spin and parity assignments in this region of "favored" first forbidden transitions.

$A=206$ (Fig. 1)

Logft=5.2 for Tl^{206} is indicative of $\Delta I=0$ or 1. $I=0$ (as opposed to $I=1$) is assigned to Tl^{206} in order to account for the absence of the 0.80-Mev γ in the decay. Odd parity is assigned from the shell model, which offers $(s_{\frac{1}{2}}p_{\frac{1}{2}})$ as the most likely configuration.

$A=212$ (Fig. 2)

The spin of Bi^{212} is established from α-γ correlation,[19] and the shell model predicts odd parity for this state. The 0.239-Mev γ is an $M1$ transition and the only assignment consistent with this and the β^- decay of Pb^{212} is 0^- for the 0.239-Mev level.

$A=210$ (Fig. 1)

Logft=5.4 for the Pb^{210} β decay appears to classify it with the Tl^{206} decay and the lower-energy β^- of Pb^{212}, both of which are $0\rightarrow0$, parity change transitions. Section 5 of the text argues for the 1^- assignment for the 5-day Bi^{210} state, and the $M1$ character of the 47-kev γ is in complete accord.

$A=208$ (Fig. 3)

The decay of Tl^{208} and the recently determined[20] excited states of Pb^{208} appear to offer another example of a "favored" first-forbidden transition. An $(s_{\frac{1}{2}},g_{9/2})$ configuration is quite plausible for Tl^{208}. This offers a 4^+ or 5^+ assignment. Because of the absence of a β^- transition to the 3^- excited state, the 5^+ assignment is preferred. Thus, another $\Delta I=0$ (yes) transition in the $A\approx208$ range appears to yield an anomalously low ft value. This is completely consistent with the rest of the region if the 5^- state is formed by exciting the 82nd proton from an $s_{\frac{1}{2}}$ orbit to an $h_{9/2}$ orbit, thus making the single particle transition $g_{9/2}\rightarrow h_{9/2}$, as is found elsewhere in this region.

[19] J. Horton and R. Sherr, Phys. Rev. **90**, 388 (1953).

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

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Alpha-Emitting Isomer: Polonium-211

FRED NOEL SPIESS*
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
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The half-life of AcC′ (Po^{211}) has been measured for the first time, and is 0.52 second rather than the 1/200 seconds widely quoted in the literature. Three short-lived alpha emitters resulting from alpha-particle bombardment of lead have been studied. They have been identified as Bi^{211} ($T_{\frac{1}{2}}=2.16$ min) and two states of Po^{211} ($T_{\frac{1}{2}}=25$ sec and 0.52 sec) by means of chemical separations, excitation functions, half-life measurements, and measurements of the energies of the emitted alpha particles. The energy measurements show that the 0.52-second state is an excited state of Po^{211}, with an excitation energy of about 0.3 Mev. A group of alpha particles having about 9-Mev energy was observed but not identified.

I. INTRODUCTION

THE existence of the isotope Po^{211} as an alpha-emitting beta-decay daughter of actinium C was first reported by Marsden and Perkins[1] in 1914. In the same article the much quoted half-life of 1/200 second was assigned to this activity on the basis of a rough range measurement and the application of the Geiger-Nuttall law. This estimated value has persisted in the literature[2] in spite of the fact that until this time no measurements of it have been made. Attempts to measure the range of these particles were made by Varder and Marsden in 1914, by Bates and Rogers in 1924, and finally a very careful measurement was made by Rutherford, Wynn-Williams, and Lewis[3] in 1931. They obtained a mean range of 6.506 cm. This value was corrected by Holloway and Livingston[4] to a value of 6.555 cm.

In 1940 Corson, MacKenzie, and Segrè[5] found this same actinium C′ as the K-capture daughter of At^{211}. The identification was made by observation of polonium x-rays having the same half-life as the At^{211} (7.5 hours), and by the presence of an alpha group having 6.55 cm range, in agreement with the measurements made by Lord Rutherford *et al.*[3]

The work reported here utilized Po^{211} as it occurs following At^{211} decay as well as that produced directly from cyclotron bombardment of lead and bismuth. As a

* Now at the University of California Marine Physical Laboratory of the Scripps Institution of Oceanography, San Diego, California.

[1] E. Marsden and P. B. Perkins, Phil. Mag. **27**, 690 (1914).

[2] *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950).

[3] Rutherford, Wynn-Williams, and Lewis, Proc. Roy. Soc. (London) **A133**, 351 (1931).

[4] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).

[5] Corson, MacKenzie, and Segrè, Phys. Rev. **58**, 672 (1940).

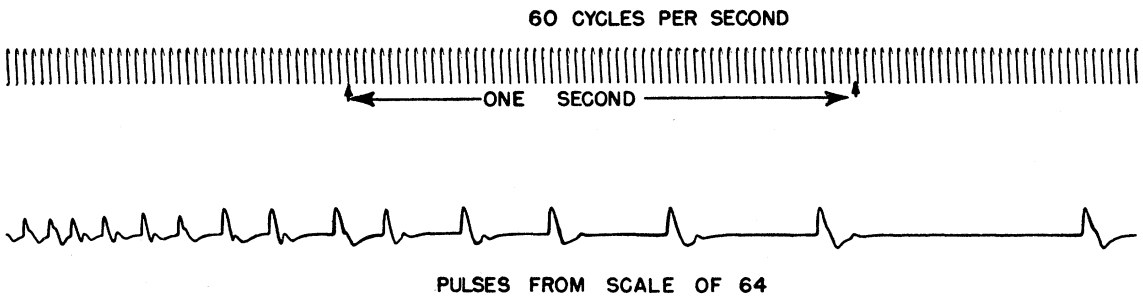

FIG. 1. Actinium C′ decay.

result of these investigations the half-life of the 6.55-cm alphas was determined directly as 0.52 second. In addition, it was found that when the AcC′ was formed from bombardment of lead or bismuth targets a second group of alphas appeared. These alphas had somewhat lower energy and a half-life of 25 seconds. Further work showed that this latter decay takes place from the ground state of Po^{211}. It thus appears that, although the 0.52-second state is the only one observed following the K-capture decay of At^{211}, it is nevertheless an excited state which decays almost entirely by direct alpha emission.

This work falls naturally into several parts: first, the measurement of the half-life of AcC′ as it occurs following K-capture decay in At^{211}; second, the study of the production of the short-lived alpha groups by bombardment of lead and bismuth; third, the measurement of the energies of the observed alpha particles; and fourth, the chemical separation experiments used in identifying the longer-lived products of bombardment.

II. ACTINIUM C′ HALF-LIFE

In facing the problem of measuring the half-life of AcC′ as it occurs in the At^{211} decay scheme two very different modes of approach presented themselves. If the half-life were actually about 1/200 second as quoted in the literature based on the Geiger-Nuttall law, then one should measure delayed coincidences between the Po^{211} x-rays (following K-capture in At^{211}) and the ensuing alpha emissions. However, experiments reported below had indicated the possibility that the half-life was of the order of 0.5 second or more, in which case some chemical separation method might be applicable. A method for making such a separation was devised based on the observation by Ghiorso[6] that while polonium will stick to platinum at dull red heat, astatine evaporates off quite easily.

One part of the experimental apparatus was a thin platinum strip (1.2 and 0.7 mils were both used) about one centimeter wide and five centimeters long. It was connected through a switch to a transformer in order that it could be brought rapidly to a dull red heat by the passage of a large current pulse. The strip was mounted on a sliding holder in order that it could be positioned rapidly over the thin window of a methane flow proportional counter. The counter window was covered with three one-quarter mil sheets of aluminum which, combined with the air path and the window thickness, was sufficient to cut out the 5.9-Mev alphas from the At^{211} decay. The counter output was amplified and fed to a scale of 64, from which output pulses were fed to a Brush recorder.

The At^{211} was made by bombarding a thick bismuth target with 28-Mev alphas from the 60-inch cyclotron. The bismuth was then heated in a vacuum and the evaporating astatine was caught in a liquid air trap. The astatine in the trap was dissolved in nitric acid. For each run a few drops of this solution were put on the platinum filament and allowed to evaporate to dryness. The amount of astatine used was such as to give an initial counting rate of 20 000 to 40 000 counts per minute through the absorber.

The procedure was to position the strip away from the counter, pass a single pulse of current through it to drive off the astatine and then slide it over the counter window in order to observe the decaying Po^{211} activity which would be recorded on the tape of the Brush recorder. Two runs were made in inverse fashion by performing the evaporation over the counter window, catching the astatine on a thin silver foil placed over the counter window, and then removing the polonium laden filament in order to watch the activity grow into the astatine again with the appropriate half-life.

The Brush recorder data were analyzed[7] and the resulting half-life was determined to be 0.52 second. A section of the Brush recorder tape for a typical run is shown in Fig. 1.

When the isomerism of the 25-second activity with the 0.52-second activity became apparent, additional runs were made in order to find out whether the 25-second period might be present in the Po^{211} as it occurs upon decay of At^{211}. The best such run showed a counting rate of 465 000 AcC′ counts per minute prior to evaporating off the astatine. After separation, the half-second activity was allowed to die out and the steady background counting rate which resulted was 520

[6] A. Ghiorso (private communication).

[7] F. N. Spiess, University of California Radiation Laboratory Unclassified Report, UCRL-1494 (unpublished).

counts per minute, with no sign of decay over a period of several minutes. This would indicate that the maximum counting rate for the 25-second activity present before driving off the astatine was less than about 50 counts per minute, or about 10^{-4} times the counting rate for the normally occurring activity. Both the 0.52-second and the 25-second activity, if any, would, prior to separation, be in equilibrium with the parent At^{211}. Thus, the ratio of 25-second to total Po^{211} activity at zero time would be approximately identical with the fraction of the At^{211} K-captures going to the state having the 25-second half-life, plus the fraction going to the 0.52-second state and decaying by gamma emission to the lower state prior to alpha emission. The sum of these two is then less than one part in 10^4.

Some mention should be made here of the fact that the half-life of 0.52 second is considerably longer than the old estimated value. This is, however, to be expected in view of recent studies of the systematics of alpha decay.[8,9] These show that the degree of prohibition of alpha decay increases appreciably as one approaches nuclei having Z near 82 and N near 126. Presumably the effect is in part related to an actual decrease in the radius of the daughter nucleus relative to the radius predicted from other alpha decay data ($r=1.57A^{\frac{1}{3}}\times10^{-13}$ cm).[10] In addition the high stability of the closed shell configurations may make very low the probability of formation of an alpha particle in a nucleus not having at least two neutrons and two protons beyond the closed shells. This would then multiply the probability of barrier penetration, for which detailed calculation can be made,[11] by an additional probability of alpha-particle formation, with consequent increase in half-life.

III. PRODUCTION OF Po^{211} FROM ALPHA-PARTICLE BOMBARDMENT OF LEAD AND BISMUTH

The experimental arrangements used in measuring the cross sections for production of these activities at various energies can be divided into three parts: beam collimating and measuring system, ionization chamber, and amplifiers and scalers.

The beam collimating and measuring system is substantially the same as that described by Kelly and Segrè.[12] It consists of an evacuated tube down which the cyclotron beam can travel, a rotating absorber carriage and a Faraday cup. These are arranged so that the deflected cyclotron beam, upon emerging from the exit port passes through a slit at one end of a pipe about 70 cm long and 7 cm in diameter. At the other end of the pipe there is a second collimating slit. Since the entire system is located in the fringing magnetic field of the cyclotron (about 2000 gauss), the pipe is fitted with three sylphon joints, one at each end and one at the middle to allow the slits and Faraday cup to be oriented properly to pick up the maximum current. The combination of slit system and magnetic field thus provides a velocity selection which insures a sufficiently monoenergetic beam for the purpose at hand.

Behind the second slit is a wheel which can be rotated to place any one of twenty carefully made, aluminum absorbers in the beam path. The beam current was measured by collecting the current from a Faraday cup in which the beam was stopped. The dimensions of the cup were such that, in the fringing cyclotron field, no secondary electrons liberated at the back wall could escape collection. The entire system of pipe, foil wheel, and Faraday cup were connected to the cyclotron tank vacuum system.

The ionization chamber used[7] was basically a parallel plate chamber with Frisch grid. The spacing from sample to grid was about $2\frac{1}{2}$ inches, while the grid to collector spacing was $\frac{7}{8}$ inch. The main difference between this and other chambers previously used was that the sample holder was mounted on one end of a sliding rod which allowed the target to be placed either in the cyclotron beam, which passed through an extension of the chamber, or in the active volume of the chamber, or in an intermediate position in which the sample in the holder could be replaced with a different sample previously loaded in the target changing magazine. The sample holder was driven from the counting to the bombarding position and back again by the action of compressed air on a piston connected to the external end of the sample holding rod. The transit time from one position to the other was about 0.1 second.

Electron collection was employed and the grid to plate voltage ratio used was such as to eliminate electron collection at the grid.[13] In order to obtain fast rising pulses the chamber was filled with a mixture of about 95 percent argon and 5 percent CO_2.[14] The pressure of the gas used was dictated by the range of the alpha particles involved and the dimensions of the chamber, and in most runs was between 20- and 25-psi gauge pressure.

The pulses were amplified by a pre-amp and amplifier system having a rise time of about 0.1 microsecond. The pre-amp was operated in the fringing field of the cyclotron (about 1000 gauss). At first the iron tube shields previously employed when the pre-amp had been operated in smaller fields were used, but without success. The final arrangement had no magnetic shielding, but utilized instead the fact that the $6AK5$'s could be oriented in such a manner that the principal electron flow was along the lines of force of the field. Under these conditions the amplification remained virtually

[8] Perlman, Ghiorso, and Seaborg, Phys. Rev. **77**, 26 (1950).
[9] I. Perlman and T. J. Ypsilantis, Phys. Rev. **79**, 30 (1950).
[10] I. Kaplan, Phys. Rev. **81**, 962 (1951).
[11] M. A. Preston, Phys. Rev. **71**, 865 (1947).
[12] E. L. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).
[13] Bunemann, Cranshaw, and Harvey, Can. J. Res. **A27**, 191 (1949).
[14] B. Rossi and H. H. Staub, *Ionization Chambers and Counters: Experimental Techniques* (McGraw-Hill Book Company, New York, 1949).

unchanged when the cyclotron magnet was turned off or on.

The cyclotron beam entered an extension of the chamber through a one-mil Dural window, traversed a short path in the gas of the chamber and passed out through a second one mil Dural window into the Faraday cup. A collimated Po^{210} source was located in the chamber on the end of a rod passing through the chamber wall. Since the source could be rotated to point into or away from the active volume, it provided a beam of alpha particles which could be turned on or off at will in order to check the operation of the system.

Data were recorded using a two-channel Brush recorder. The output of the Faraday cup, amplified with a Brush dc amplifier, was fed to one channel, while the output of the pulse amplifier, scaled down by a factor of 4, 16, or 64 was fed to the other. In addition a signal was supplied to the latter pen to indicate the time at which the target entered and left the beam.

The ordinary lead and bismuth targets were made by evaporating a thin layer onto one-mil aluminum in a high vacuum chamber. In this way highly uniform, thin (0.1-mg/cm²) samples were produced. Since only small amounts of enriched lead were available these targets were made by electroplating, in spite of the fact that the resulting samples did not have the high uniformity shown by the evaporated samples.

As a result of the work done with the equipment described above, it was found that when ordinary lead targets were bombarded with alphas from the 60-inch cyclotron three different alpha-decaying products resulted. The half-lives of these alpha emitters were 0.5, 25, and 130 seconds.

Since the 0.5-second alphas were found to have the same energy as the AcC′ alphas following At^{211} decay, and since the half-life was the same as that determined as described above for Po^{211}, it was evident that this was Po^{211} produced by the only possible reaction—$Pb^{208}(\alpha,n)Po^{211}$. The 130-second half-life agreed with that for Bi^{211} (AcC), and subsequent chemical separations verified that this was actually bismuth, which must have been formed by the reaction $Pb^{208}(\alpha,p)Bi^{211}$.

Identification of the 25-second activity was the only remaining problem. Chemical separations, to be described below, showed that these alphas came from polonium. The final assignment of this activity to Po^{211} rests on the measurements of the variation of the yields of all three of these activities as the lead isotope content was varied. In these measurements it was found that the ratio of yield of 130-second to yield of 25-second activity at an alpha bombarding energy of 35 Mev was independent of lead isotope ratio over a wide range (30 to 90 percent in Pb^{208}, 8 to 60 percent in Pb^{207}, and 2 to 25 percent in Pb^{206}). The same was found at both 18 and 20 Mev for the ratio of 0.5-second to 25-second activity. Since both the 130- and 0.5-second activities resulted from the presence of Pb^{208} only, then it was apparent that the 25-second activity was the result solely of bombardment of the Pb^{208} also. The only polonium isotope which could be produced from Pb^{208} and not from Pb^{207}, would be Po^{211} (neglecting possibility of an α,γ reaction). The conclusion was thus forced that the 25-second activity was isomeric with the 0.52-second activity.

TABLE I. Cross sections in millibarns (10^{-27} cm²) for several reactions.

Alpha particle bombarding energy Mev	$Pb^{208}(\alpha,n)Po^{211}$ 0.52-second	$Pb^{208}(\alpha,n)Po^{211}$ 25-second	$Pb^{208}(\alpha,p)Bi^{211}$	$Bi^{209}(\alpha,pn)Po^{211}$ 25-second
18	2.6	0.01	<0.01	
20	15	0.17	<0.01	
21½	90	2.3	<0.01	
23	46	4.6	0.01	
24½	30	5.5	0.07	
26	25	4.7	0.11	
27	11.5	2.7	0.54	
28	9.6			
30½	8.2			<0.1
33				0.3
33½	5.9			
34				0.4
36	5.2			0.6
37½	4.8			
39	4.1	2.3	3.7	1.2

Absolute cross sections for production of both Po^{211} states from the reaction $Pb^{208}(\alpha,n)Po^{211}$ were determined at several energies. In addition cross sections for the $Pb^{208}(\alpha,p)Bi^{211}$, and $Bi(\alpha,pn)Po^{211}$, (25-second state only) were measured. The results of these measurements are listed in Table I, and will be discussed in Sec. VI, below.

IV. ALPHA-PARTICLE ENERGY MEASUREMENTS

The energies of the alpha particles from both the 0.52- and the 25-second emitters were determined using the argon-filled parallel-plate ionization chamber, with Frisch grid, described above. The output pulses from the chamber were amplified by a linear amplifier and the output of the amplifier was fed through a delay line (40 or 60 feet of RG65U) to the y-deflection plates of a Dumont 248 oscilloscope. The same pulse was put through a pulse shaper and discriminator to provide sharp pulses to trigger the sweep of the scope and square pulses to intensify the trace briefly. The pulses displayed on the scope were photographed on Super XX or Linagraph Pan film using a General Radio oscillograph recording camera. Drive motors were used which provided film speeds from 5 ft/sec to 1½ in./sec, in order that speeds appropriate to the level of activity would be available. After processing, the film was viewed using a microfilm viewer, and the pulse heights were measured.

Since the voltage produced at the pre-amp input by each alpha pulse is known to be proportional to the alpha energy with this type chamber, a curve of pulse generator output voltage *vs* oscilloscope pulse height could be used to give the alpha energy *vs* pulse-height relationship under these operating conditions if the energy corresponding to one particular pulse height were known. However, since three well-defined alpha

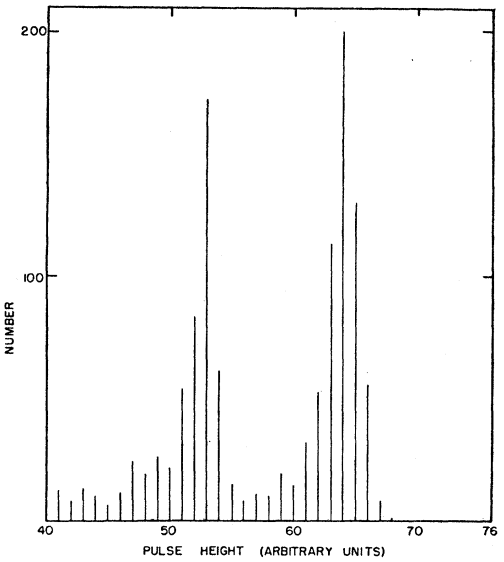

FIG. 2. Astatine pulse-height distribution.

groups were readily available, it was possible to construct directly a pulse height *vs* alpha energy curve covering the necessary energy range. The three groups used were Po^{210} (5.30 Mev), At^{211} (5.9 Mev), and Po^{211} (7.43 Mev) from an astatine source. The pulse-height distributions for these three calibrating points are shown in Figs. 2 and 3A. The shape of the resulting pulse height *vs* energy curve agreed within the experimental error with the pulse height *vs* pulse generator voltage curve, so it was possible to extend the energy curve upward by using the pulse generator points, and thus find the energy of the long-range alphas which were observed.

The most important energy measurement was that of the 25-second activity since it would determine the excitation energy of the Po^{211} isomer. This determination was made by bombarding a thin (0.1-mg/cm^2) lead sample with 22-Mev alphas for 30 seconds, waiting about 20 seconds, and then photographing the resulting pulses occurring over a period of about a minute. At this bombarding energy very little AcC is formed. Figure 3B shows the resulting pulse-height distribution, with peak at 62.0 divisions. This indicates that the energy of these alphas is 7.14±0.05 Mev. This same pulse height distribution shows, in contrast to the Po^{210} and astatine calibration samples, alphas with energies as high as 9 Mev. At this date not much is known about these groups except that they must be in cascade with some other activity, since it would be difficult to imagine a 9-Mev alpha emitter with half-life long enough to allow its observation as long as a half minute after its production. This group may be the same as that reported[15] to occur somewhere in the natural decay chain following actinium B.

[15] M. Curie and W. A. Lub, J. phys. et radium 4, 513 (1933).

V. CHEMICAL SEPARATION EXPERIMENTS

These separations were made in order to determine the element to which each of the two longer-lived activities should be assigned. It could be assumed that after a bombardment with alphas of less than 40 Mev, the heavy elements present in a lead target would be lead, bismuth, and polonium. Two different separations were thus made. In the first, polonium was extracted alone from the combination, and the 25-second activity was observed to go with the polonium fraction. In the second, bismuth and polonium together were extracted from lead, and in this case both the 130- and the 25-second activities were in the bismuth-polonium portion.

In both separations the target material used was lead carbonate, since it was easily soluble in either warm hydrochloric or nitric acid. A slurry of the carbonate was spread on a strip of 10-mil aluminum and allowed to dry. It was then covered with $\frac{1}{4}$ mil aluminum in order that the active material would not be lost during the transfer from the bombarding area to the working area.

The sample was attached to a piece of aluminum rod, which, upon completion of the bombardment was blown by compressed air through a pipe to a point outside the cyclotron shielding where the chemical and counting equipment were set up.

The counter used was a methane flow proportional counter into which the samples could be inserted rapidly by means of a tight-fitting sliding panel. The output pulses were amplified and then fed to a scale of 64. The scaled-down pulses were recorded on a Brush recorder.

The analysis for polonium[16] was relatively simple. The lead carbonate was dissolved in hot, 6*N* HCl containing 1.0 mg per liter of Bi as a holdback. A piece of

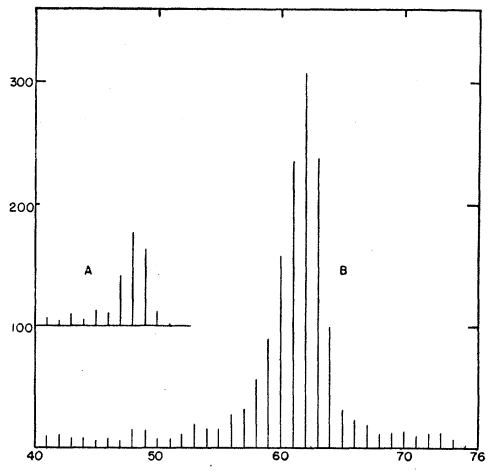

FIG. 3. (A) Polonium-210 pulse-height distribution. (B) Pulse-height distribution for intermediate-lived activity. (No pulses observed above 75.)

[16] W. W. Meinke, University of California Radiation Laboratory Report, UCRL-432 (unpublished), p. 84–1 (under remarks).

silver foil was inserted in the solution and stirred in it for about one minute, after which it was removed, washed in distilled water, and finally counted in the proportional counter. This process could be completed with sufficient rapidity to give an initial counting rate of more than 600 counts per minute of the 25-second activity, following a 30-second bombardment with about 2 microamperes of 30-Mev alphas.

The separation of polonium and bismuth from lead[17] went as follows. The lead carbonate was dissolved in about 5 cc of hot HNO_3, and about 20 mg of Bi in solution was added. The solution was boiled to concentrate the HNO_3, at which point a large part of the lead precipitated as $PbNO_3$. The solution was decanted into a centrifuge cone containing NaOH to neutralize the HNO_3 and then two drops of a one percent solution of Thionalide (Thioglycollic acid β-amino napthalide) were added. This precipitated the Bi as an organic complex which carried the Po with it. The solution was centrifuged and the liquid was poured off. The precipitate was first washed and then completely dissolved in acetone. The acetone solution was then dropped onto a hot platinum disk to evaporate the liquid. The disk was then flamed and finally placed in the counter. This process was completed in about 4 minutes from the end of the bombardment, which was fast enough to allow observation of the tail of the 25-second activity after a bombardment at 25 Mev.

The method given by Meinke[18] for separating Bi and Po from Pb by chemical plating on Ni was tried. Although both decay periods could be crudely identified, the yields obtainable in the available times were not sufficient to give counting rates comparable to those obtained as outlined above by Prodinger's method.[17]

The data obtained from the Po extractions showed the half-minute activity clearly, thus allowing an opportunity for determining that it was exactly 25 seconds. After decay of the 25-second activity only, a steady counting rate (about 300 counts per minute, attributable to the Po^{210}) was observed, with no trace of the 2.2-minute activity. Thus this experiment showed that the 25-second decay period should be assigned to some isotope of Po, while the 2.2-minute activity should not.

The results of the Po and Bi extraction clearly showed both the 25-second and the longer activity, whose half-life was accurately measured as 2.15 minutes. Here the 2.2-minute activity was present in the separated sample with a counting rate (extrapolated back to the end of the bombardment) 640 times as great as that of the Po^{210}, in contrast with the polonium separation experiment in which the same ratio was less than 0.4. Thus the 2.2-minute material was apparently a Bi isotope, and the agreement between the observed half-life and that known for AcC (Bi^{211}) indicated that this reaction could definitely be assigned as $Pb^{208}(\alpha,p)Bi^{211}$.

VI. CONCLUSIONS

In this section three topics will be discussed in some detail. They are first, the excitation functions for the production of the two Po^{211} states; second, the identification of the 0.52- and 25-second alpha-decay periods as arising from isomeric nuclear states; and third, a comparison of the information regarding the two isomeric states, particularly the implications bearing on spin assignments.

A rough excitation function for the reaction $Pb^{208}(\alpha,n)Po^{211}$ is presented in Table I above. It is desirable to compare this excitation function with others of the same sort and with theoretically predicted (α,n) excitation functions, but to date no other (α,n) reactions in this portion of the periodic table have been investigated. One can, however, assume that an (α,n) reaction should have a cross section which behaves in a way similar to a (p,n) and use for comparison the results of Kelly[19] for the $Bi^{209}(p,n)Po^{209}$ reaction. Both show a steep rise limited by the barrier, followed by a sharp drop at the onset of the competing $2n$ reaction and a long, high-energy tail in which the cross section falls off quite slowly, having a magnitude roughly one-tenth of that at the peak.

A method of comparison with theory is to use the total cross sections for alpha bombardment as calculated by Weisskopf.[20] This can be compared directly with the lowest two or three experimental points, which are in a region not too heavily influenced by the competing $(\alpha,2n)$ and (α,p) reactions. Such a comparison shows that the experimental points give agreement with theory if a nuclear radius of $1.4A^{\frac{1}{3}}\times10^{-13}$ cm is used. This value is close to the $1.43A^{\frac{1}{3}}\times10^{-13}$ cm found in a similar way by Kelly[19] for $Bi^{209}+\alpha$ based on excitation functions for the $(\alpha,2n)$ and $(\alpha,3n)$ reactions.

The excitation function for the production of the 25-second state alone is depressed considerably below that for the more normal appearing curve for the 0.52-second activity at the low-energy end, but takes on comparable values at the high-energy end. One logical assumption as to the reason for this behavior is that it is due to an appreciable centrifugal barrier, indicating that this state (25-second) probably has a high angular momentum.

The following argument, based on the lack of variation in 25-second to 0.52-second yield ratio with change in isotopic concentration shows that the 25-second activity should be assigned to Po^{211}: Consider two targets, a and b, each of thin lead, but having different

[17] Wilhelm Prodinger, *Organic Reagents Used in Quantitative Inorganic Analysis* (Elsevier Publishing Company, New York, 1940).

[18] W. W. Meinke, University of California Radiation Laboratory Report, UCRL-432 (unpublished), p. 83–1.

[19] E. L. Kelly, Ph.D. thesis, University of California, 1951 (unpublished).

[20] V. F. Weisskopf *et al.*, Lecture Series in Nuclear Physics, Atomic Energy Commission Report, MDDC-1175 (U. S. Government Printing Office, Washington, D. C., 1947).

percentages of the various stable isotopes. When each of these is bombarded with a constant alpha current for a time, T, at an energy such that only the (α,n) reaction contributes, then the ratio of the number of 0.52-second to the number of 25-second nuclei formed would be

$$R_a=\left(\frac{N_{0.52}}{N_{25}}\right)_a=\frac{0.52\sigma_{0.52}(1-e^{-1.33T})}{25\sigma_{25}(1-e^{-0.028T})}\left(\frac{p_{208}}{p_x}\right)_a;$$

$$R_b=\left(\frac{N_{0.52}}{N_{25}}\right)_b=\frac{0.52\sigma_{0.52}(1-e^{-1.33T})}{25\sigma_{25}(1-e^{-0.028T})}\left(\frac{p_{208}}{p_x}\right)_b;$$

where p_{208} is the percent of Pb^{208} in the target, and p_x is the percent of the lead isotope from which the 25-second activity is formed by an (α,n) reaction. The σ's are the appropriate cross sections. If both targets are bombarded at the same energy and for the same length of time then σ_{25}, $\sigma_{0.52}$, and T will be the same in both equations above and the following relation will hold:

$$\left(\frac{N_{0.52}}{N_{25}}\right)_a\left(\frac{N_{2.5}}{N_{0.52}}\right)_b=\frac{R_a}{R_b}=\left(\frac{p_{208}}{p_x}\right)_a\left(\frac{p_x}{p_{208}}\right)_b.$$

The two targets used were (a) natural lead and, (b) lead enriched in Pb^{207}. Inserting the appropriate values for the isotope percentages, one finds that the possible values of R_a/R_b are: for $x=208$, the ratio should be unity. For $x=207$, the ratio is 5. If $x=206$, the ratio is 0.5. The experimentally determined yield ratios are given below for two different bombarding energies. The ratios of the R's are seen to be essentially

Bombarding energy	R_a	R_b	R_a/R_b
18 Mev	11.5	10.2	1.1
20 Mev	3.3	3.6	0.9

one within the accuracy of these runs. The result, then, is to show that the 25-second, as well as the 0.52-second activity, is produced from an alpha-particle bombardment of Pb^{208} at energies near and below the threshold for the $(\alpha,2n)$ reaction. Taken with the chemical identification of the 25-second activity as polonium, this means that the best assignment of the state decaying by 25-second alpha emission is to Po^{211} isomeric with the state giving rise to the 0.52-second activity.

In addition, this is the only polonium isotope to which the 25-second, 7.14-Mev activity can be assigned without assuming it to arise from a state having at least 1.9-Mev excitation above the ground state. This would require a very highly forbidden gamma transition to the ground state, and from what is known of nuclear energy levels there would in such an energy range be several intermediate states to which jumps could be made, not all of which could involve highly forbidden transitions also. Thus again the only possible assignment consistent with the chemical identification is to Po^{211}.

Some information is available which makes possible a tentative assignment of spins to the two states of Po^{211}. The usual data on which such assignments are made, are lacking in this case. Nothing is known of the conversion coefficients for the unobservable (in these experiments) transition between the two states, nor of more than a lower limit on the half-life for such a transition. Neither of the two spins has been measured directly, and the K-capture decay from At^{211} to the 0.52-second state gives no information, since the At^{211} spin is itself unknown. The information available concerns alpha decay to a well-known nucleus, limit on half-life for decay from upper to lower state, and relative cross sections for production of the two states.

In the ensuing discussion it will be assumed that both decays terminate at the ground state of Pb^{207}, which in turn allows the assignment of the entire 0.3-Mev energy difference to excitation of the 0.52-second state above the 25-second state. This assumption is made in view of the fact that the first level above the ground state in Pb^{207} is at about 0.5 Mev.[21–23]

Observation of alpha half-lives and energies shows that if a nuclear radius[10] of $1.57A^{\frac{1}{3}}\times10^{-13}$ cm is used in the decay formula of Preston[11] with the observed alpha-decay energies, then the calculated decay constant for most even-even nuclides agrees with the observed. This is not the case, however, for odd-even, even-odd, or odd-odd nuclei, or for nuclei in the vicinity of the closed shells at 82 or 126 protons or neutrons.[8] In these cases the calculated value is greater than the observed, indicating that the actual decay is inhibited in some way relative to the simple decay of the even-even types.

In the case of Po^{211}, since it seems that both states decay to the ground state of Pb^{207}, the nuclear radius should be the same for both decays and should be somewhat below the $A^{\frac{1}{3}}$ law prediction. By applying the most rigorous available development of the barrier penetration theory including angular momentum change,[11] and using the observed energies and several assumed radii (from 1.27 to $1.47A^{\frac{1}{3}}\times10^{-13}$ cm), it was found that the prohibition of the 25-second relative to the 0.52-second decay is accounted for by assuming an angular momentum change of 5 or 6 units for the 25-second decay, and 0 or 1 for the 0.52-second activity. This in turn implies (from the Pb^{207} spin of $\frac{1}{2}$) that the spin of the 25-second state is large (9/2 to 13/2), while the spin of the $\frac{1}{2}$-second state is small (1/2 or 3/2). These calculations do not single out a well-defined nuclear radius unless some assumption is made with regard to the retardation due to even-odd nuclear character, but indicate that values between 1.3 and $1.4A^{\frac{1}{3}}\times10^{-13}$ cm are the most acceptable.

The lack of observed decay of the 0.52-second to the 25-second state, as noted above, indicates again that

[21] J. A. Harvey, M.I.T. Progress Report, Office of Naval Research Report, ONR-NP-1586, April 1, 1950 (unpublished).
[22] E. C. Campbell and M. Goodrich, Phys. Rev. **78**, 640 (1950).
[23] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

there is a large spin difference between the two states. Theoretical calculations of the decay constants for gamma emission,[24] including the large effects of K and L conversion as one must for large Z, are not particularly reliable for this case; however, they indicate that at least a 2^5-pole transition would be required. Comparison with the assignments made by Goldhaber and Sunyar[25] for the isomers of Pa^{234}, Hg^{199}, and Hg^{197} indicate that electric 2^4-pole or any higher order transition should suffice to give the necessary decay constant of less than 10^{-4} sec^{-1}. These limits do not contradict the spin difference which is required by the alpha decay considerations, above, nor do they indicate which state has the higher spin.

A third indication of the large difference in spin comes from the different forms which the excitation functions for the production of the two activities take. The contrast can be most easily explained by postulating that the centrifugal barrier depresses the probability of formation of the 25-second activity for low bombarding energies. This argument agrees with the alpha-decay discussion also in the assignment of the larger spin to the 25-second state.

The one-particle model of the nucleus, particularly as developed by Mayer[26] using the assumption of strong coupling, gives an explanation of the magic numbers and predicts the spins properly in most instances for even-odd and odd-even nuclides. Goldhaber and Sunyar,[25] by making an additional assumption to cover a few special cases, are able to assign spins to a large number of isomers in such a way that they agree with the predicted sequence of levels given by Mayer. In the region in which we are interested (127 neutrons, beginning of a new shell) nothing is known of the magnitude of the splitting due to the spin-orbit coupling, but the order of levels is thought to be $1i_{11/2}$, $2g$, $3d$, $4s$, etc.

This sequence of levels would make the appearance of isomers very unlikely, and indeed the shell model predicts isomers when the odd nucleons are a few units *less* than the magic numbers, and excludes them when the nucleons are a few more than the magic numbers. This is borne out very clearly by the "islands" of isomerism. Now Po^{211}, with 84 protons and 127 neutrons, is positively out of a possible island of isomerism. There are indications of such an island for $N<126$ and, e.g., Pb^{207} belongs to it, but $N=127$ is definitely outside of it.

We have thus to look for another type of explanation for this isomerism, and this is most likely given by the "core isomerism" first indicated by Goldhaber[27] for the case of Mo^{93}. Applying the ideas of Goldhaber to our case, we consider, according to the shell model, that our odd neutron is $i_{11/2}$ or $g_{9/2}$, whereas the last 2 protons in the "core" are either $(h_{9/2})^2$ or $(f_{7/2})^2$. In the ground state of the isomer, in which the core is not excited, the core has $I_{\text{core}}=0$, and I for the whole nucleus is the $I_{\text{o.n.}}$ of the odd neutron; hence the I of the nucleus as a whole is 11/2 or 9/2 according to whether the odd neutron is in the $i_{11/2}$ or $g_{9/2}$ state. By exciting one of the protons of the core, possibly to a configuration $(h_{9/2}f_{7/2})$, the core can assume a spin up to 8 (even parity). The ground state and the excited state of the nucleus as a whole have thus the same parity and can have a spin difference up to 8 units.

All the evidence presented here indicates that the 25-second state is the lower, and thus probably has its core in the ground state. This would mean that the spin to be assigned to this state would be most probably 9/2 in view of recent work[28] indicating the 127th neutron to be a 9/2 state. If the excited core should combine with this to give a very low spin for the 0.52-second state, all would be well, except for one sizeable difficulty, namely the very strong preference of the electron capture decay of At^{211} for the 0.52-second state, which, if the spin of At^{211} were $\sim 9/2$ as expected, would not seem logical with the spins postulated here.

In any event it seems quite probable that this is the second known case of core isomerism as well as the first clear-cut example of an alpha-decaying isomer.

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[25] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
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[27] M. Goldhaber, Phys. Rev. **89**, 1146 (1953).
[28] Fred, Tomkins, and Barnes, Phys. Rev. **92**, 1324 (1953).