Energy Levels of Polonium-210*

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The energy levels of Po^{210} have been studied as populated by the electron-capture decay of At^{210}. An experimental level scheme has been constructed by using data obtained from conversion electron and gamma-ray measurements made with beta-ray and scintillation spectrometers and coincidence counting techniques. A theory of the energy levels of Po^{210} has been developed using the method of Pryce to predict the levels of a nucleus containing two odd protons beyond the double-closed shell from the experimentally known levels of Bi^{209}, the nucleus containing a single odd proton beyond the closed shell. Certain features of the theoretically predicted level scheme and the experimental level scheme show reasonable agreement. The spin assignment for At^{210} has been discussed with respect to the log*ft* values for its electron capture decay.

1. INTRODUCTION

THE study of energy level schemes of nuclei in the immediate vicinity of the double-closed shell at ${}_{82}Pb_{126}{}^{208}$ is of fundamental interest since here the collective aspects of nuclear structure are expected to be at a minimum and therefore the manifestations of single-particle behavior should be most clearly in evidence. Nuclei consisting of a single particle or "hole" in the double-closed shell are Pb^{207}, Pb^{209}, Tl^{207}, and Bi^{209}; of these the levels of the single neutron "hole" (Pb^{207}) have been well defined as the result of extensive studies[1] of the decay of Bi^{207} and Pb^{207m}. Using the known Pb^{207} level system as a basis for theoretical calculation, Alburger and Pryce[2] have carried out also an experimental-theoretical study of the "two-hole" nucleus, Pb^{206}, observed from the decay of Bi^{206}. The success of their approach, in spite of the necessarily approximate assumptions, indicates the feasibility of gaining information about other "two-particle" nuclei in like manner.

We have applied similar techniques to a study of the levels of Po^{210}, a nucleus composed of two protons plus the Pb^{208} core. The properties of these levels can be studied conveniently through the electron-capture decay of At^{210}. Closed-decay-cycle calculations[3] predict approximately 4-Mev electron-capture disintegration energy for this nuclide and its 8.3-hour half-life[4] allows an intensive study to be made of its decay properties. Other radioactive nuclides which decay to Po^{210} yield little information since the alpha-decay parent, Em^{214}, is unknown and the beta disintegration energy of RaE (Bi^{210}), 1.17 Mev,[4] is insufficient to populate even the first excited level of Po^{210}.

The experimental work reported here was begun in 1952 and a preliminary report has been issued previously.[5] The present paper contains information on the level structure of Po^{210} obtained from conversion electron and gamma-ray measurements made with beta-ray and scintillation spectrometers and coincidence counting techniques. Our experimental data are in agreement for the most part with the results reported recently by Mihelich *et al.*[6] although additional information was gained in the present work through the use of more intense samples of $At^{210,211}$ which were almost completely free of At^{209}.

A theory of the energy levels of Po^{210} has been developed by use of the method of Pryce[7] and experimental data available on the excited levels of Bi^{209}. Although complete correlation between the theoretically predicted level scheme and the experimental data has not been achieved, certain features of the theoretical level scheme agree surprisingly well with the experimental level scheme. The complexity of the level structure of Po^{210} is indicated by the large number of weak and unassigned conversion electrons observed in the experimental study.

2. ISOTOPE PRODUCTION

The astatine samples used for this study were produced by helium-ion bombardments of bismuth in the Crocker laboratory 60-inch cyclotron. At a bombarding particle energy of 38 Mev, the yield of At^{210} produced via the $(\alpha,3n)$ reaction on the Bi^{209} target material is near the maximum while the yield of the $(\alpha,4n)$ reaction is extremely low.[8] Thus astatine samples were produced containing isotopes of mass numbers 210, 211, and 212, the latter two from $(\alpha,2n)$ and (α,n) reactions. Neither of these isotopes interferes with a study of At^{210} since At^{212} has a half-life of only 0.22 second[4] and At^{211} produces only extremely low intensity gamma rays and conversion electrons besides the x-rays and Auger electrons which result from electron capture.[6,9] A series of bombardments of bismuth with 48-Mev helium ions

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] D. E. Alburger and A. W. Sunyar, Phys. Rev. **99**, 695 (1955).
[2] D. E. Alburger and M. H. L. Pryce, Phys. Rev. **95**, 1482 (1954).
[3] Glass, Thompson, and Seaborg, J. Inorg. & Nuclear Chem. **1**, 3 (1955).
[4] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[5] R. W. Hoff, University of California Radiation Laboratory Report UCRL-2325, September, 1953 (unpublished).
[6] Mihelich, Schardt, and Segrè, Phys. Rev. **95**, 1508 (1954).
[7] M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773 (1952).
[8] E. L. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).
[9] P. R. Gray, Phys. Rev. **101**, 1306 (1956).

TABLE I. Conversion lines observed from At^{210} decay.

Electron energy (kev)	Shell	Transition energy (kev)	Relative intensity: Perm.-mag. spectr. 100 gauss	Perm.-mag. spectr. 340 gauss	$\pi\sqrt{2}$ spectr.	Lens spectr.	Remarks
29.54	L_I	46.47	vw				
30.28	L_{II}	46.51	vvs		57		
32.72	L_{III}	46.53	vvs		41		
42.62	M_{II}	46.46	vs		28		
43.16	M_{III}	46.45	vs				
45.60	N_{II}	46.45	s				
45.75	N_{III}	46.46	s		6.8		
46.37	O_{II}	46.5	m				$E_\gamma = 46.48$ kev
67.22	L_{II}	83.45	m				
69.62	L_{III}	83.43	m				
79.59	M_{II}	83.43	w				
80.14	M_{III}	83.43	vw				$E_\gamma = 83.44$ kev
23.05	K	116.2	s		25		
99.10	L_I	116.0	s		4.3		
99.75	L_{II}	116.0	w				
112.0	M_I	116.1	m		3.5		
115.2	N_I	116.2	vw				$E_\gamma = 116.1$ kev
32.06	K	125.2	vw				
108.3	L_I	125.2	w				
108.9	L_{II}	125.1	w				$E_\gamma = 125.2$ kev
101.8	K	194.9	w				$E_\gamma = 194.9$ kev (most intense line of At^{209})
152.3	K	245.4	vvs		26		
228.1	L_I	245.0	m				
228.9	L_{II}	245.1	s		22		
231.3	L_{III}	245.1	ms				
241.1	M_{II}	244.9	m				
241.7	M_{III}	245.0	w		6.8		
244.2	N_{II}	245.0	wm				
244.8	O_{II}	244.9	vw				$E_\gamma = 245.1$ kev
309.2	K	402.3		s		0.37	
385.1	L_I	402.0		m			
397.8	M_I	402.0		vw			$E_\gamma = 402.1$ kev
759.7	K	852.9		w			
836.5	L_I	853.4		vvw			$E_\gamma = 853$ kev
1087.9	K	1181.1		m	(1.6)	(1.6)	$\pi\sqrt{2}$ and lens intensities normalized here.
1164.5	L_I	1181.4		w	0.32		
1176.7	M_I	1180.9		vvw			$E_\gamma = 1181$ kev
1343	K	1436		vw	0.21	0.12	$E_\gamma = 1436$ kev
1389	K	1482		vw		0.16	$E_\gamma = 1482$ kev
~1505	K	1598		...			$E_\gamma = 1598$; observed only in lens spectr.

has been made by Stoner[10] to study the decay properties of At^{209}; direct comparison of his results with our data on At^{210} has enabled us to make definite assignments of gamma rays and internal conversion electron lines to the decay of At^{210}.

The targets were made by melting pure bismuth metal[11] onto a 0.010-inch aluminum plate in a layer 0.050 inch thick. The target plate was mounted so as to intercept the deflected beam of the cyclotron after its energy had been degraded to the desired value by means of 0.001-inch aluminum absorbers. Water-cooling of the back of the target plate and a beam limit of 15 microamperes were necessary to prevent overheating of the target and subsequent loss of astatine by volatilization.

Following bombardment, chemical purification was obtained by volatilization of the astatine from the bismuth targets. The bismuth metal was heated above its melting point to 300–350°C, at which temperatures the astatine distilled onto a water-cooled 0.25-mil platinum foil. When necessary, a collimator was used in the volatilizer to produce line sources for beta spectroscopy. Another method of producing line sources which gave excellent results involved the distillation of astatine from the target onto a layer of frost on a glass finger cooled with liquid nitrogen.[9] The frost was rinsed into a centrifuge cone with dilute perchloric acid, and the astatine was chemically plated onto a 10-mil silver wire by placing the wire into the solution and stirring for an hour. These wires were then mounted directly in the appropriate permanent-magnet beta spectrographs.

3. INTERNAL CONVERSION SPECTRUM

A study was made of the internal conversion electron spectrum of At^{210}, using a number of instruments. Four 180° permanent-magnet photographic-recording spectrographs which operate at ~0.1% resolution were used to make energy determinations of the conversion electron lines. The stability of the magnetic field (under proper temperature regulation) and the high resolution of these instruments permit accurate energy measurements to be made. An electron energy range from 10 to 1600 kev was examined with magnets with field strengths of 53, 100, 215, and 340 gauss. The experimental techniques and energy calibrations used in the operation of the permanent-magnet spectrographs have been described previously.[12]

Unfortunately, it was not possible to measure relative conversion-line intensities from the permanent-magnet spectrograph plates by densitometry because of high photographic backgrounds apparently caused by diffusion of astatine off the source wires. Intensity measurements of the more abundant electron lines were made

TABLE II. At^{210} conversion lines with doubtful assignments.

Electron energy (kev)	Shell	Transition energy (kev)	Visual intensity: 100 gauss	215 gauss	340 gauss
71.77			wm		
75.76	L_{II}	91.99	wm		
78.32	L_{III}	92.12	w		
95.27			vw		
157.1			w	wm	
184.7				w	
205.4	K	298.5		vw	
223.3				vw	
282.4	L_{II}	298.6			vw
406.3	K	499.5			w
522.0	K	615.2			w
529.3					vw
537.8					vw
542.5					vw
608.8	K	702.0			vw
724.3	K	817.5			wm
863.0					w

[10] A. W. Stoner, University of California Radiation Laboratory Report UCRL-3471, June, 1956 (unpublished).

[11] Limits on impurities: As 0.0001%, Sb 0.01%, Fe 0.002%, Cu 0.005%.

[12] W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956).

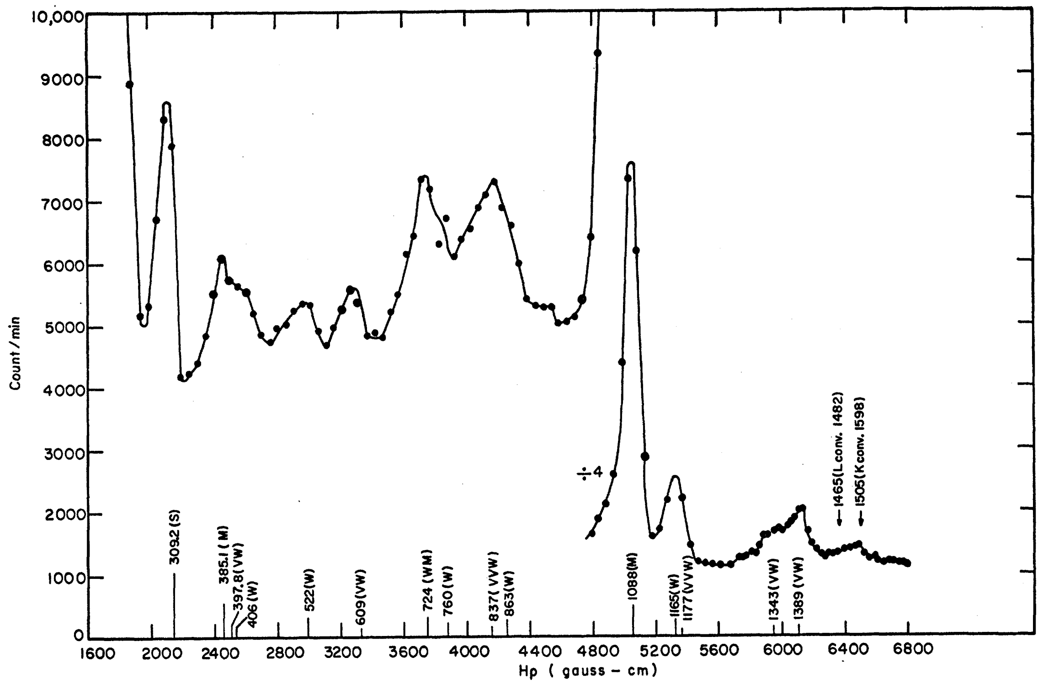

FIG. 1. Conversion electron spectrum of At^{210} from 300 to 1600 kev.

with a $\pi\sqrt{2}$ double-focusing beta spectrometer,[13,14] which now operates at ~0.3% resolution and utilizes a Geiger-Mueller counter detector whose window absorption for electrons of energies greater than 20 kev is negligible. Intensities of some of the weaker lines were also measured in a magnetic lens spectrometer of ~2% resolution by virtue of its increased transmission over the double-focusing spectrometer.

The energies and intensities of the more abundant conversion electrons are listed in Table I. Binding energies for the electron shells in polonium were taken from the compilation of Hill, Church, and Mihelich.[15] Not included in the table are the *K* Auger electrons arising from the $At^{210,211}$ electron capture which were observed but are not pertinent to this discussion of the decay of At^{210}. The less intense electron lines with probable assignments, where made, are listed in Table II. The relative visual intensity estimates of lines observed in the permanent-magnet spectrographs are meaningful only for a given plate, and hence in Table I the intensity figures from several different exposures are listed in separate columns.[16] For comparison, the conversion electron spectrum obtained with the lens spectrometer in the range 300–1600 kev is shown in Fig. 1, together with the permanent-magnet lines in that interval. It is believed that the accuracy of the electron line energies determined in the permanent-magnet spectrographs is better than 0.2%.

Assignment to At^{210} of all electron lines in Tables I and II is considered to be definite since it was possible to compare the At^{210} plates with plates obtained in the same instruments, from a sample containing both At^{209} and At^{210} in comparable amounts. Many extremely weak lines observed in only one plate have not been included in the tables due to our lack of confidence in their actual existence. The possibility of lines being due to daughter products and impurities (At^{211}, Po^{210}, Po^{211}, Bi^{206}, Bi^{207}, neutron-deficient bromine and iodine isotopes) was also considered, but no lines were found that could be attributable to any of these sources.

It has been found that the 83.4-kev transition listed in Table I, which was assigned to At^{209} decay by Mihelich *et al.*,[6] occurs instead in the decay of At^{210}. Also, a 90.8-kev transition is known[6] to occur in the decay of At^{209}, but this is not to be confused with the "probable" transition of 92.0 kev listed in Table II; the assignment is uncertain but the lines definitely belong to At^{210}. An indication of the slight amount of At^{209} in our "pure" At^{210} samples is given by our observation of the most intense At^{209} line (*K* line of the 195-kev transition[6]) as a "weak" line in the At^{210} spectrum.

4. GAMMA-RAY SPECTRUM

The gamma-ray spectrum of an $At^{210,211}$ mixture was measured with a sodium iodide crystal scintillation spectrometer. The detector was a cylinder of sodium

[13] G. D. O'Kelley, University of California Radiation Laboratory Report UCRL-1243, June, 1951 (unpublished).

[14] T. O. Passell, University of California Radiation Laboratory Report UCRL-2528, March, 1954 (unpublished).

[15] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).

[16] It should also be noted that visual intensity estimates are comparable only for electron lines of similar energies because of the variation of efficiency of the emulsion with electron energy and the dependence of line intensity upon ρ.

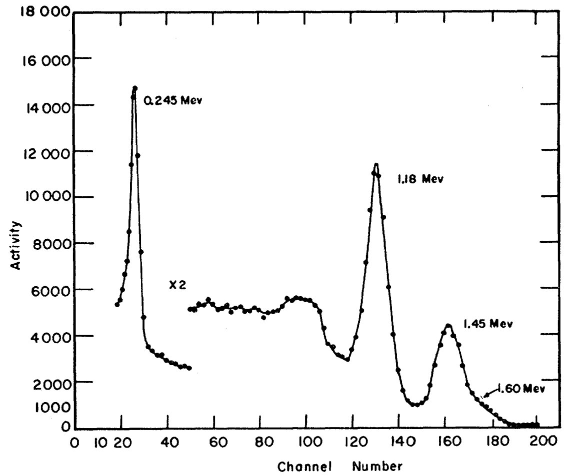

FIG. 2. Photon spectrum of At^{210} from 200 to 1700 kev.

iodide (thallium-activated), 4.5 cm in diameter and 5.2 cm high, optically connected to an RCA 6655 photomultiplier. The signal from the photomultiplier was preamplified and fed directly into a 256-channel differential pulse-height analyzer.[17] Gamma rays were observed at 0.245, 1.18, 1.45, and 1.60 Mev, in addition to the K and L x-rays of polonium (Figs. 2 and 3). The photopeak at 1.45 Mev consists mainly of unresolved contributions from the two gamma rays at 1.436 and 1.482 Mev (see Table I). The relative intensities of the most prominent photons were measured with the sample approximately 4 cm from the sodium iodide crystal; using experimentally determined counting efficiencies and photopeak yields for this crystal,[18] we calculate the following relative intensities: 0.245 Mev : 1.18 Mev : 1.45 Mev : 1.60 Mev$=0.81 \pm 0.08 : 1.00 \pm 0.09 : 0.61 \pm 0.08 : 0.18 \pm 0.03$.

Figure 3 shows the gamma-ray spectrum in the higher energy region. Possible photopeaks from gamma rays at 2.2 and 2.6 Mev are seen, although they may in part be due to the simultaneous detection in the crystal of the two intense gamma rays at 1.18 and 1.45 Mev. Photons from the less intense transitions such as the 116 and 402 kev were not observed in the gamma-ray spectrum, the former probably being obscured by the very abundant polonium K x-rays.

5. COINCIDENCE MEASUREMENTS

Coincidence measurements have been performed between various pairs of At^{210} gamma rays in an attempt to place the observed transitions in the Po^{210} level scheme. Two 1-inch$\times 1\frac{1}{2}$-inch diameter sodium iodide (thallium-activated) crystals, optically mounted to Dumont 6292 photomultipliers, were used as detectors. The signal from each photomultiplier was amplified in a suitable preamplifier and linear amplifier and was then fed to a coincidence unit of 20-μsec resolving time. The signal from the gate crystal was analyzed with a single-channel analyzer whose output was also fed to the coincidence unit. The output of the coincidence unit was used to gate a 50-channel differential pulse-height analyzer whose input was fed directly from the signal crystal.

Gamma rays of 0.245 Mev, 1.18 Mev, and the 1.436–1.482 Mev pair were all found to be in coincidence with each other, in agreement with the observations of Mihelich *et al.*[6] The coincidence information, coupled with intensity considerations, suggested that these transitions be placed as shown in Fig. 4. As mentioned by Mihelich *et al.*,[6] it is more reasonable that the 46.5-kev transition follow the 1436-kev transition rather than precede it; otherwise there would have to be approximately equal competition between the 46.5-kev and the 1482-kev transition. Such competition is unexpected although not impossible.

Some conversion electron-photon coincidence measurements were also made with a sodium iodide crystal as the gamma-ray detector and a magnetic-lens beta spectrometer with an anthracene crystal as the detector of focused electrons. The signal from the sodium iodide crystal was fed through a single-channel, pulse-height selector which was set to accept only pulses from the photopeaks of the 1.436–1.482 Mev pair with some contribution from the 1.6-Mev gamma ray. To accommodate high counting rates, a fast-slow coincidence arrangement was used with a 5.5×10^{-8}-second resolving time in the fast coincidence unit. With this equipment, definite coincidence rates were observed between the 1.436, 1.482 (and 1.6) Mev "gate" pulses and the 0.245-Mev, 0.402-Mev, and 1.181-Mev transitions. A rather

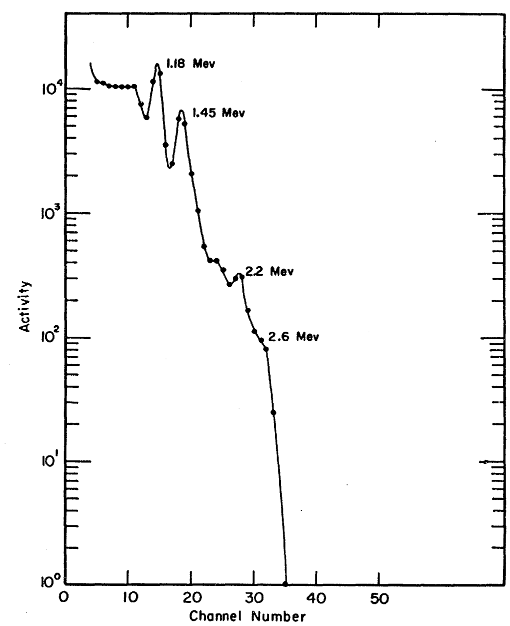

FIG. 3. Photon spectrum of At^{210} from 1 to 3 Mev.

[17] R. W. Schumann and J. P. McMahon, Rev. Sci. Instr. 27, 675 (1956).
[18] H. I. West (private communication).

TABLE III. Transition intensities and multipolarities.

E_γ (kev)	Conversion electron ratios and conversion coefficients	Exptl. value	Theoretical values $E1$	$E2$	$M1$	$M2$	Multipolarity	Transition intensity (this work)	Transition intensity (Mihelich *et al.*[a])
46.5	$L_{I}+L_{II}/L_{III}$ conversion ratio	57/41	2/1	103/100	13/0	17/6	$E2$	44	34
	$L_{I}/L_{II}/L_{III}$ conversion ratio	vw/vvs/vvs	1/1/1	3/100/100	12/1/0	16/1/6			
83.4	$L_{I}/L_{II}/L_{III}$ conversion ratio	···/m/m	20/10/12	5/100/100	12/1/0	11/1/3	$E2$	···	
116.1	$L_{I}/L_{II}/L_{III}$ conversion ratio	s/w/···	30/10/12	1/20/12	12/1/0	80/10/16	$M1$	12	5
	K/L conversion ratio	5.9	5.3	<1	5.7	3			
125.2	$L_{I}/L_{II}/L_{III}$ conversion ratio	vw/w/w	3/1/1	6/100/55	12/1/0	45/5/9	$E2$	···	
245.1	$L_{I}/L_{II}/L_{III}$ conversion ratio	m/s/ms	5/10/1	10/50/16	12/1/0	100/12/10	$E2$	97	99
	K conversion coefficient	1.1×10^{-1}	4×10^{-2}	1×10^{-1}	1	3			
	K/L conversion ratio	1.2	5.4	1.0	5.5	3.5			
402.1	K conversion coefficient	$\geq3.5\times10^{-2}$	1.3×10^{-2}	3.5×10^{-2}	2.4×10^{-1}	6×10^{-1}	not $E1$	≤4	···
1181	K conversion coefficient	4.7×10^{-3}	1.7×10^{-3}	4.3×10^{-3}	1.0×10^{-2}	2.5×10^{-2}	$E2$	100	100
	K/L conversion ratio	4.7	5	5	>6	5			
1436 and 1482	K conversion coefficient	1.2×10^{-3}	1.2×10^{-3}	2.5×10^{-3}	6×10^{-3}	1.4×10^{-2}	$E1$	61	1436–35 1482–48
1598	···	···	···	···	···	···	($E1$)	18	19

[a] See reference 6.

tentative result indicates that the 702-kev transition (K conversion electron at 609 kev) is also in coincidence with the 1.436-, 1.482-Mev "gate" pulses.

6. TRANSITION INTENSITIES AND MULTIPOLARITIES

In Table III we have summarized the experimental data on conversion electron ratios and conversion coefficients for the transitions in the level scheme of Po^{210}. It is possible on the basis of these data to assign multipolarities for most of the transitions. Theoretical values of the K conversion coefficients, K/L conversion ratios, and L-shell conversion ratios have been obtained from the work of Sliv[19] and Rose *et al.*[20]

The L-subshell conversion pattern of low-energy transitions depends quite sensitively upon the multipole order. Hence, observation of the L-subshell conversion ratios often allows definite assignments to be made even in the absence of total conversion coefficient information. The 46.5-kev transition from At^{210} decay, for example, displays the pattern associated with low-energy $E2$ transitions of high Z, that of approximately equal L_{II} and L_{III} conversion and very much less L_{I} conversion. Similarly, the conversion electrons associated with the 83.4-kev and 125.2-kev transitions show patterns characteristic of $E2$ radiation. The possibility of appreciable admixtures of magnetic dipole radiation can be eliminated, since for this type of radiation, L_{I} shell conversion predominates.

The 116.1-kev transition is assigned as an $M1$ on the basis both of its L-subshell pattern and K/L conversion ratio. L_{III} conversion is not observed; hence $E2$ admixture in this transition is either very small or absent.

The 245.1-kev transition, from its L-subshell pattern, K shell conversion coefficient, and K/L conversion ratio, is classified as predominantly $E2$ radiation. Although we do not have a quantitative L_{I}/L_{II} ratio,

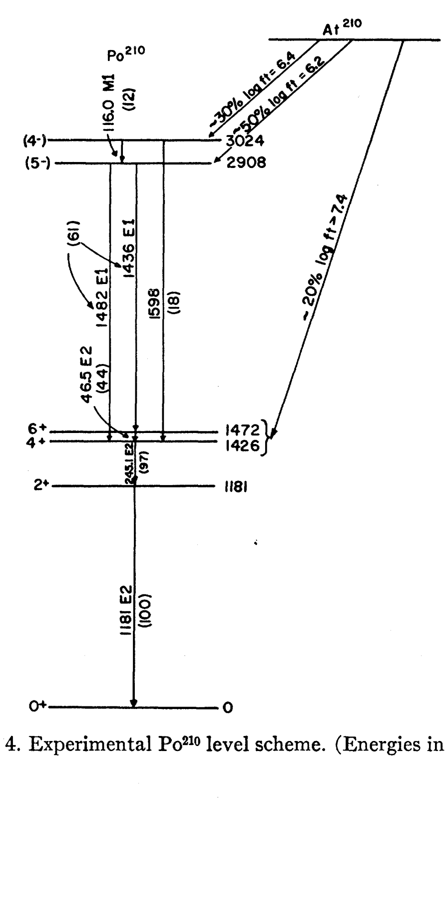

FIG. 4. Experimental Po^{210} level scheme. (Energies in kev.)

[19] L. A. Sliv (privately circulated tables of relativistic screened K conversion coefficients for nuclei of finite size).

[20] Rose, Goertzel, and Perry, Oak Ridge Laboratory Report ORNL-1023 (unpublished); M. E. Rose, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. XIV.

it appears from the qualitative observation that $M1$ admixture is small, probably less than 15%. The K conversion coefficient and the K/L conversion ratio also compare closely with theoretical values for $E2$ radiation and indicate that the transition is fairly "pure."

Conversion electrons only have been observed for the 402.1-kev transition. However, a limit can be set upon the amount of gamma radiation and therefore a lower limit, 3.5×10^{-2}, can be set on the K conversion coefficient. This eliminates an $E1$ assignment for this transition.

The 1181-kev transition, from its K conversion coefficient, is classified as an $E2$ transition. The K/L conversion ratio, although in agreement with the $E2$ designation, is not particularly sensitive to multipolarity for transitions of this energy.

The K conversion coefficient for the combination of the 1436-kev and 1482-kev transitions is equal to the theoretical value for an $E1$ transition of this energy. This fact, coupled with the comparable intensities of the K conversion lines of these transitions, indicates that both are almost certainly electric dipole transitions.

The above data are in complete agreement with the multipolarity information of Mihelich *et al.*[6] for the transitions discussed.

The transition intensities, listed in the next to last column of Table III, have been derived from data on relative intensities of gamma rays and conversion electrons plus experimental and theoretical conversion coefficients. The intensities of the 245.1-, 1181-, 1436-, 1482-, and 1598-kev transitions have been calculated directly from experimental data and are normalized to 100% for the 1181-kev transition. The intensity of the 46.5-kev transition has been calculated from experimental conversion electron intensities, since the theoretical L conversion coefficient for an $E2$ transition of this energy is approximately 300 and therefore the photon intensity is negligible. The intensity of the 116.1-kev transition has been derived from the experimental conversion electron intensity and the theoretical K conversion coefficient for an $M1$ transition of this energy. An upper limit has been set on the intensity of the 402.1-kev transition from the upper limit of the K conversion coefficient and the experimental conversion electron intensity.

In the last column of Table III we give the transition intensities as measured by Mihelich *et al.*[6] For the most part, our intensity data agree well with theirs. However, there are some discrepancies, particularly in the relative abundances of the 1436-, 1482-kev transitions and the 116.1-kev transition, whose principal effect is to change the relative amounts of electron capture branching of At^{210} to the various levels of Po^{210}.

TABLE IV. Bi^{209} levels.

Level configuration	Energy (Mev)
$h_{9/2}$	0
$f_{7/2}$	0.90
$i_{13/2}$	1.60

7. EXPERIMENTAL LEVEL SCHEME

An experimental level scheme for Po^{210} consistent with coincidence measurements, total transition intensities, and energy sums is shown in Fig. 4.

Because Po^{210} is an even-even nucleus with ground state spin 0+, the $E2$ nature of the 1.181-Mev transition determines uniquely the 2+ character of the first excited state. The spin of the second excited state could be either 4+, 2+, or 0+, and has been shown by the angular correlation experiments of Mihelich *et al.*,[6] to be 4+. The 46.5-kev transition, de-exciting the 1.472-Mev level, is also electric quadrupole. Although Mihelich *et al.*[6] have assigned to this level a spin and parity of 4+, their angular correlation experiments do not eliminate the possibility of a 6+ designation, and it will be seen that the latter assignment is preferred from theoretical considerations. The levels at 2.908 and 3.024 Mev have odd parity as evidenced by the $E1$ character of the 1.436- and 1.482-Mev transitions and the $M1$ character of the 0.116-Mev transition. We are unable to place uniquely in the level scheme many of the weak transitions listed in Tables I and II.

8. THEORETICAL LEVEL SCHEME

We have used the method of Pryce[7] to calculate a theoretical level scheme for Po^{210} from the known levels of Bi^{209}. It is assumed that the levels of Bi^{209} arise from excitations of a single proton outside the double-closed shell core of Pb^{208}. All possible double combinations of these proton levels are constructed for Po^{210}, taking into account the interaction energy between the two protons but neglecting configuration interaction and Coulomb interaction.

Existing data on the Bi^{209} levels come mostly from inelastic neutron scattering experiments[21]; we have listed in Table IV the ground state and first two excited states. The ground state is known experimentally[22] to have spin 9/2 and hence probably has the configuration $h_{9/2}$. The first excited state at 0.90 Mev de-excites by magnetic dipole radiation[23]; of the possible spins 7/2, 9/2, and 11/2, only 7/2 is found among the group of states available from the single-particle model ($f_{7/2}$, $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, $i_{13/2}$). Thus, we place the $f_{7/2}$ level at 0.90 Mev. The assignment of a configuration to the second excited state at 1.6 Mev is less certain, but the observation[23] of a transition from this state to ground (9/2) but not to the first excited state (7/2) indicates that the spin of

[21] M. A. Rothman and C. E. Mandeville, Phys. Rev. **93**, 793 (1954); Eliot, Hicks, Beghian, and Halban, Phys. Rev. **94**, 144 (1954); R. M. Kiehn and C. Goodman, Phys. Rev. **95**, 989 (1954); Scherrer, Allison, and Faust, Phys. Rev. **96**, 386 (1954).
[22] J. E. Mack, Revs. Modern Phys. **22**, 64 (1950).
[23] F. Asaro (private communication).

the second excited state is high. It seems reasonable, therefore, to postulate that this is the $i_{13/2}$ state.

Taking these lowest three configurations for the 83rd proton, one calculates, using vector addition, the energies of a number of levels of different spins for Po^{210}. If there were no interaction between the two odd protons of Po^{210}, each level would have an energy just equal to the sum of the energies of the two Bi^{209} levels from which it arises. Because of the interaction, however, some levels are depressed while others remain unshifted. We have listed in Table V the possible Po^{210} configurations thus obtained with their spins, parities, and energies uncorrected for the proton-proton interaction.

The interaction energy for two like nucleons is $2\alpha P(I; l,l')\epsilon_s$, in the notation of reference 7. All factors in this expression except ϵ_s are evaluated from the orbital angular momentum and total angular momentum of each proton and the resultant angular momentum of the coupled protons. The quantity ϵ_s must be estimated from theory and is determined by the degree of overlap of the radial wave functions of the protons and by the strength of the proton-proton interaction. While Alburger and Pryce[2] have estimated ϵ for each configuration in constructing the level scheme of Pb^{206}, we have taken an average value of $\epsilon = 0.3$ Mev for all configurations. The interaction energy and total energy for each level of Po^{210} are now obtained, and are given in Table VI. The ground state of Po^{210} is that in which both of the odd protons have an $h_{9/2}$ configuration. The interaction energy for the lowest level of this configuration, the 0+ state, depresses the total energy approximately 1.5 Mev. This is taken to be the ground state of Po^{210} and each energy level listed in the last column of Table VI is adjusted to this zero energy. Two-proton configurations including unknown excited levels of Bi^{209} with energy greater than the $i_{13/2}$ level have not been included in Table VI, but it can be seen that the minimum unshifted energy for such configurations would be greater than 3.1 Mev on the adjusted energy scale.

In addition to the levels calculated as described above, excited levels will occur in Po^{210} due to the excitation of the Pb^{208} core. The first two excited levels of Pb^{208} are at 2.615 Mev ($I = 3-$) and 3.198 Mev ($I = 5-$).[24] These

TABLE V. Po^{210} proton configurations.

Configuration	Unshifted energy, Mev	Spins	Parity
$h_{9/2}^2$	0	0, 2, 4, 6, 8	+
$h_{9/2}f_{7/2}$	0.90	1, 2, 3···8	+
$h_{9/2}i_{13/2}$	1.60	2, 3, 4···11	−
$f_{7/2}^2$	1.80	0, 2, 4, 6	+
$f_{7/2}i_{13/2}$	2.50	3, 4, 5···10	−
$i_{13/2}^2$	3.20	0, 2, 4···12	+

[24] Elliot, Graham, Walker, and Wolfson, Phys. Rev. **93**, 356 (1954).

TABLE VI. Calculated energies of Po^{210} levels.[a]

Configuration	Parity	Energy (uncorr.) (Mev)	Spin	Interaction coeff, $2\alpha P$	Interaction energy, $2\alpha P\epsilon$	Total energy	Total energy[b]
$h_{9/2}^2$	+	0	0	5	−1.5 Mev	−1.5	0
		0	2	1.2	−0.36	−0.36	1.14
		0	4	0.68	−0.20	−0.20	1.30
		0	6	0.37	−0.11	−0.11	1.39
		0	8	0.20	−0.06	−0.06	1.44
$h_{9/2}f_{7/2}$	+	0.90	1	0	0	0.90	2.40
		0.90	2	0.17	−0.05	0.85	2.35
		0.90	3	0	0	0.90	2.40
		0.90	4	0.36	−0.11	0.79	2.29
		0.90	5	0	0	0.90	2.40
		0.90	6	0.65	−0.20	0.70	2.20
		0.90	7	0	0	0.90	2.40
		0.90	8	1.6	−0.48	0.42	1.92
$h_{9/2}i_{13/2}$	−	1.60	2	0	0	1.60	3.10
		1.60	3	0.16	−0.05	1.55	3.05
		1.60	4	0	0	1.60	3.10
		1.60	5	0.31	−0.09	1.51	3.01
		1.60	6	0	0	1.60	3.10
		1.60	7	0.50	−0.15	1.45	2.95
		1.60	8	0	0	1.60	3.10
		1.60	9	···	···	···	···
		1.60	10	0	0	1.60	3.10
		1.60	11	···	···	···	···
$f_{7/2}^2$	+	1.80	0	4	−1.2	0.60	2.10
		1.80	2	0.95	−0.29	1.51	3.01
		1.80	4	0.47	−0.14	1.66	3.16
		1.80	6	0.23	−0.07	1.73	3.23
$f_{7/2}i_{13/2}$	−	2.50	3	3.3	−1.0	1.50	3.00
		2.50	4	0	0	2.50	4.00
		2.50	5	1.3	−0.39	2.11	3.61
		2.50	6	0	0	2.50	4.00
		2.50	7	0.75	−0.23	2.27	3.77
		2.50	8	0	0	2.50	4.00
		2.50	9	···	···	···	···
		2.50	10	0	0	2.50	4.00
$i_{13/2}^2$	+	3.20	0	7	−2.1	1.10	2.60
		3.20	2	1.7	−0.51	2.69	4.19
		3.20	4	0.94	−0.28	2.92	4.42
		3.20	6	0.61	−0.18	3.02	4.52

[a] Notes: (1) For l_j^2, $I=0$ configurations, interaction coefficient $= (2j+1)/2$. (2) For configurations where both particles have $j = l + \frac{1}{2}$, the states of lowest spin lie lowest. For configurations where $j = l + \frac{1}{2}$ and $j = l - \frac{1}{2}$, the states of highest spin lie lowest.
[b] Adjusted to zero.

levels are thought to arise from an excited proton since they are not produced in the reaction $Pb^{207}(d,p)Pb^{208}$; the lowest neutron excitation level in Pb^{208} is at 3.48 Mev.[24,25] More complex excited levels are also expected to occur with excitation both of the neutrons in the core and the two odd protons. However, levels from this type of excitation should not appear until well above 3 Mev. Thus, it is expected that the levels listed in Table VI will be representative of the structure of Po^{210} under approximately 3 Mev; above this energy there should be many more levels than are given in the table.

The predicted and experimentally observed levels of Po^{210} are compared in Fig. 5. The similarity between the two level schemes is rather striking in view of the assumptions involved. The calculations predict a band of even-parity levels of configuration, $h_{9/2}^2$, which start with the ground state and have spins 0, 2, 4, 6, and 8 in order of increasing energy; the observed energy spacings of this band are reasonably close to the calculated spacings. Such agreement may constitute evidence for a 6+ assignment of spin and parity to the 1472-kev level, since it is not expected theoretically that a second 4+ level (in addition to the 4+ level at 1426 kev) will be found nearby.

[25] J. A. Harvey, Phys. Rev. **81**, 353 (1951); Can. J. Phys. **31**, 278 (1953).

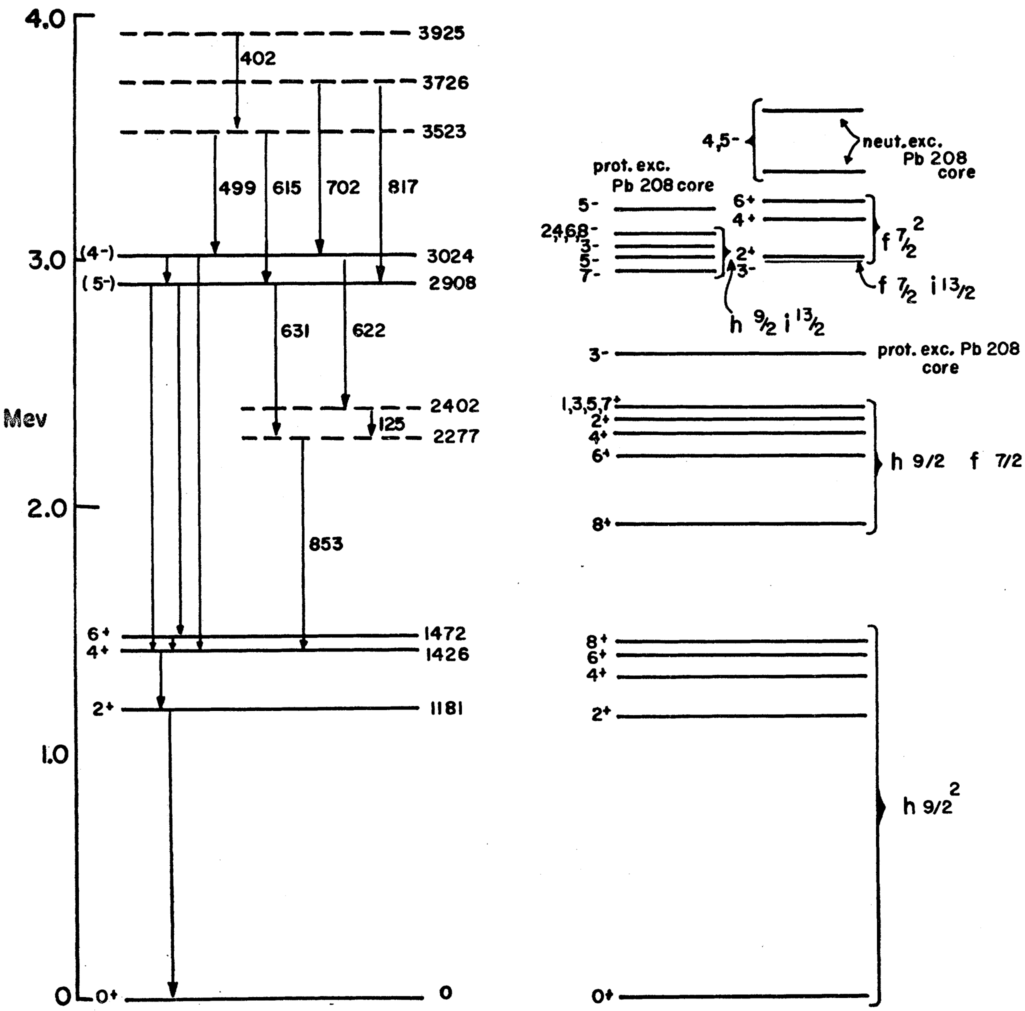

FIG. 5 Experimental and theoretical Po^{210} levels. (Transition energies in kev.)

Perhaps the most interesting feature of the theoretical level scheme is the prediction of a group of odd-parity levels at around 3 Mev arising from the $h_{9/2}i_{13/2}$ configuration, in good agreement with the experimental observation of a 5− state at 2.908 Mev which de-excites by a pair of $E1$ transitions to the 4+ and 6+ levels of the $h_{9/2}{}^2$ band. There is also found experimentally a level at 3.024 Mev which de-excites to the 5− level by a magnetic dipole transition, indicating that it has odd parity and spin 4, 5, or 6. A transition is observed to de-excite this level also to the 4+ but not to the 6+ level; hence the most probable assignment for this state is 4−. This is consistent with the location of predicted 5− and 4− states at 3.0 Mev and 3.1 Mev, respectively.

In attempting to fit the remaining transitions listed in Tables I and II into the level scheme shown in Fig. 5, a feature of the theoretical level scheme should be noted; there are no levels predicted between the ground state and the observed 6+ level at 1472 kev, other than those already discussed. Therefore, the experimental evidence (Sec. 5) that the 402- and 702-kev gamma rays are in coincidence with the 1436-, 1482-kev pair places these transitions somewhere above the 2908-kev (5−) level.

The gamma transitions were correlated numerically in an attempt to place each transition in the level scheme of Po^{210}. Energy sums of two gamma rays were compared with each other and with energies of single gamma rays, with a criterion for acceptance being agreement to within 0.1%. A large number of such sums were obtained and then examined for validity. Certain of these sums indicated transition pairs which violated experimental evidence for the known level scheme and were eliminated on this basis; others were eliminated because they inferred the existence of new levels below 1472 kev in contradiction to the theoretical predictions. The remaining sums are listed in Table VII. Certain of these sums are incompatible with each other; g with c and e, f with c. Sum g is not an independent combination, but rather is a consequence of the sums

c and e. Inasmuch as the probability for the chance expectation that the sum of two transition energies is equal to a third transition energy is much less than that for the sums of two pairs of transitions to be equal, sums c and e were regarded as the more valid and f and g were eliminated.

Levels derived from these remaining energy sums are shown in Fig. 5 as dashed lines. Levels at approximately 3.6 and 4.0 Mev are expected from the observation by Mihelich *et al.*[6] of 2.2- and 2.6-Mev photons in coincidence with the 0.245-Mev transition. The validity of the level scheme derived from these energy sums is in doubt due to lack of sufficient experimental evidence; the appearance in our photographic electron spectra of many very weak lines not listed in Tables I and II is further proof of the complexity of this level scheme. More intense sources of At^{210} and more powerful experimental techniques will be required in order to allow substantially more information about the levels of Po^{210} to be learned.

9. Log*ft* VALUES AND SPIN OF At^{210}

From the thermodynamic data of Glass, Thompson, and Seaborg,[3] one estimates a total electron-capture disintegration energy for At^{210} of about 3.9 Mev. The transition intensity data of the present work indicate that approximately 80% of the electron-capture disintegrations populate the levels at 2.908 Mev (5−) and 3.024 Mev (4−) (see Fig. 4). From this information, log*ft* values of 6.2 and 6.4 are calculated for the decay to the 5− and 4− levels, respectively. Most of the remaining electron-capture disintegrations (approximately 20%) populate the pair of levels at 1.426 Mev (4+) and 1.472 (6+). Without attempting to specify the exact amount of decay to either of these levels, a lower limit on log*ft* of 7.4 is calculated for this decay. In contrast, the transition intensity data of Mihelich *et al.*[6] indicate negligible electron-capture decay to any levels other than those at 2.908 Mev (5−) and 3.024 Mev (4−), with approximately 75% population of the 2.908-Mev level. They conclude that the spin of At^{210} is probably 4−, 5−, or 6±. However, this difference between our work and that of Mihelich *et al.*[6] in the relative population of the levels of Po^{210} does not materially affect the conclusion which we draw in the following paragraphs regarding the spin of At^{210}.

TABLE VII. Energy sums of transitions, in kev. ($\gamma_1+\gamma_2=\gamma_3+\gamma_4$, within 0.1%.)

Sums	γ_1	γ_2	γ_3	γ_4	$\gamma_1+\gamma_2$	$\gamma_3+\gamma_4$
a	46.5	1436.1	630.9	853.1	1482.6	1484.0
b	46.5	1436.1	1482.1	···	1482.6	1482.1
c	116.0	499.4	615.1	···	615.4	615.1
d	116.0	630.9	125.1	622.1	746.9	747.2
e	116.0	701.9	817.4	···	817.9	817.4
f	83.4	817.4	402.0	499.4	900.8	901.4
g	499.4	817.4	615.1	701.9	1316.8	1317.0

A consideration of the single-particle states available for the odd proton and neutron in At^{210} leads to the conclusion that the parity of the ground state is almost surely even and that the spin is 4 or 5. In its ground state, the odd proton of $_{83}Bi^{209}$ is in an $h_{9/2}$ configuration[22]; its first excited state ($f_{7/2}$) lies at 0.9 Mev and the second excited state (probably $i_{13/2}$) is reached at 1.6 Mev. It therefore seems likely that the ground-state proton configuration of $_{85}At^{210}$ is $h_{9/2}{}^3$. The odd neutron in At^{210} (the 125th) should have the same configuration as the odd neutron in Pb^{207}, which is in a $p_{1/2}$ state.[22] The two nucleons can couple to $(h_{9/2}{}^3, j=9/2)_P$ $(p_{1/2})_N$ with resultant spins 4 or 5 and even parity, or perhaps $(h_{9/2}{}^3, j=7/2)_P$ $(p_{1/2})_N$ with resultant spins 3 or 4 and even parity. The possibility of spin 3 is eliminated by the log*ft* product, 6.2, for the decay to the 5− level which indicates that the electron capture transition is much faster than it would be were it of the $\Delta I=2$, (yes) type. Configurations of odd parity of At^{210} would probably involve an $i_{13/2}$ proton or a $g_{9/2}$ neutron, but neither of these possibilities seems likely for the ground state of At^{210} since the levels involving these configurations in Bi^{209} and Pb^{207} are excited by at least a Mev above the respective ground states.

A spin and parity assignment of 5+ for At^{210} would be consistent with the log*ft* value of 6.2 observed for decay to the 5− level of Po^{210}, but under ordinary circumstances such an assignment would be quite inconsistent with the failure to observe substantial population of the 4+ and/or 6+ levels at 1426 and 1472 kev, respectively, since these transitions would be favored both by energy and by the selection rules. Such allowed transitions would be expected to have log*ft* values ≤ 6 rather than a log*ft* of >7.4 as indicated from the 20% branching to 4+ and/or 6+ levels at 1426 and 1472 kev. An explanation may perhaps be given for the retarded nature of these allowed transitions in terms of the description by de-Shalit and Goldhaber[26] of the effects of the "purity" of states near closed shells upon beta-decay *ft* values. If, as discussed above, the proton and neutron configurations of At^{210} are the pure states $h_{9/2}{}^3$ and $p_{1/2}$ respectively, then the electron capture decay to the levels of the ground state band of Po^{210} (with neutron configuration $p_{1/2}{}^2$) must convert an $h_{9/2}$ proton into a $p_{1/2}$ neutron. The large change of l involved in such a decay process may cause the observed retardation of several orders of magnitude. Although the same situation applies to all final states which involve only excited protons, it is expected that neutron excited states of the Pb^{208} core will contribute at the higher excitation energies since Pb^{208} is known to have a pair of levels at 3.5 and 3.8 Mev in which a neutron has been raised to the $g_{9/2}$ state.[24] Thus, the 5− and 4− levels of Po^{210} at 2.908 and 3.024 Mev, predicted to have a configuration $(h_{9/2}i_{13/2})_P$ $(p_{1/2}{}^2)_N$, will also have some

[26] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).

$(h_{9/2}{}^2)_P\ (p_{1/2}g_{9/2})_N$ character as the result of configuration mixing. Such mixing would permit a single-particle transition to take place from the $h_{9/2}$ proton state to the $g_{9/2}$ neutron state with normal speed for a transition of the $\Delta I=0$ (yes) type.

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Beta-Gamma Circular Polarization Correlation Experiments*

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A circular polarization analyzer for γ rays is described. Measurements on circular polarization of bremsstrahlung due to β particles from P^{32} and Tm^{170} agree with previous and concurrent measurements and, together with Co^{60} circular polarization correlation studies, establish a check on the calculated calibration curve of the analyzer. We have studied the β-γ circular polarization correlation in the following allowed j-j transitions: Na^{24}, Sc^{44}, Sc^{46}, V^{48}, and Co^{58}. The result for Sc^{46} indicates the presence of a strong interference between Gamow-Teller and Fermi couplings. The β interaction, therefore, should contain a combination of S and T, or (and) V and A, interactions with small or no phase difference between the interaction constants. If one assumes maximum interference, our experiments give information on the ratio of Gamow-Teller to Fermi interaction. The once-forbidden transition Au^{198} gives the maximum possible asymmetry. All results are in agreement with the 2-component neutrino theory and the assumption of V, A or alternatively S, T, P interaction.

I. INTRODUCTION

Recently Lee and Yang[1] have proposed that parity is not conserved in beta-decay processes. One of the consequences of nonconservation of parity, the anisotropy in the angular distribution of electrons emitted by polarized nuclei, has been verified by Wu *et al.*,[2] Ambler *et al.*,[3] and Postma *et al.*[4] with cryogenically polarized Co^{60} and Co^{58} nuclei. Another consequence, the prediction that nuclear electrons are longitudinally polarized, has been confirmed by Frauenfelder *et al.*,[5] Goldhaber *et al.*,[6] and de Waard and Poppema.[7]

A different experimental approach to study the consequences of nonconservation of parity is the measurement of the circular polarization of γ rays in coincidence with preceding β particles.[8] This method was described and employed in earlier communications.[9–11] The same method has been used by Schopper.[12] The β-γ circular polarization correlation experiments furnishes essentially the same information on the relative magnitude of parity-conserving and parity-nonconserving parts in the β interaction as the cryogenic polarization experiments mentioned above.[8] But they have the advantage of being extendible to a larger number of different nuclei.

After emission of electrons the initially unoriented nuclei are polarized in or opposite to the direction of the electron emission. The β-γ circular polarization correlation method makes use of the fact that subsequent γ quanta, if emitted in or opposite to the direction of the electrons, must be circularly polarized. The degree and sense of circular polarization, which can be measured experimentally, gives information on the relative magnitude of parity-conserving and parity-

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