# Electron Capture of $At^{210}$(8.3 h) to $Po^{210}$

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The electron capture decay of $At^{210}$(8.3 h) to excited states in $Po^{210}$ has been studied with scintillation spectrometers and coincidence and directional correlation techniques. Previously observed transitions of 46.7 keV($E2$), 246 keV($E2$), 404 keV, 702 keV, 1185 keV($E2$), 1441 keV($E1$), 1488 keV($E1$), and 1604 keV($E1$) were verified, as well as transitions of 495 and 2250 keV. No evidence for a 2600-keV transition was found. The data are consistent with a level scheme with states at 1185 keV ($2^+$), 1431 keV ($4^+$, $T_{1/2}=1.8\pm0.2$ nsec), 1478 keV ($6^+$, $T_{1/2}=38.4\pm5.1$ nsec), 2919 keV ($5^-$), 3035 keV ($5^-$), and 3680 keV. The last three levels are populated with electron capture branches with log $ft$ values of 5.90, 6.40, and 5.90, respectively. The $At^{210}$ ground state was determined to be approximately 3830 keV above that of $Po^{210}$, by comparison of the relative intensities of $L$ capture and $K$ capture. The transition probabilities are calculated for transitions depopulating the 1431- and 1478-keV levels using a configuration mixing model. The effects of coupling single-particle states to surface vibrations are included in the calculations.

## I. INTRODUCTION

PREVIOUS studies of the electron capture decay of $At^{210}$ to excited states in $Po^{210}$ were those of Mihelich *et al.*[1] and Hoff and Hollander.[2] These authors presented conversion-electron data, transition energy and intensity determinations, and level schemes whicn were in essential agreement. There were some minor conflicts as to the presence and placement of weak transitions, as well as electron capture feeding intensities. Conversion electron data, and preliminary directional correlation data of Mihelich *et al.*, led to angular momentum and parity assignments for five excited states and the multipole orders of the associated transitions. Sunyar[3] first reported the measurement of a 1.5-nsec half-life, while this group[4] recently investigated the half-lives of the 1431- and 1478-keV levels.

In this work, the singles photon spectra were obtained with scintillation spectrometers employing NaI(Tl) crystals of dimensions $1\frac{1}{2}$ in. diam×2 in. thick and 3 in. diam×3 in. thick. A conversion-electron gamma-ray coincidence experiment was performed using a 404-$K$ keV gate. Several gamma-gamma coincidence experiments were performed for which the gates were the prominent high-energy photopeaks. Directional correlations were measured for the following cascades: 246–1185 keV (1441–1488 keV composite)–246 keV in prompt and delayed coincidence, and 1604–246 keV.

The transition probabilities for the $E2$ transitions from the 1431- and 1478-keV levels have been calculated. These calculations were made on the basis of a two-particle configuration mixing model.[2,5,6] The effects of coupling single-particle states to surface vibrations were included.[7]

## II. PROCEDURE AND RESULTS

### A. Source Preparation

The $At^{210}$ activity was produced by the $Bi^{209}(\alpha,3n)At^{210}$ reaction with the 40-MeV $\alpha$ beam of the Argonne National Laboratory 60-in. cyclotron. The targets consisted of 40 to 70 mg of bismuth metal evaporated on 3-mil Al foil. After the irradiation, the bismuth was dissolved off the Al foil with concentrated $HNO_3$. For the first run, the At activity was extracted from the Bi carrier using the method outlined by Bagnall.[8] Since the only undesirable activities proved to be $At^{209}$ and $At^{211}$, extraction procedures were simplified to dissolving carrier and activity in 6$N$ $HNO_3$. The presence of $At^{209}$ and $At^{211}$ was found to be no greater than 5 and 4%, respectively, of the initial activity.

### B. Scintillation Spectrometer Spectra

The gamma-ray transition intensity data were determined from spectra obtained with the 3-in.×3-in. and $1\frac{1}{2}$-in.×2-in. NaI crystals. The source distances were 20, 30, and 40 cm for the former and 10 cm for the latter. A typical 3-in.×3-in. gamma-ray singles spectrum is reproduced in Fig. 1. Spectra taken at 20, 30, and 40 cm include photopeaks corresponding to 2250 $\pm40$ and 2600$\pm$80 keV. Using calculated crystal efficiencies,[9] one may show that the 2600-keV photopeak can be accounted for, within statistical error, as the summing of the 1185- and 1441–1488-keV composite photopeaks. The spectra were decomposed using the

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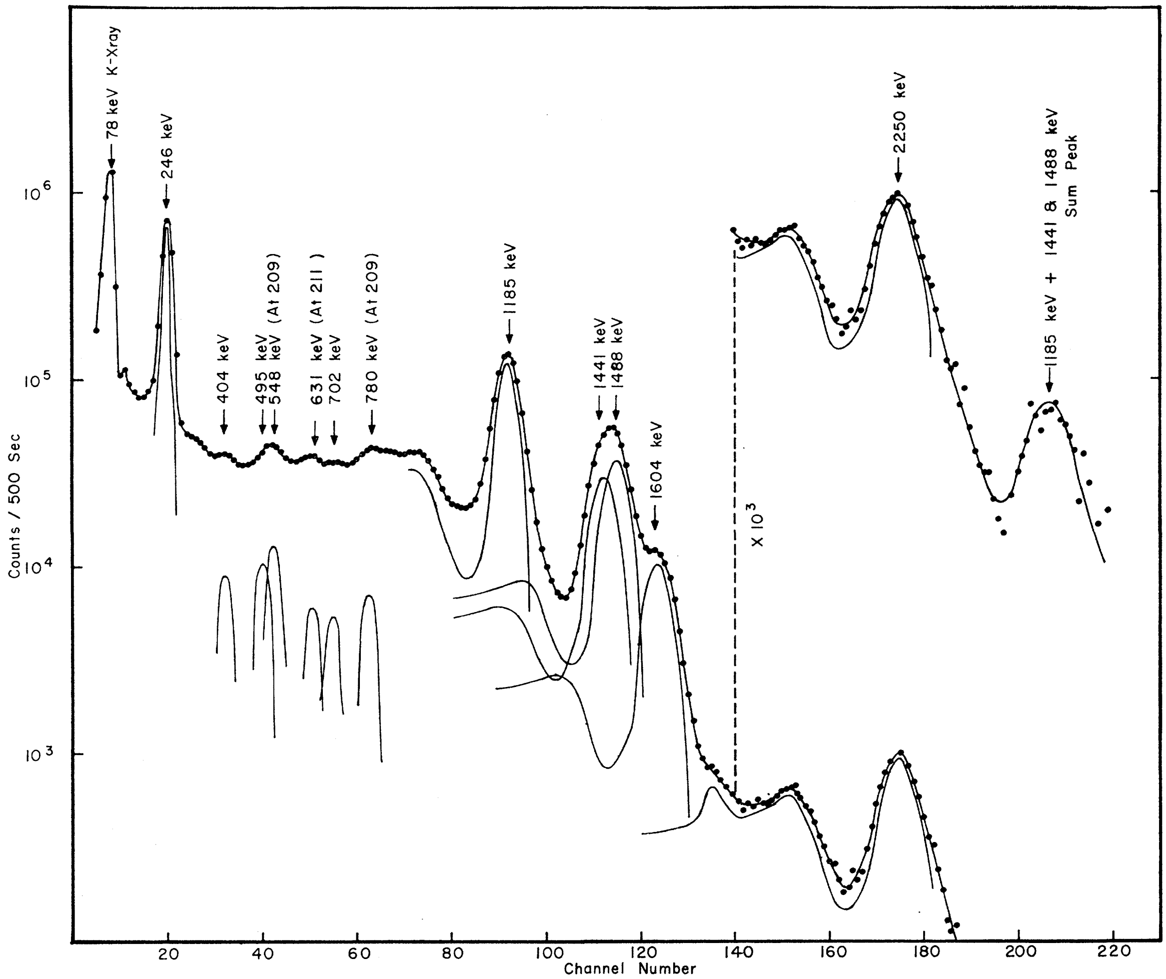


FIG. 1. A typical gamma-ray spectrum taken with a 3-in.×3-in. NaI crystal with the source at 30 cm. A partial decomposition of the spectrum is shown.

transition energies as determined by the conversion electron data of Ref. 1. These electron data, the gamma-ray intensities, and the resulting transition intensities are summarized in Table I. Theoretical $K$ and $L$ conversion coefficients were obtained from Rose.[10]

### C. Coincidence Measurements

Three gamma-gamma coincidence experiments were performed, the first of which consisted of a 2250-keV gate with a display range from $K$ x rays to 1300 keV ($2\tau=5.0\times10^{-7}$ sec). The gate crystal, a $1\frac{1}{2}$-in.×2-in. NaI, was 2 cm distant from the source and a $1\frac{1}{2}$-in. ×1-in. NaI display crystal was at 2.5 cm. The detectors had an angular separation of 180° with no absorbers. The 1185- and 246-keV transitions, and the $K$ x-ray peak are present in the coincidence display. No other gamma transitions with relative intensity of 10% or greater were observed. Thus, a level at 3680±40 keV is established, this level being depopulated by the 2250-keV transition which proceeds to the 1431-keV level. The ratio of total electron capture intensity to $K$-electron capture intensity, as a function of the energy available for the capture process, has been calculated.[11]

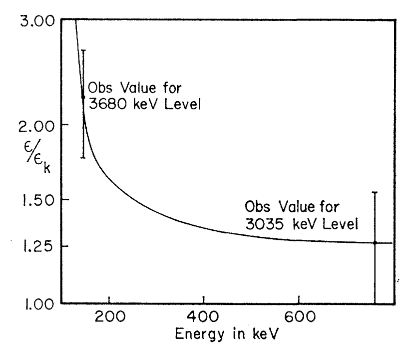


FIG. 2. The ratio $\epsilon/\epsilon_K$ of the intensities of the total electron capture to $K$-electron capture, is plotted along the ordinate. The abscissa is the energy, $E$, available for the capture process. The curve is drawn for the electron capture of At to Po.

[10] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958).

[11] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (Interscience Publishers, Inc., New York, 1959), Chap. 5, p. 59 ff.

TABLE I. Transition intensity data.

| Energy (keV) | Photon intensity[a] | $K$-conversion electron intensity[b] | $\epsilon_K$[c] | $\epsilon_{total}$[c] | Total transition intensity | Multipolarity[g] and criterion |
|---|---|---|---|---|---|---|
| $K$ x-ray | 1523.0±126.0 | | | | 98.8± 8.3 | |
| 46.7 | | d | | 339[e] | 31.2± 8.3 | $E2$ (I.C.C.) |
| 116.7 | | 58.0 | 8.5[e] | 9.0[e] | 4.9± 1.3 | $M1$ (I.C.C.) |
| 246 | 1249.0± 83.2 | 125.3±2.0 | 0.170[e] | 0.235[e] | 100.0 | $E2$ (I.C.C. and D.C.) |
| 404 | 26.6± 3.3 | 23.0 | 0.086±0.011 | 0.094±0.012 | 1.9± 0.4 | $M1+E2$ (I.C.C.) |
| 495 | 23.4± 10.5[f] | | | | 1.5± 0.7 | |
| 702 | 50.0± 33.3 | 0.50 | $(1.0\pm0.7)\times10^{-3}$ | | 3.3± 2.4 | |
| 1185 | 1665.0±100.0 | 6.8 | $(4.1\pm1.1)\times10^{-3}$ | $(5.1\pm1.3)\times10^{-3}$ | 108.3±13.7 | $E2$ (I.C.C. and D.C.) |
| 1441 | 587.7± 18.3 | 0.62 | $(1.1\pm0.3)\times10^{-3}$ | $(1.2\pm0.4)\times10^{-3}$ | 38.2± 3.7 | $E1$ (I.C.C.) |
| 1488 | 724.3± 21.6 | 0.82 | $(1.4\pm0.3)\times10^{-3}$ | $(1.5\pm0.4)\times10^{-3}$ | 47.0± 4.6 | $E1$ (I.C.C. and D.C.) |
| 1604 | 231.4± 11.7 | 0.32 | $(1.4\pm0.4)\times10^{-3}$ | $(1.5\pm0.5)\times10^{-3}$ | 15.0± 1.8 | $E1$ (I.C.C. and D.C.) |
| 2250±40 | 40.0± 3.3 | | | | 2.6± 0.4 | ($E1$) |

[a] Photon intensity scale is normalized to the internal conversion coefficient for the 246-keV transition. $K$ x-ray intensity corrected for the escape peak and fluorescent yield.
[b] Conversion electron intensity of Ref. 1 multiplied by 10.
[c] Experimental internal conversion coefficients obtained from Ref. 1, unless otherwise indicated.
[d] $K$-conversion energetically impossible.
[e] Theoretical total conversion coefficients are taken to be $\alpha_K+1.3\alpha_L$, where $\alpha_K$ and $\alpha_L$ are from Ref. 10.
[f] Intensity determined from 404-$K$ keV conversion electron-gamma coincidence experiment.
[g] I.C.C. indicates determination based on internal conversion coefficients, and D.C. indicates directional correlation criterion.

In Fig. 2 the solid curve is the plot of such a function for an allowed transition with $Z=84$. Using the 246 and 1185-keV transition intensities for the determination of the total electron capture intensity, and suitably correcting the $K$ x-ray intensity, the total electron capture intensity to $K$-electron capture intensity ratio was determined to be 2.21±0.45. As shown in Fig. 2, the measured value of this ratio for the 3680-keV level is consistent with an available capture energy of $150^{+26}_{-17}$ keV. Hence, the difference between the $At^{210}$ and $Po^{210}$ ground-state energies is $3830^{+66}_{-57}$ keV.

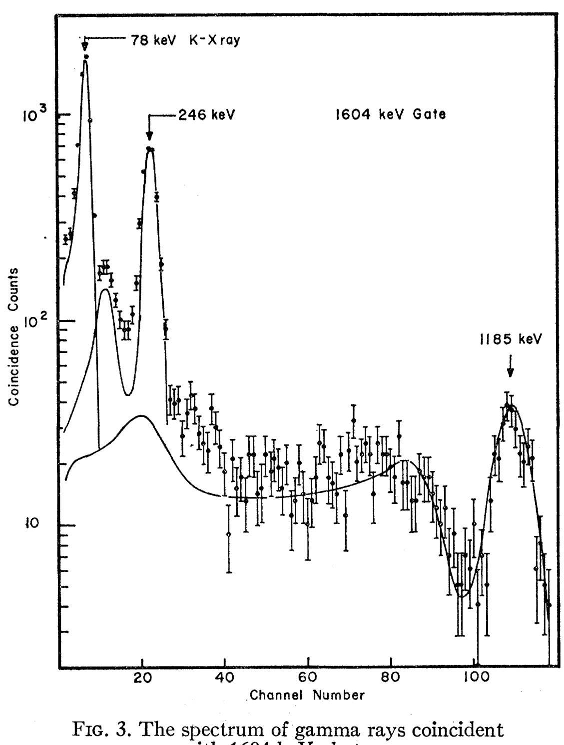


FIG. 3. The spectrum of gamma rays coincident with 1604-keV photons.

For the 1604-keV gate coincidence experiment ($2\tau=3.7\times10^{-7}$ sec), a $1\frac{1}{2}$-in.×2-in. NaI gate crystal was at 4 cm and a $1\frac{1}{2}$-in.×1-in. NaI display crystal was at 5 cm, with a 90° angular separation. With a coincidence range from 70 to 1500 keV, the 1185- and 246-keV transitions and the $K$ x-ray photopeak are present in the coincidence spectrum as shown in Fig. 3. As in the case for the 3680-keV level, a determination of the ratio of the total electron capture intensity to the $K$-electron capture intensity for the 3035-keV level is consistent with the postulated level scheme (see Fig. 2).

A third gamma-gamma coincidence experiment was performed, gating on the 1441–1488-keV composite photopeak with a $1\frac{1}{2}$-in.×1-in. NaI crystal. A coincidence range of 200 to 2200 keV was displayed with a $1\frac{1}{2}$-in.×2-in. NaI crystal ($2\tau=5.0\times10^{-7}$ sec). The detectors were 2 cm from the source and in 180° geometry. There were no peaks in the coincidence spectrum attributable to the 404-, 495-, or 702-keV transitions.

A conversion-electron gamma-ray coincidence experiment ($2\tau=3.5\times10^{-7}$ sec) was performed in an intermediate-image beta-ray spectrometer. The momentum resolution was 2.8% and the current was set to focus the 404-$K$ conversion electrons at the detector. The display crystal was a 1-in.×2-in. NaI crystal at a distance of 2 cm and shielded by 1.9 g/cm² of Pb. Due to fluorescence radiation from the Pb shielding, the $K$ x-ray intensity could not be determined. The 246-, 495-, and 1185-keV transitions are found to be coincident with the 404-$K$ conversion electrons (see Fig. 4). These data do not eliminate the possibility of the 1441–1488-keV composite transitions or the 1604-keV transition being coincident with the 404-keV transition. The

TABLE II. Directional correlation data and multipolarity assignments based on conversion electron and directional correlation data.

| Correlation | $A_2$ | $A_4$ | Possible spin sequence | Multipolarity |
|---|---|---|---|---|
| 246–1185 keV | 0.0923±0.0217 | 0.0357±0.0329 | 4(Q,O)2(Q)0 | 246 keV ($E2+<0.3\%$ $M3$) |
| 1441–1488 keV (composite–246 keV prompt) | −0.0698±0.0168 | 0.0065±0.0210 | | |
| 1488–246 keV[a] | −0.0836±0.0212 | 0.0078±0.0251 | 3(D,Q)4(Q)2<br>5(D,Q)4(Q)2 | 1488 keV ($E1+<0.2\%$ $M2$)<br>($E1+<0.4\%$ $M2$) |
| 1604–246 keV[b] | −0.0816±0.0235 | 0.0017±0.0289 | 3(D,Q)4(Q)2<br>5(D,Q)4(Q)2 | 1604 keV ($E1+<0.6\%$ $M2$)<br>($E1+<0.2\%$ $M2$) |

[a] Corrected for 1441–46.7–246 keV cascade, see text.
[b] This correlation was analyzed assuming a simple cascade with the intermediate state as the 1431 keV ($4^+$) level.

relative intensities of the coincident photons of 246, 495, and 1185 keV are 1.00, 0.90±0.41, and 1.54±0.55, respectively.

### D. Directional Correlation Measurements

Directional correlation measurements were made for a number of cascades. All the determinations were performed with a moveable 2-in.×2-in. NaI crystal, gating the high-energy photopeaks and a coincidence circuit having a resolving time of approximately 11 nsec. For the 246–1185-keV cascade, the fixed crystal was a $1\frac{1}{2}$-in.×1-in. NaI, gating the 246-keV transition. This crystal had no frontal shielding but was laterally shielded by 4.9 g/cm$^2$ of Pb. The moveable crystal was frontally shielded by 1 gm/cm$^2$ of Pb and 90 mg/cm$^2$ of Cu, with a lateral shielding of 4.9 g/cm$^2$ of Pb. The other correlation measurements were done using a 2-in.×2-in. NaI crystal as the fixed detector, with no frontal shielding. The lateral shielding on both detectors was 4.9 g/cm$^2$ of Pb.

Table II lists the measured Legendre polynomial expansion coefficients for the directional correlations, corrected for geometry and the interference due to the Compton distribution of higher energy photons in the energy gates. The directional correlation of the 246–1185-keV cascade confirms the assignment of 2 and 4 to the 1185- and 1431-keV levels.[1] The values of $A_2$ and $A_4$ allow an octopole mixture no greater than 0.3% for the 246-keV transition. This is consistent with the $E2$ multipolarity of the 246-keV transition, as established by conversion electron data.[1,2] The 1604–246-keV correlation data are compatible with either a 3(D,Q)4(Q)2 cascade, with a maximum of 0.6% quadrupole admixture, or a 5(D,Q)4(Q)2 cascade with a maximum of 0.2% quadrupole admixture. This correlation does not fit a 4(D,Q)4(Q)2 cascade for any value of quadrupole admixture. The absence of a crossover transition to the 1185-keV ($2^+$) level would indicate that the spin assignment of 5 for the 3035-keV level is preferable. The $E1$ character of the 1604-keV transition dictates a negative parity assignment.

The correlations for the 246–1185- and 1604–246-keV cascades had to be corrected only for the angular resolution and Compton contribution to the energy gates. The (1441–1488 keV) composite–246-keV correlation had two components, that due to the 1488–246-keV cascade and that due to the 1441–46.7–246-keV triple cascade in which the unobserved intermediate transition is highly converted and proceeds from a 38-nsec metastable state. The correlation of the "prompt" cascade was obtained by the following procedure. First, the correlation was measured at various delay times (12.5 to 28 nsec). The angular distribution observed in delay was isotropic within experimental errors for all delay times. The contribution of this

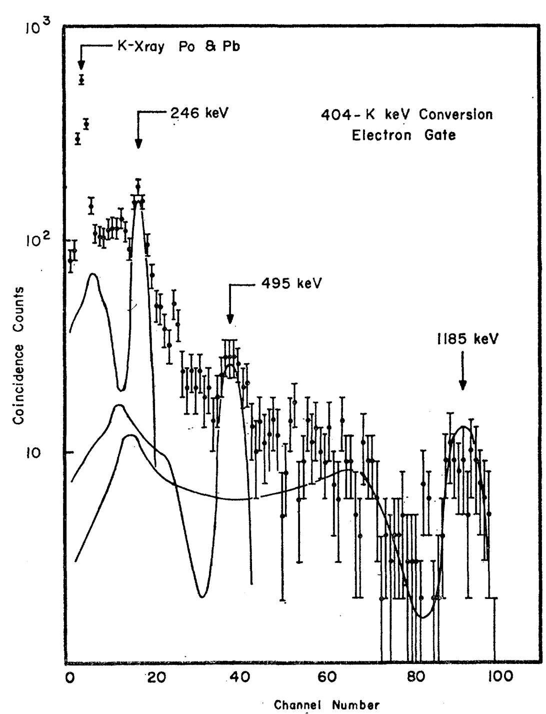


FIG. 4. The spectrum of gamma rays coincident with 404-$K$ conversion electrons.

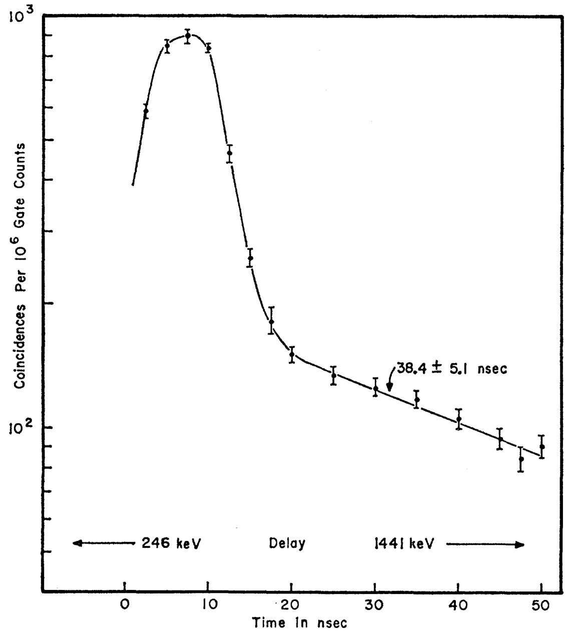


FIG. 5. The delayed coincidence curve obtained when gating on the (1441–1488-keV) composite and the 246-keV photopeaks.

correlation was subtracted from the composite measurement at zero delay, assuming that the delayed correlation is not a rapidly varying function of time. In this way, it was determined that the 1488–246-keV correlation contributed 83.5% while the 1441–46.7–246-keV triple correlation contributed 16.5%. Thus, the corrected values of $A_2$ and $A_4$ for the 1488–246-keV cascade are $-0.0836\pm0.0212$ and $0.0078\pm0.0251$, respectively. These values are compatible with a $3(D,Q)4(Q)2$ cascade with a maximum quadrupole mixing of 0.2%, or a $5(D,Q)4(Q)2$ cascade with a maximum quadrupole admixture of 0.4% (see Table II for summary). The absence of a crossover transition to the 1185-keV level indicates that the spin assignment of 5 is preferable. The large dipole content of the 1488-keV transition is in complete agreement with conversion electron data. Thus, a spin and parity assignment of $5^-$ may be given to the 2919-keV level.

### E. Half-Life of the 1478-keV Level

Employing the coincidence circuit mentioned above ($2\tau=10.8$ nsec), a delayed coincidence curve (Fig. 5) was obtained between the (1441–1488-keV) composite and the 246-keV transitions. The value of $38.4\pm5.1$ nsec has been previously reported,[4] the half-life being assigned to the 1478-keV level.

## III. DISCUSSION

Using the measured value of 3830 keV for the ground-state energy difference, the log$ft$ values were determined according to the procedure of Ref. (11). The total electron capture branches to the 3680-, 3035-, and 2919-keV levels are found to be $2.4\pm0.2$, $18.9\pm1.7$, and $73.3\pm2.4\%$, respectively. The corresponding log$ft$ values are 5.90, 6.40, and 5.90, respectively. These log$ft$ values indicate that the electron capture to these levels proceeds via allowed transitions, with a possibility of an $l$-forbidden transition for the branch to the 3035 keV level. Thus, the ground state of At is tentatively assigned as $4^-$, $5^-$, or $6^-$. On the basis of the similarity of log$ft$ values for the electron captures to these high-lying levels, a tentative assignment of $5^-$ or $4^-$ is given to the 3680-keV level. It would then follow that the 2250 keV transition would be of $E1$ multipolarity.

Tentative levels are postulated at 2330 and 1835 keV. These are indicated by dashed lines in the level diagram (see Fig. 6).

## IV. THEORETICAL TRANSITION PROBABILITIES

Since $Po^{210}$ has two protons beyond the $\gamma=4$ shell and closes the $\gamma=5$ neutron shell, it has provided an

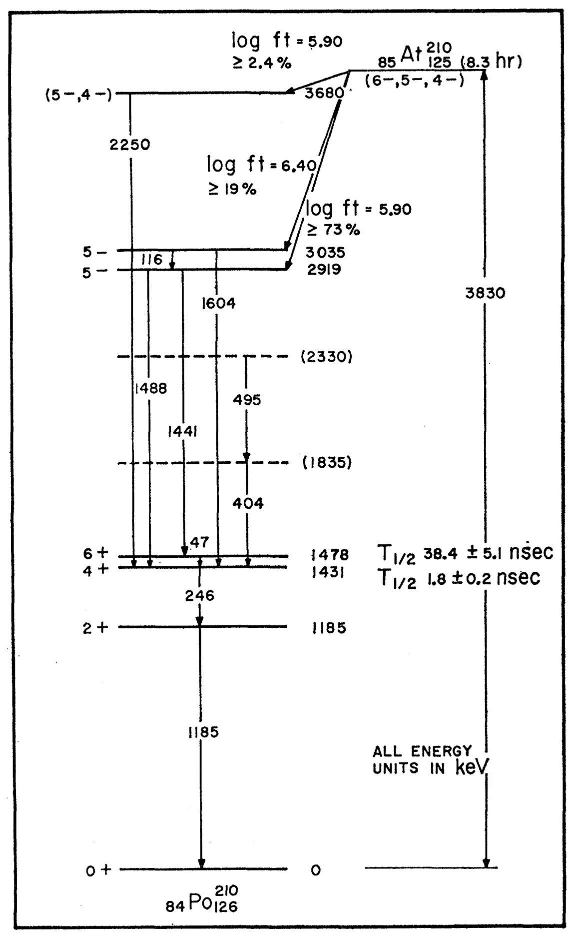


FIG. 6. Revised energy-level diagram for $Po^{210}$. Dashed levels indicate tentative assignments. Although the 1604- and the 2250-keV transitions are shown terminating at the 1431-keV ($4^+$) level, the possibility that they populate the level at 1478 keV ($6^+$) may not be discounted. No transitions of $1604\pm46.7$ keV or $2250\pm46.7$ keV were observed.

excellent test for shell-model calculations.[12,2,5,6] These calculations predict the low-lying energy levels with reasonable accuracy. The calculations of Newby and Konopinski[5] take into account the interaction between the two protons, and provide wave functions which are a linear combination of the two-proton configurations. Guman *et al.*[6] have calculated levels and wave functions of the low-lying levels considering the two-proton interactions as well as the single-particle coupling to surface vibration. We have made a calculation employing the Newby and Konopinski wave functions for the 1185 keV ($2^+$), 1431 keV ($4^+$) and the 1478-keV ($6^+$) levels to determine the transition probabilities of the 246-keV $E2$ and the 46.7-keV $E2$ transitions. A second calculation gives the 246-keV $E2$ transition probability based on the Guman *et al.* wave functions for the first three levels. As the wave functions for the first $6^+$ level were not presented by Guman *et al.*,[6] it was not possible, at this time, to determine the particle-surface coupling effect for the 46.7-keV $E2$ transition.

The two-particle wave functions coupled to the surface oscillation may be written as

$$|E,I\rangle=\sum_{j_1j_2}\frac{C^I(j_1j_2J;NR)}{[2+2\delta j_1j_2]^{\frac{1}{2}}}\{|[j_1,j_2]_J;NR\rangle - (-1)^{j_1+j_2-J}|[j_2,j_1]_J;NR\rangle\}, \quad (1)$$

where $j_1$ and $j_2$ denote the proton single-particle states. The $E2$ transition probability for a gamma ray of frequency $\omega$ is given by[13]

$$P(E2)=\frac{4\pi}{75}\left(\frac{\omega}{c}\right)^5\frac{B(E2)}{\hbar}. \quad (2)$$

The reduced transition probability (employing the angular momentum coupling rules of Rose[14]) is

$$B(E2)=\sum_{\mu M}\{C^{I2I'}_{M\mu M'}\}^2\cdot\sum_{\text{all } j}C^{I'}(j_{1'}j_{2'}J';N'R') \times C^I(j_1j_2J;NR)\cdot[\langle I':J';N'R'\|\mathfrak{M}_{\text{sp}}\|I:J;NR\rangle + \langle I':J';N'R'\|\mathfrak{M}_{\text{coll}}\|I:J;NR\rangle]^2. \quad (3)$$

The $E2$ operator, as given by Nilsson[15] for the independent particle part is

$$\mathfrak{M}_{\text{sp}}=e_{\text{eff}}\sum_{i=1}^{2}r_i^2Y_{2\mu}(\theta_i\phi_i);\quad e_{\text{eff}}=e\left(1+\frac{Z}{A^2}\right)\left(\frac{\hbar}{m\omega_0}\right)^{\frac{1}{2}}. \quad (4)$$

The collective part as given by Bohr[16] is

$$\mathfrak{M}_{\text{coll}}=\frac{3z}{4\pi}eR_0^2\left(\frac{\hbar\omega}{2C}\right)^{\frac{1}{2}}(b_\mu^2+(-1)^\mu b_{-\mu}^2). \quad (5)$$

For $E2$ transitions, one obtains

$$\langle I':J';N'R'\|\mathfrak{M}_{\text{sp}}\|I:J;NR\rangle=\delta_{RR'}\delta_{NN'}(-1)^{R+I}\left[\frac{(2J+1)(2J'+1)(2I+1)}{4\pi(1+\delta_{j_1j_2})(1+\delta_{j_{1'}j_{2'}})}\right]^{\frac{1}{2}} \times W(JI,J'I';R2)\{\langle J';j_{1'}j_{2'}\|\mathfrak{M}_{\text{sp}}\|J;j_1j_2\rangle-(-1)^{j_{1'}+j_{2'}-J'}\langle J';j_{2'}j_{1'}\|\mathfrak{M}_{\text{sp}}\|J;j_1j_2\rangle - (-1)^{j_1+j_2-J}\langle J';j_{1'}j_{2'}\|\mathfrak{M}_{\text{sp}}\|J;j_1j_2\rangle+(-1)^{j_1+j_2-J+j_{1'}+j_{2'}-J'}\langle J';j_{2'}j_{1'}\|\mathfrak{M}_{\text{sp}}\|J;j_2j_1\rangle\} \quad (6)$$

and

$$\langle J';j_ij_k\|\mathfrak{M}_{\text{sp}}\|J;j_mj_n\rangle=e_{\text{eff}}\delta_{jkjn}(-1)^{j_n-\frac{1}{2}}[(2j_n+1)(2j_i+1)]^{\frac{1}{2}}C^{j_mj_i2}_{\frac{1}{2}-\frac{1}{2}0}W(j_mJ,j_iJ';j_n2)(\gamma_il_i\|r^2\|\gamma_ml_m); \quad (7)$$

$$\langle I':J',N'R'\|\mathfrak{M}_{\text{coll}}\|I:J,NR\rangle=\frac{3z}{4\pi}eR_0^2\left(\frac{\hbar\omega}{2C}\right)^{\frac{1}{2}}\delta_{JJ'}\delta_{j_1j_{2'}}\delta_{j_1j_{2'}}(-1)^{J+I}(2I+1)^{\frac{1}{2}}W(R'RI'I;2J) \times[(-1)^{-R}(2R'+1)^{\frac{1}{2}}(N'R'\|b_2\|NR)+(-1)^{-R'}(2R+1)^{\frac{1}{2}}(NR\|b_2\|N'R')], \quad (8)$$

where the $(NR\|b_2\|N'R')$ are those of Choudhury,[17] the radial matrix elements are given in (15), the $C^{j_mj_i2}_{\frac{1}{2}-\frac{1}{2}0}$ is a Clebsch-Gordan coefficient, and the $W(j_m,J;j_i,J':j_n,2)$ is a Racah coefficient.

For the calculation, the collective excitation energy $\hbar\omega$ was taken as 1.3 MeV, the effective surface tension parameter $C$ was chosen to be 75 MeV and the nuclear radius $R_0$ as $1.25A^{1/3}\times10^{-13}$ cm consistent with Guman *et al.*[6] Table III presents the observed transition probabilities, the calculated transition probabilities based on configuration-mixed wave functions of Newby and Konopinski, and the 246-keV $E2$ transition probabilities based on the wave functions of Guman *et al.*

As can be seen in Table III, for the case of 246-keV transition, both types of calculated transition probabilities are in approximate agreement with the observed value. The calculated transition probability including collective effects characterized by single-phonon

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TABLE III. Comparison of the observed transition probabilities with calculated transition probabilities for the 246 and 46.7 keV $E2$ transitions.

| Energy (keV) | Angular momentum Initial | Final | $P_{(\mathrm{obs})}{}^{(\mathrm{sec}^{-1})}$ | $P_{\mathrm{sp}}{}^{(\mathrm{sec}^{-1})\mathrm{a}}$ | $P_{\mathrm{coll}}{}^{(\mathrm{sec}^{-1})\mathrm{b}}$ |
|---|---|---|---|---|---|
| 246 | 4 | 2 | $3.1\pm0.4\times10^8$ | $0.272\times10^8$ | $0.412\times10^8$ |
| 46.7 | 6 | 4 | $5.4\pm0.7\times10^4$ | $0.264\times10^4$ | c |

a Interacting particle calculations using the wave functions from Ref. 5.
b Collective calculations using the wave functions from Ref. 6.
c Wave function for the $6^+$ level were not available in (6).

states shows some improvement over the other, which includes configuration mixing effects only. The 46.7-keV transition probability as calculated, including only configuration mixing effects, is not in as good agreement as that of the 246-keV transition.

There is still an enhancement factor unaccounted for. This enhancement may be explained through a recent approach,[18] which employs a modified Brueckner-Gammel-Thaler[19] two nucleon potential in the determination of the configuration mixing for the first excited states of $Po^{210}$. Another possibility, under present investigation, is that of a pairing interaction effect,[20,21] in the quasiparticle approximation.

*Note added in proof.* Since the submission of this paper, Kim and Rasmussen[22] have published wave functions for $Po^{210}$ and computed $E2$ transition probabilities using an effective charge of 1.814$e$. In our calculations, the effective charge is taken to be 1.002$e$. The values of the ratio $P(E2)_{\mathrm{obs}}/P(E2)_{\mathrm{cal}}$ for the 246-keV transition are 11.4, 7.5, and 11.2 using the wave functions of Newby and Konopinski, Guman *et al.*, and Kim and Rasmussen, respectively.

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# Absolute Positive Pion Photoproduction Cross Sections from Hydrogen*

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Absolute differential cross sections for the photoproduction of pions of 33.8-MeV laboratory kinetic energy from protons were measured at eight angles between 29.5 and 146.1° in the center-of-mass system. The over-all absolute accuracy is 4%, while the relative accuracy within the angular distribution is 3%. Comparison is made to various theoretical calculations, with and without inclusion of the effect of a $\gamma$-$\pi$-$\rho$-meson coupling. Existing calculations based on dispersion theory give only fair agreement with the data.

## I. INTRODUCTION

DURING the past several years considerable refinement has been achieved in the theory in the theory of the reaction

$$\gamma+p\rightarrow\pi^{+}+n$$

at energies below the $T=\frac{3}{2}$, $J=\frac{3}{2}$ resonance. Arguments based on dispersion theory, such as those of Chew, Goldberger, Low, and Nambu[1] lead to detailed predictions for the absolute differential cross sections in terms of the pion-nucleon scattering phase shifts, and the pion-nucleon coupling constant. Ball,[2] and more recently McKinley,[3] have attempted to introduce the effect of a $\gamma$-$\pi$-$\rho$-meson coupling into dispersion-theory calculations. The new theoretical work encouraged this attempt

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