X- and gamma-rays of ^{241}Am. Digital gain stabilization was employed for all measurements. The relative photopeak efficiency function of the Ge(Li) detector in the anti-Compton spectrometer was determined with standard intensity sources in the energy range 60-2800 keV, and the uncertainty in this efficiency function varied from about ± 8% below 100 keV to ± 3% in the range 280-1300 keV.

In Table 1, a summary is given of the energies and intensities of the ^{210}At gamma rays observed in this work. In the cases of the lowest-energy transitions, with known multipolarities, we have included also the total transition intensities, computed with use of the theoretical conversion coefficients of Sliv and Band[14]). The quoted errors in the intensity values of Table I reflect the uncertainties in the detector efficiency function as well as the statistical errors in estimation of photopeak areas.

Some of the very weak lines of Table 1 are of uncertain origin or assignment. This is true of the 602.4- and 726.0-kev lines. The line at 1718.6 ±0.6 keV may be due to the intense 1719.7 keV transition of ^{206}Bi, formed in the weak (0.18%) alpha-branching[11]) of ^{210}At. Other ^{206}Bi lines in the high-energy part of the gamma spectrum would not have been seen because of their low intensities. It is certain, however, that none of the lines observed below 1200 keV are due to ^{206}Bi. In particular, the line at 881.6 keV should not be confused with the ^{206}Bi 880.8-keV transition, as another and more intense ^{206}Bi line at 803.3-keV was not observed. The gamma-rays at 544.8 ±0.5 keV and 782.9 ±0.7 keV may be due to ^{209}At, as the relative intensities of these lines agree, within error limits, with the values reported

by Stoner[15]) for the 544.5- and 780-keV transitions of ^{209}At. The other ^{209}At gamma-ray, at 195.0 keV, is too weak to have been seen in our spectrum.

3.2 INTERNAL CONVERSION ELECTRON SPECTRUM; CONVERSION COEFFICIENTS AND MULTIPOLARITIES

As mentioned in the previous section, the portion of the ^{210}At spectrum below 150 keV was examined with a Si(Li) spectrometer, and the conversion electron and X-ray lines so observed are shown in fig. 4. In fig. 5 the conversion electron spectrum in the range 100-400 keV is shown. In the low-energy region the resolution of the Si(Li) detectors is much poorer than that of the 180° magnetic spectrographs used by Hoff and Hollander[2]); however our data do provide more accurate intensity values of the stronger lines than were previously available. In the higher-energy region ($E > 150$ keV) the K-conversion coefficients were determined by simultaneous measurement of electron and gamma spectra with the spectrometer described by Easterday et al.[16]) and Hollander[17]). This "conversion-coefficient spectrometer" contains both a Ge(Li) detector (6 cm^3) and a Si(Li) detector (3 mm depletion depth), and is calibrated with sources having known conversion coefficients.

In the case of the strong 46.5-keV transition, the measured L_{II}/L_{III} subshell conversion ratio, 1.1 ±0.1, confirms the previous assignments[1,2]) of this transition as E2. The measured absolute conversion coefficients of the higher-energy transitions are shown in fig. 6 together with the theoretical values of Sliv and Band[14]). From a comparison of these the multipolarity assignments shown in Table 2 were obtained. Quantitative estimates of multipole mixing ratios are not given, as the data are not accurate enough.

Some comments should be made about the conversion coefficients of the 125.2- and 402.4-keV transitions: our estimate of $\alpha_{(L_I + L_{II})} > 3.0$ for the 125.2-keV transition suggests that this transition has appreciable M1 character. This is consistent with the observation by Hoff and Hollander[2]) of only the L_I and L_{II} lines of this transition (Table I of Ref. 2), although due to an error in Table II of Ref. 2 this transition was assigned as E2. In the case of the 402.4-keV transition, our value of α_K, $(1.53 \pm 0.26) \times 10^{-1}$, is appreciably higher than the result of Schima, et al.[3]), and suggests that this transition is more nearly pure M1 in character.

With these new data, we can account for most of the conversion-electron lines of unknown or doubtful assignment reported in references 1 and 2. The energies of these lines and our suggested assignments for them are given in Table 3. The energies of all the high-energy electron lines agree with values calculated for K- or L- lines from our measured gamma-ray energies, except for the 542.5- and 700-keV lines. The origin of these two lines is unknown.

4. The Level Scheme: energies, spins, and parities

The data obtained in this study have been combined with previous results and have led to the construction of the level scheme shown in fig. 7. We have relied heavily on the accuracy of the gamma-ray energy and intensity measurements for the insertion of new energy levels and for the placement of new transitions between known levels. This was necessary because of the relative weakness of most of the new transitions found in our work. Several coincidence experiments were attempted to help in establishing the gamma-ray cascades implied by this scheme, but no new information could be added from the coincidence measurements to the results reported in (1,2,3). Of the fourteen levels shown in fig. 7, those shown with broken lines are relatively uncertain and should be taken as only tentatively identified. The levels are discussed in related groups below:

4.1 LEVELS AT 1180, 1426, 1472 keV

These levels had been well identified in the previous studies of ^{210}At decay[1,2]), and the assignments of 2^+, 4^+, and 6^+, respectively, to them were established by the E2 multipolarities of the 1180.4-, 245.3-, and 46.5- keV transitions and by the angular distribution measurements reported in (1) and (2). Our data support these assignments.

4.2 LEVELS AT 2908 and 3024 keV

The multipolarities of the 1482.9- and 1436.2- keV transitions, which depopulate the 2908-keV level to the 4^+ and 6^+ levels at 1426 and 1472 keV, were previously determined to be E1[1,2]), and this fixes the spin and parity of the 2908-keV level as 5-. Angular distribution results for the 1482.9 - 245.3 cascade are consistent with the spin sequence 5(D,Q)4(Q)2 (maximum quadrupole mixing of 0.4%) [3]).

The parity of the 3024-keV level is established as odd by the E1 and M1(E2) assignments of the 1599.0- and 116.5- keV transitions, respectively, and its spin is limited to the values 4 or 5. The angular distribution results of Schima, et al.[3]) on the 1599.0-245.3 keV cascade are reported to be in agreement with the spin sequences 5(D,Q)4(Q)2 (maximum quadrupole mixing of 0.6%) and 3(D,Q)4(Q)2 (maximum quadrupole mixing of 0.2%), but not with the sequence 4(D,Q)4(Q)2 for any value of quadrupole admixture. Schima et al., chose spin 5 as the most likely assignment for the 3024-keV level, noting the absence of a transition to the 2^+ level at 1180 keV. On the other hand, there is some evidence from the present study that indicates a 4- assignment for the 3024-keV level. We have observed the 1551.9-keV transition from this level to the 6^+ level at 1472 keV, and its low intensity compared to that of the 1599-keV E1 transition favors an M2 rather than an E1 assignment; the intensity ratio is: $I_{1599}/I_{1552} = 89$. One notes in contrast that the intensity ratio for the two known E1 transitions depopulating the 2908-keV level is almost unity;

$$I_{1483}/I_{1436} = 1.7.$$

Thus, we favor the 4- assignment for the 3024-keV level. The angular distribution measurements of reference 3 on the 1599-245 keV cascade are not consistent with this assignment, but these measurements were made with scintillation detectors, and it is possible that because of the poor resolution there may have been appreciable contribution to the high-energy photopeak from the intense unresolved E1 doublet (1436-1483 keV).

4.3 LEVELS AT 3427, 3524, 3726 keV:

The parity of these levels has been established as odd by observation of M1 or M1 + E2 transitions connecting them with the known odd-parity levels at 2908 and 3024 keV. A probable spin of 5 is assigned to the level at 3427 keV because of the observation of transitions in almost equal intensity from it to the 4^+ and 6^+ levels of the ground-state band. This assignment is consistent with the observation also of transitions to the $(4)^-$ and 5^- levels at 3024 and 2908 keV. A spin of 6 is likely for the levels at 3524- and 3726-keV because of the absence of transitions to the 4^+ level at 1426 keV and the presence of transitions to 6^+, 5^-, and $(4)^-$ states.

4.4 LEVELS AT 2381 AND 2402 keV:

These levels are populated by the decay of the $(4)^-$ and 5^- levels at 3024 and 2908 keV and they decay to the 4^+ and 6^+ members of the ground-state band. The most likely spin and parity assignments are $(4^+, 5^{\pm})$.

4.5 TENTATIVE LEVELS AT 3779, 3711, AND 3698 keV:

The assignment of levels at 3779, 3711, and 3698 keV is based primarily on the observation of pairs of transitions from each to the 6^+ and 4^+ levels at 1472 and 1426 keV. Little can be said concerning the character of these levels and their presence in the level scheme should be considered uncertain.

4.6 LEVEL AT 2325 OR 2278 keV

One of the more intense of the new gamma-ray lines found in this study is that at 853.1 ± 0.4 keV, but unfortunately there appear to be no definitive sum-relationships that might establish its position in the ^{210}Po level scheme. Two sums appear, which involve very weak transitions (584.0- and 1200.3-keV), and these sums, if valid, would define a level at 2325 keV. Another sum appears,

with the 630.9-keV transition, and this would define the level at 2278 keV. A delayed coincidence experiment with the 1181-keV transition might decide between these alternatives, as in the first case the intermediate state would have a half-life of 38 nsec(1472-keV state) while in the second case the delay would be 1.8 nsec(1426-keV state).

The multipolarity of the 853-keV transition has been established as M1(E2) (see Table 2) so the parity of the state is even, if either of the above interpretations of its location is correct.

The high intensity of the 853-keV transition, and the very weak intensity of the γ-transitions that feed it, indicate that this state is populated directly by ^{210}At electron-capture. Therefore the spin choices are restricted to 4, 5, or 6.

5. Theoretical Considerations

The proximity of $^{210}_{84}Po_{126}$ to the double-closed-shell nucleus $^{208}_{82}Pb_{126}$ has led to a number of shell-model calculations of the level structure of this nucleus. Using known single particle energies of the odd proton in $^{209}_{83}Bi_{126}$, Hoff and Hollander[2]) calculated the two-proton level structure with a delta-function force. It was assumed that the two protons beyond the closed 82-proton shell occupy the $h_{9/2}$ orbital in the ground state. Their calculations clearly predicted a ground-state band of levels due to the coupling of the 83rd and 84th protons in the $(h_{9/2})^2$ configuration, and this is in good agreement with the observed energies of the low-lying excited states (2^+, 4^+, and 6^+). The calculations further predicted the presence of a band of negative-parity states due to the $(h_{9/2}, i_{13/2})$ configuration at about the same excitation energy as the observed 5^- and $(4)^-$ levels (3 MeV).

Recently, Kim and Rasmussen[5]) and Redlich[6]) have performed much more detailed calculations on the ^{210}Po nucleus. However both sets of calculations exclude collective interactions and neither takes into account the contribution of neutron orbitals from the ^{208}Pb core. The theory of Kim and Rasmussen uses a finite-range central force and tensor forces for the proton-core and proton-proton interactions, with no spin-orbit force. The calculations of Redlich are based on a Gaussian singlet-even potential. The level energies that resulted from these calculations are shown in fig. 8 along with the experimental scheme. It is of interest to discuss the experimental state assignments in terms of these theoretical schemes.

One is immediately aware of the limitation of the radioactive decay of ^{210}At as a means of studying excited levels of ^{210}Po: only the levels of

spin 4, 5, or 6 are populated. Nonetheless some valid comparisons with the theoretical calculations can be made, and these are discussed below.

5.1 GROUND-STATE BAND

The lowest-lying 2+, 4+, and 6+ states clearly belong to the $(h_{9/2})^2$ configuration. Although the 8+ state of this configuration is not seen from ^{210}At decay, there is evidence concerning it from the ^{208}Pb(α, 2n)^{210}Po reaction, studied by Yamazaki and Ewan[18]). They have observed that the 245- and 1180-keV transitions (depopulating the 4+ and 2+ members of the ground band) follow a decay of ~150 μ sec., and they postulate that this lifetime is due to the low-energy 8+ → 6+ transition, which was unobserved in their gamma-ray spectrum.

5.2 HIGHER EXCITED STATES

Three levels are seen at an excitation of about 2400 keV, and they probably have <u>even</u> parity and spins 4, 5, or 6. It seems reasonable to identify these as members of the $(h_{9/2}, f_{7/2})$ configuration, which occurs in the theoretical spectrum at about this excitation energy. The $(f_{7/2})^2$ configuration also produces states of 4+ and 6+ but they are not expected to be excited in the decay of ^{210}At.

Next in the experimental spectrum are the well-identified odd-parity levels at 3 MeV, with probable spins 4 and 5. Quite good agreement is found with the location of these levels in the theoretical spectrum of the $(h_{9/2}, i_{13/2})$ configuration.

Both the theoretical and experimental pictures become less clear at higher excitations. Three higher-lying odd-parity levels are seen (3427-, 3524-, and 3726-keV) and these may belong to the $(f_{7/2}, i_{13/2})$ configuration.

Little is known about the states at 3698-, 3711-, and 3779-keV.

It is interesting that both in the theoretical and experimental spectra some grouping of levels appears, and this has facilitated the making of level assignments, such that consistent assignments of almost all observed levels could be made to configurations calculated from the simple two-proton model.

Finally we note the theoretical prediction of the lowest-lying member of the $(h_{9/2}, i_{13/2})$ configuration, the 11-level, calculated by Kim and Rasmussen[5]) to be at ~2.9 MeV. They also pointed out that this level is expected to decay by an E3 transition to the 8^+ member of the $(h_{9/2})^2$ ground-state band. Yamazaki and Ewan[18]) have observed an isomeric transition of energy 1292 keV decaying with a lifetime of about 25 ns, which is close to the theoretical lifetime for a single-particle E3 transition, although much shorter than the lifetime predicted by Kim and Rasmussen. Yamazaki and Ewan assigned this as the 11- to 8+ transition. This assignment does not actually fix the energy of the 11- state, since the succeeding low-energy 8+ to 6+ transition has not yet been observed (Sec. 5.1), but, the 11- energy would be approximately 2.8 MeV, in good agreement with the theory of Kim and Rasmussen.

6. ^{210}At Electron-Capture Decay Rates and Purity of the ^{210}Po Levels

The ^{210}At electron-capture branching ratios to the various ^{210}Po levels were estimated in our work from the total gamma-ray intensity depopulating each level. These intensities were corrected for fractional decay by K-capture and then used for calculation of the log ft values given in the decay scheme. The total decay energy was taken as $Q_{EC} = 3830^{+66}_{-57}$ keV[3]). Our results for decay to the levels at 3024 and 2908 keV are in good agreement with previous measurements and we have been able to set somewhat higher limits to log ft values for the transitions to the 6+ and 4+ levels at 1472 and 1426 keV.

It was pointed out by Hoff and Hollander[2]) that the ^{210}At EC decays of the allowed type to the ^{210}Po ground band of levels are highly hindered, whereas those decays of 1st-forbidden type to the 4- and 5- levels at ~3 MeV are unhindered. The hindered decays can be understood in terms of the configurations involved: decay of ^{210}At (with assumed configuration $P(h_{9/2})^3$, $N(p_{1/2})$) into the ground band of ^{210}Po (with assumed configuration $P(h_{9/2})^2$, $N(p_{1/2})^2$) must convert an $h_{9/2}$ proton into a p1/2 neutron, and this transition is hindered because of the large ℓ change involved. This is also true for transitions into the even-parity levels at ~2400 keV (with assumed configuration $P(h_{9/2}, f_{7/2})$, $N(p_{1/2})^2$). The same hindrance is to be expected for transitions to all final excited states that involve only proton excitations, and thus the unhindered beta decays cannot be understood in terms of a two-proton model of ^{210}Po as used in the theoretical calculations of Kim and Rasmussen and Redlich. However, these unhindered transitions to the odd-parity states may be due to neutron excitation of the ^{208}Pb core of ^{210}Po. In ^{208}Pb the 5^- and 4^- states

of the $(p_{1/2}, g_{9/2})$ neutron configuration and the 5^- and 6^- states of the $(p_{1/2}, i_{11/2})$ neutron configuration have been established at excitation energies of about 3.4 and 4.2 MeV, respectively[19,20]). The energies of these ^{208}Pb states are close to those of the 4- and 5- states in ^{210}Po (~3 MeV) and it is reasonable to assume that the same neutron configurations also contribute to the odd-parity states in ^{210}Po. The beta-decay components proceeding via these admixtures would be unhindered, as the transition would be from an $h_{9/2}$ proton to a $g_{9/2}$ or $i_{11/2}$ neutron.

8. Acknowledgements

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Table 1

Gamma-rays observed in the decay of ^{210}At

Gamma-ray energy (keV)	Gamma-ray intensity (percent of ^{210}At decays)[a]	Transition intensity[b]
46.4 ±0.3	0.110 ±0.016	30.5 ±4.6
116.5 ±0.3	0.68 ±0.05	5.6 ±0.4
125.2	≤0.036	≤ 0.25
202.0 ±0.3	0.17 ±0.02	
245.3 ±0.3	79.0 ±2.4	99.1 ±3.0
298.9 ±0.5	0.125 ±0.008	
316.9 ±0.3[c]	0.143 ±0.008	
402.4 ±0.3	0.78 ±0.03	0.94 ±0.04
499.1 ±0.5	0.13 ±0.02	
506.9 ±0.3	0.63 ±0.02	
518.7 ±0.4	0.13 ±0.01	
527.6 ±0.3	1.10 ±0.04	
544.8 ±0.5[d]	0.093 ±0.01	
584.0 ±0.5	0.32 ±0.02	
602.4 ±0.6[d]		
615.1 ±0.5	0.31 ±0.02	
623.1 ±0.4	0.52 ±0.02	
630.9 ±0.5	0.30 ±0.02	
639.5 ±0.5[c]	0.23 ±0.02	
643.7 ±0.5	0.46 ±0.02	

Table 1 (Cont)

Gamma-ray energy (keV)	Gamma-ray intensity (percent of ^{210}At decays)[a]	Transition intensity[b]
701.1 ±0.3	0.43 ±0.02	
726.0 ±0.6[d]		
782.9 ±0.7[d]	0.095 ±0.024	
790.6 ±0.7	0.093 ±0.023	
817.8 ±0.4	1.72 ±0.06	
853.1 ±0.4	1.39 ±0.05	
870.6 ±1.0	0.079 ±0.020	
881.6 ±0.6[c]	0.25 ±0.03	
909.4 ±0.8	0.092 ±0.023	
930.6 ±0.5	0.96 ±0.04	
956.7 ±0.5	1.83 ±0.07	
977.2 ±0.6	0.63 ±0.04	
1087.9 ±0.8[c]	≥0.14 ±0.02[e]	
1180.4 ±0.7	100	
1200.3 ±1.0	0.16 ±0.04	
1203.8 ±0.7[c]	0.72 ±0.25	
1289.4 ±0.7[c]	0.46 ±0.03	
1324.4 ±0.7	0.36 ±0.03	
1436.2 ±0.6	29.0 ±1.5	
1482.9 ±0.6	47.7 ±2.4	
1551.9 ±0.8	0.16 ±0.02	

Table 1 (Cont)

Gamma-ray energy (keV)	Gamma-ray intensity (percent of ^{210}At decays)[a]	Transition intensity[b]
1599.0 ±0.6	14.2 ±0.99	
1647.5 ±0.8[c]	0.089 ±0.01	
1718.6 ±0.6[f]	0.108 ±0.01	
1955.1 ±0.7	0.38 ±0.03	
2001.9 ±0.9	0.11 ±0.01	
2052.4 ±1.0	0.049 ±0.007	
2225.8 ±0.9	0.047 ±0.007	
2238.9 ±1.2	0.011 ±0.004	
2253.8 ±1.0	1.42 ±0.12	
2272.8 ±1.0	0.33 ±0.03	
2284.5 ±1.2	0.012 ±0.003	
2306.0 ±1.0	0.029 ±0.004	
2353.3 ±0.8	0.125 ±0.014	

[a]) Intensity values have been normalized to 100 for the 1180.4-keV gamma ray. The absolute intensity of this transition is known from the level scheme to be 100% and the correction for internal conversion is not significant.

[b]) Transition intensities were computed from the measured gamma-ray intensities with the use of the theoretical conversion coefficients of Sliv and Band[14]).

[c]) Assigned to the decay of ^{210}At but not included in the decay scheme.

[d]) Assignment to the decay of ^{210}At is uncertain.

[e]) Corrected for contribution from the single-escape peak of the 1599.0-keV transition (see Sec. 3.1).

[f]) This line may be due to the decay of ^{206}Bi (see Sec. 3.1).

Table 2

Multipolarity assignments of some ^{210}At transitions

Transition energy (keV)	Experimental K-conversion Coeficients			Multipolarity
	This work	From Ref. 1	From Ref. 2	
116.5	3.5 ±0.5	5.9		M1(+E2)
245.3	(9.3 ±1.1)× 10^{-2}	1.1 × 10^{-1}	1.7 × 10^{-1}	E2
402.4	(1.53 ±0.26)× 10^{-1}	≥3.5 × 10^{-2}	8.6 × 10^{-2}	M1(E2)
615.1	(2.3 ±0.5)× 10^{-2}			(E2+M1)
630.9	≤5 × 10^{-2}			(M2)?
701.1	≤2 × 10^{-2}			E2
817.8	(2.8 ±0.7)× 10^{-2}			M1(E2)
853.1	(2.0 ±0.5)× 10^{-2}			M1(E2)
1180.4	(4.37 ±0.35)× 10^{-3}	4.7 × 10^{-3}	4.1 × 10^{-3}	E2
1436.2		1.2 × 10^{-3}	1.1 × 10^{-3}	E1
1482.9			1.4 × 10^{-3}	E1
1599.0			1.1 × 10^{-3}	E1

Table 3

Assignment of some weak conversion lines observed in previous studies

Electron energy (keV) and assignment From Ref. 1		From Ref. 2		Proposed assignment
		71.77		
		75.76	L_{II}-91.99	
		78.32	L_{III}-92.12	
		95.27		
		157.1		
		184.7		L_{II}-202.0 ±0.3
		205.4	K-298.5	K-298.9 ±0.5
		223.3		K-316.9 ±0.3
		282.4	L_{II}-298.6	L-298.9 ±0.5
		406.3	K-499.5	K-499.1 ±0.5
		522.0	K-615.2	K-615.1 ±0.5
		529.3		K-623.1 ±0.4
538	M-542 ^{209}At (?)	537.8		K-630.9 ±0.5
		542.5		
608	K-701	608.8	K-702.0	K-701.1 ±0.3
700				
727	K-820	724.3	K-817.5	K-817.8 ±0.4
762	K-855			K-853.1 ±0.4
837	L_I-854			K-930.6 ±0.5, L-853.1 ±0.4
865	K-958	863.0		K-956.7 ±0.5
885				K-977.2 ±0.6
923				L-930.6 ±0.5
939	L-956			L-956.7 ±0.5

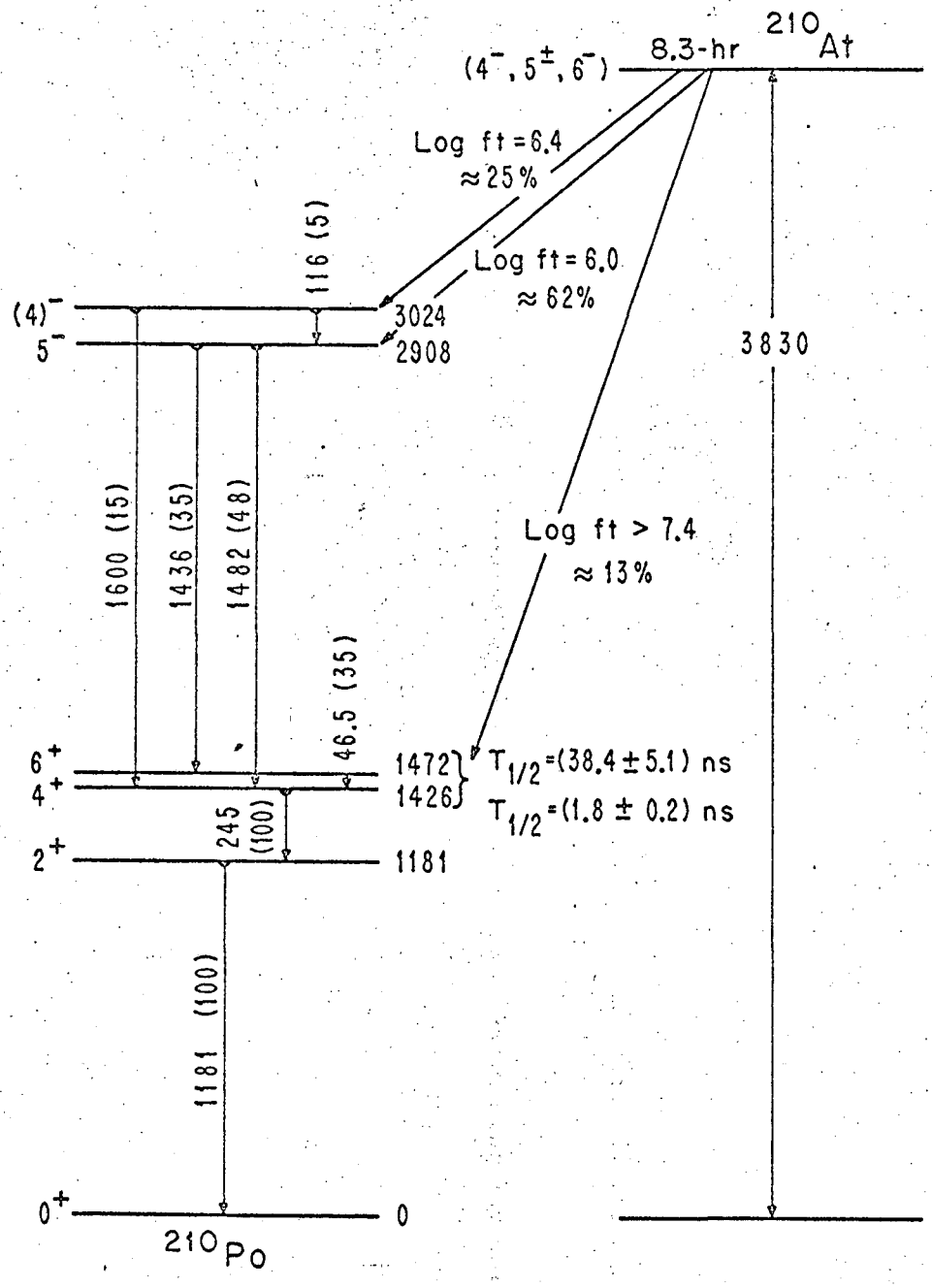


Figure 1. XBL677-3665

Decay scheme of ^{210}At, from the studies of Mihelich et al.[1]), Hoff and Hollander[2]), and Schima et al.[3]).

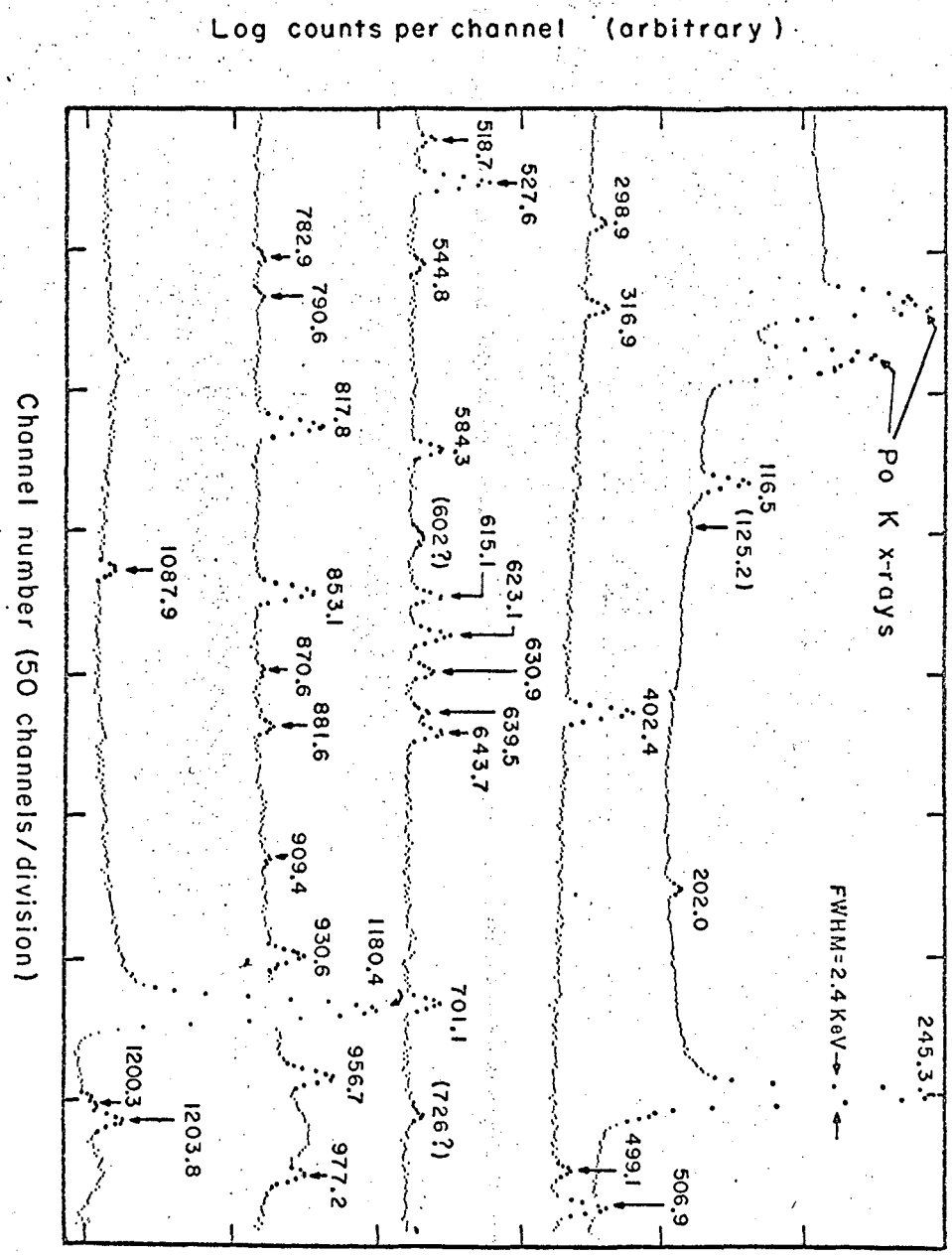


Figure 2.
Spectrum of ^{210}At gamma rays in the energy range 50 to 1250 keV, taken with Compton-rejection Ge(Li) spectrometer.

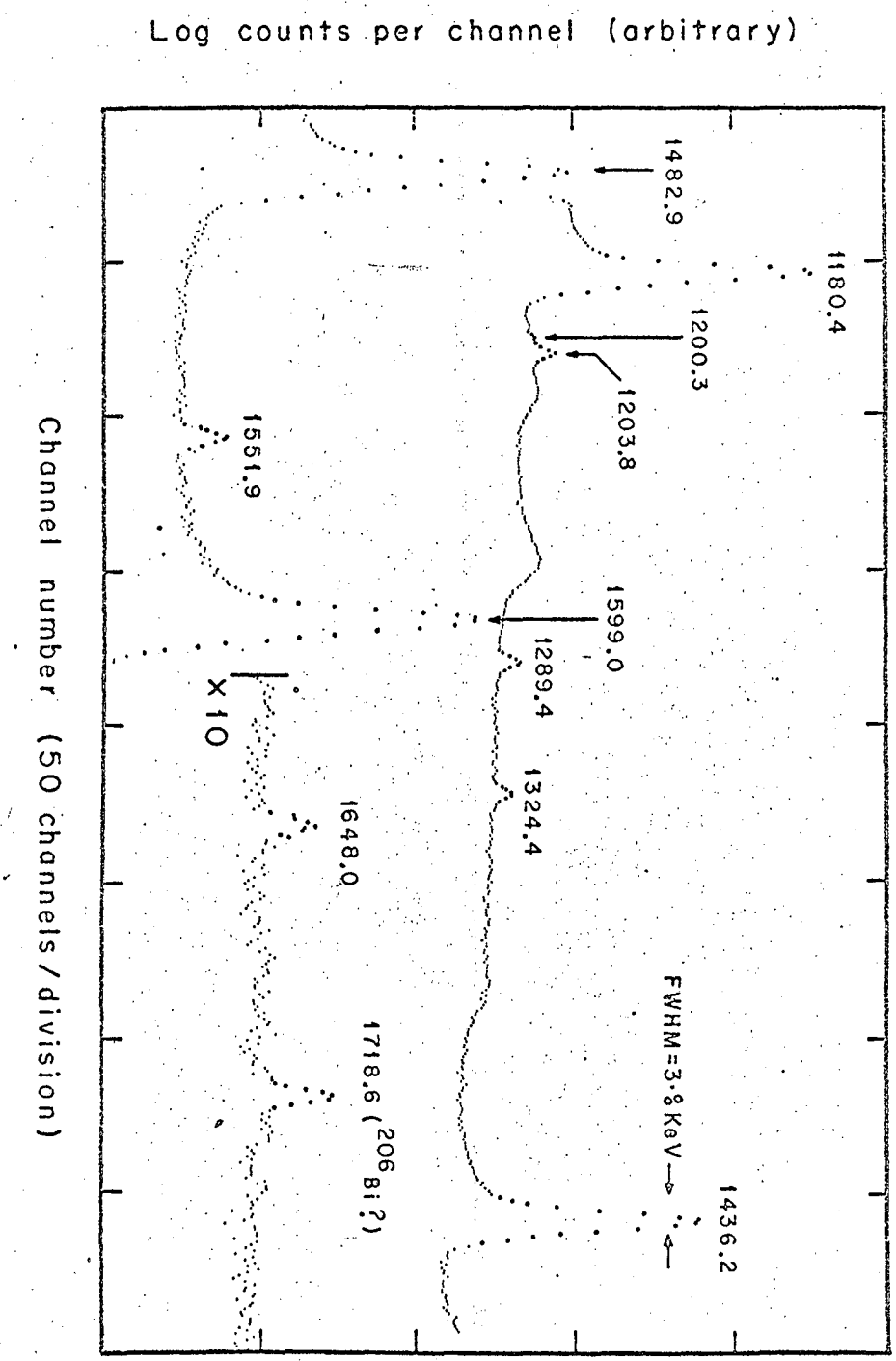
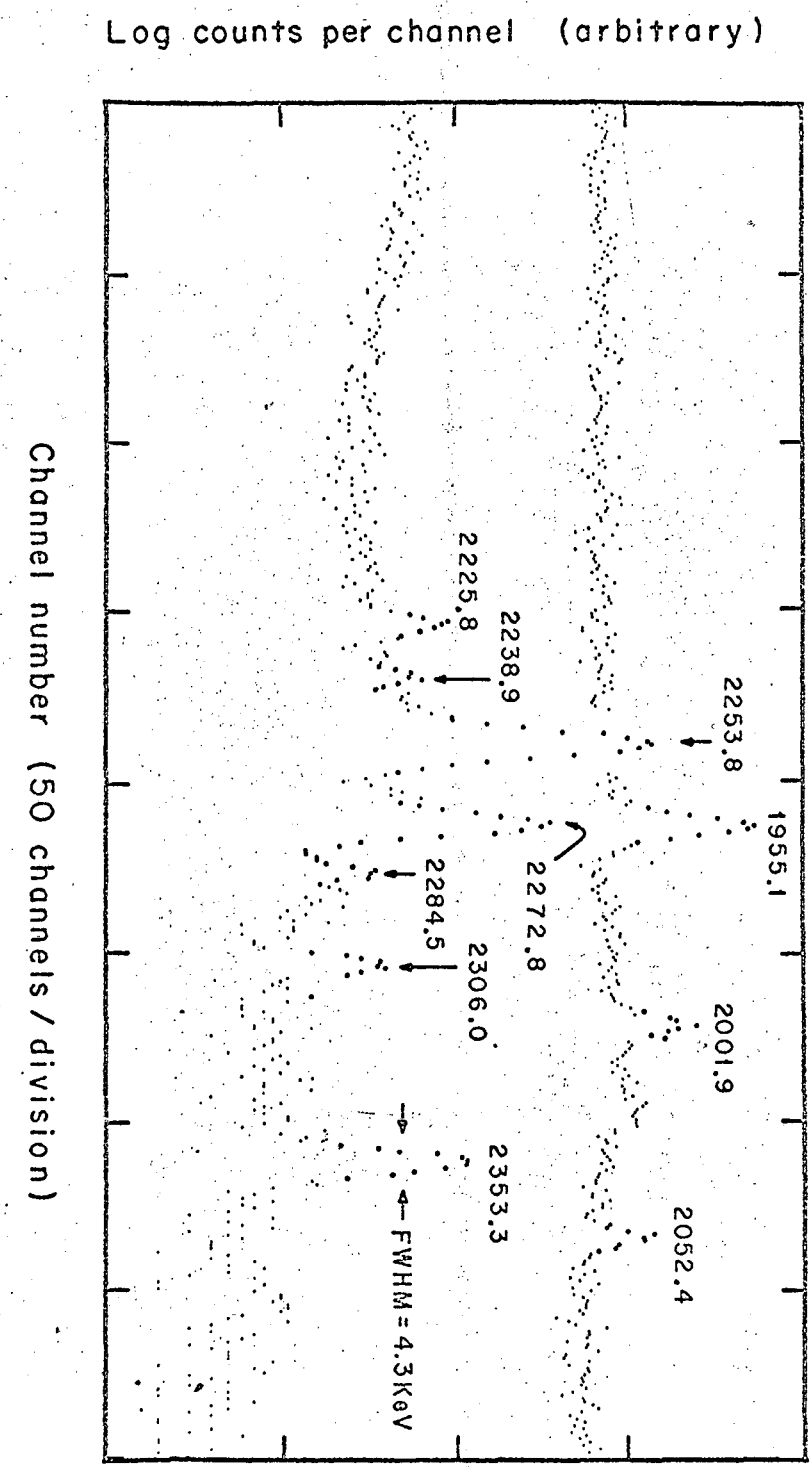


Figure 3-A.

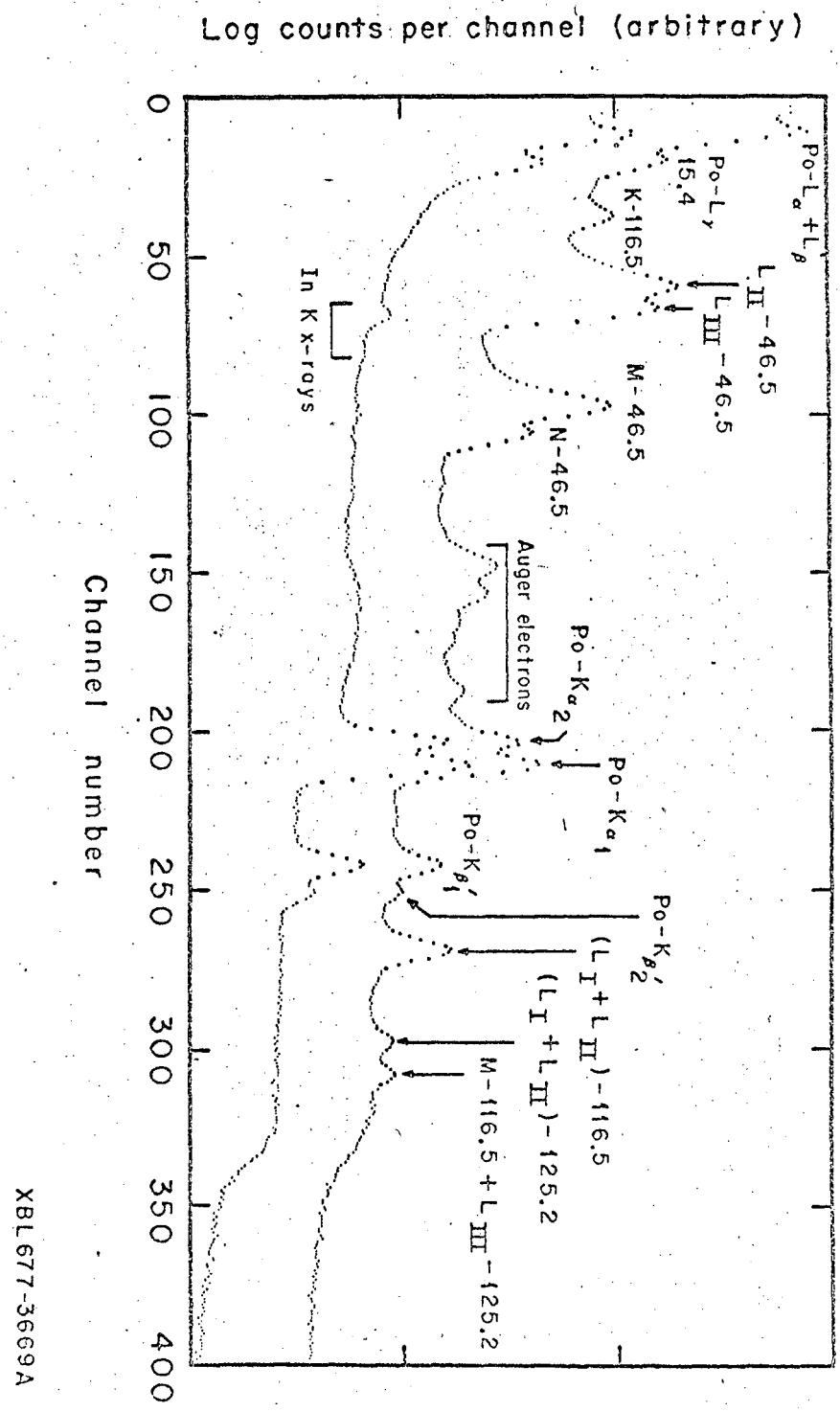
Spectrum of ^{210}At gamma rays in the energy range 1150 to 1750 keV.



XBL677-3672A

Figure 3-B.

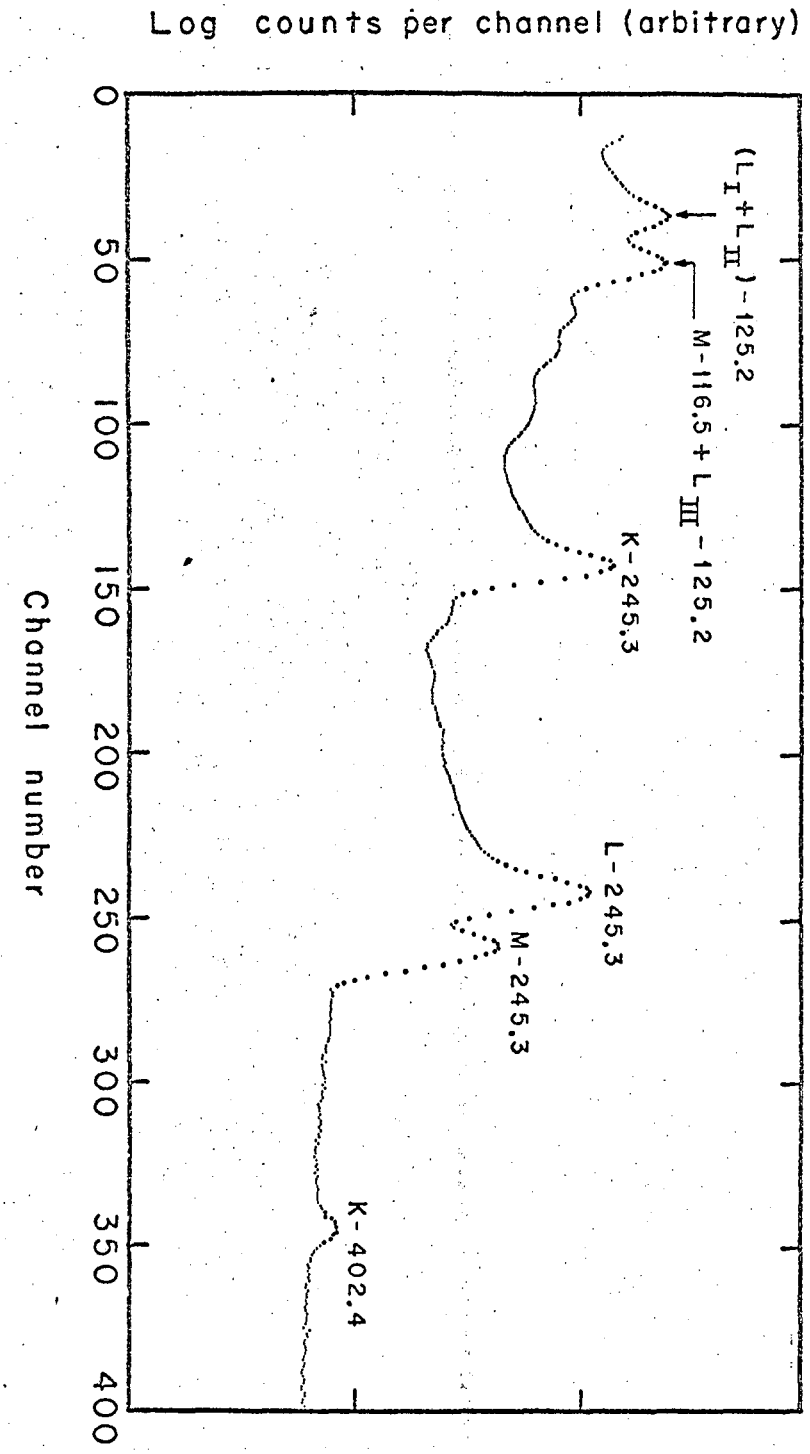
Spectrum of ^{210}At gamma rays in the energy range 1750 to 2400 keV.



XBL677-3669A

Figure 4.

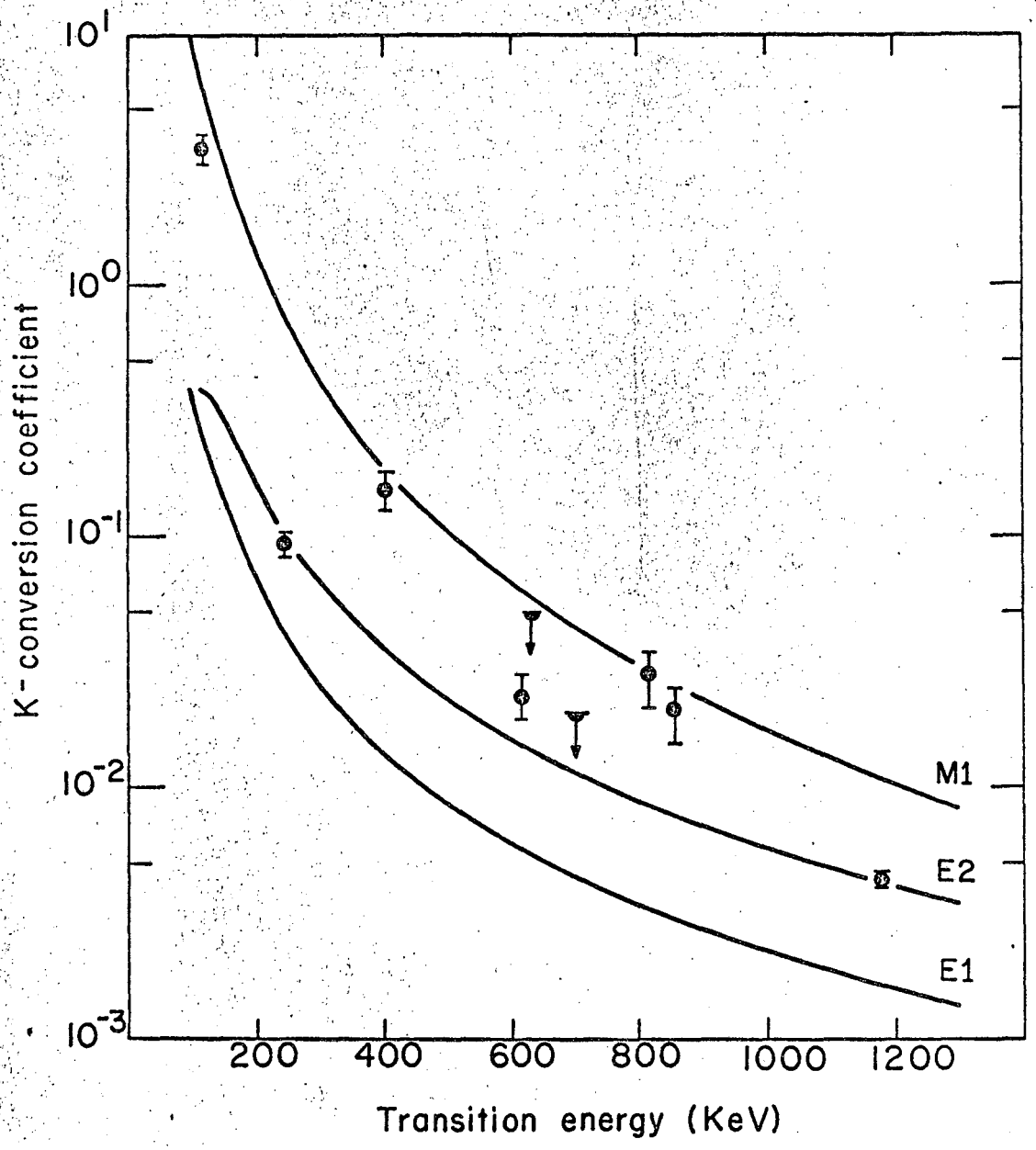
X-ray and conversion-electron spectrum of ^{210}At in the energy range 10 to 150 keV, taken with Si(Li) spectrometer.



XBL677-3668A

Figure 5.

Conversion-electron spectrum of ^{210}At in the energy range 100 to 350 keV.



XBL6711-5568

Figure 6.

Comparison of experimental and theoretical K-conversion coefficients of some ^{210}At transitions for M1, E1, and E2 multipolarities. (lines are theoretical Sliv and Band[14]) values, points are experimental values.)

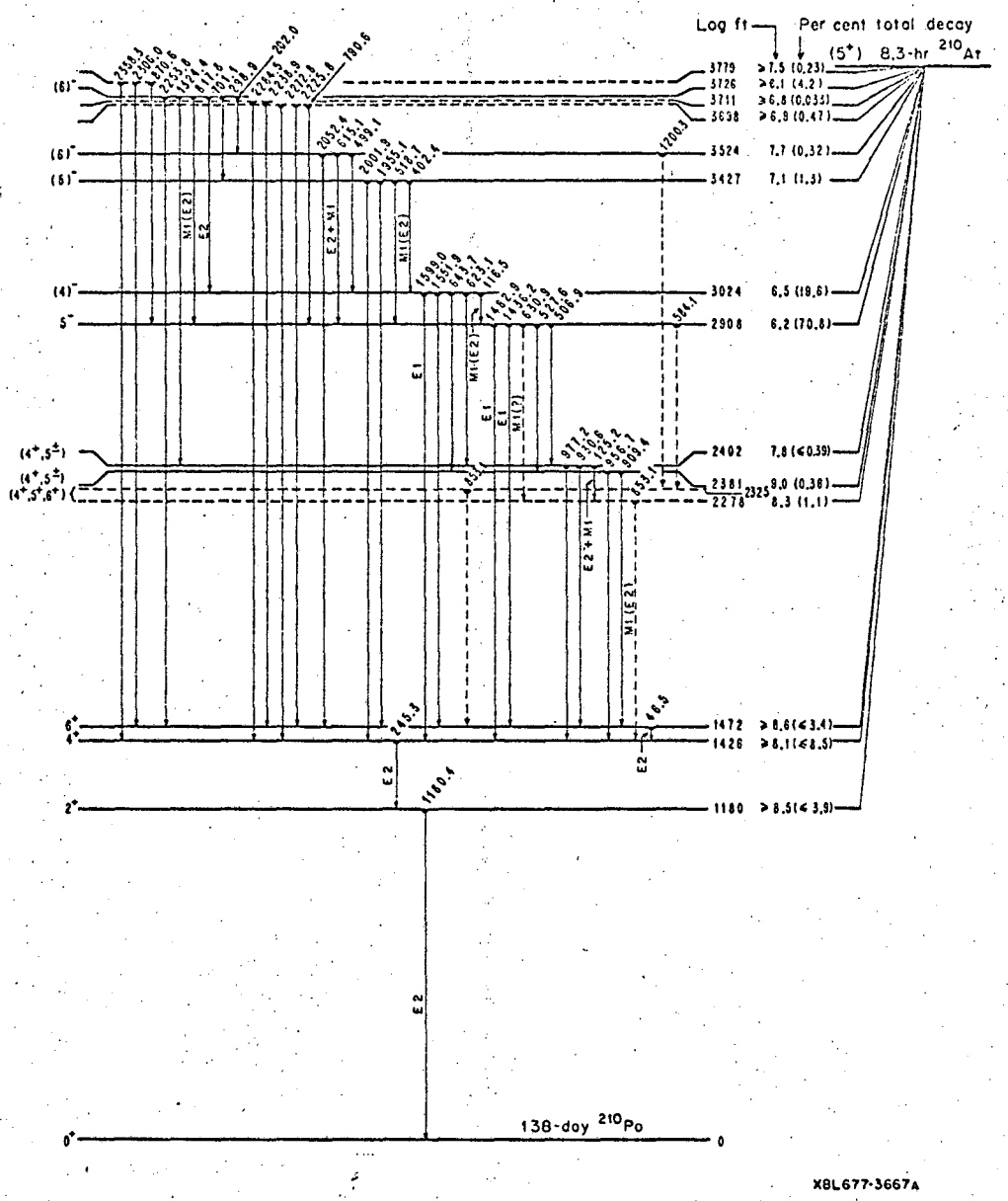


Figure 7.

Experimental decay scheme of ^{210}At.

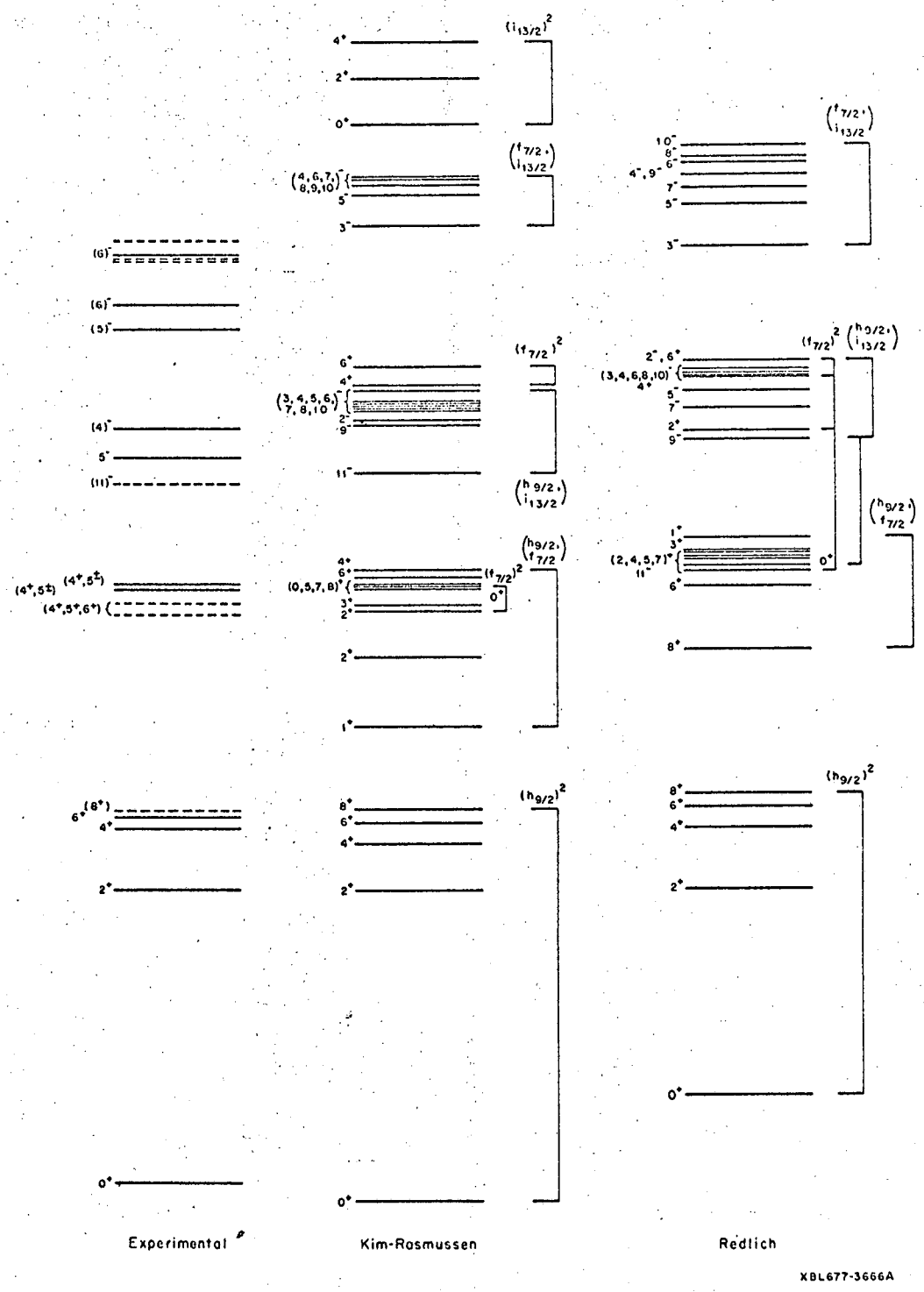


Figure 8.

Comparison of experimental levels of ^{210}At with theoretical results of Kim and Rasmussen[5]) and Redlich[6]) from two-proton models.

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