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SOME SHORT-LIVED ALPHA EMITTERS IN THE NEIGHBORHOOD OF POLONIUM 211

Fred Noel Spiess
(Thesis)

October 8, 1951

Berkeley, California

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Fred Noel Spiess
Radiation Laboratory, Department of Physics
University of California, Berkeley, California

ABSTRACT

Three short-lived alpha emitters resulting from alpha particle bombardment of lead have been studied. They have been identified as Bi^{211} ($T_{1/2}$ = 2.16 min.) and two states of Po^{211} ($T_{1/2}$ = 25 sec. and 0.52 sec.) by means of chemical separation, excitation functions, half-life measurements, and measurements of the energies of the emitted alpha particles. The half-life of Po^{211} as it occurs following the K-capture decay of At^{211} has been measured for the first time, and is 0.52 sec. rather than the 5×10^{-3} sec. widely quoted in the literature. The energy measurements indicate that the 0.52 second state is the upper state of Po^{211}, with an excitation energy of about 0.3 Mev. A group of alpha particles of about 9 Mev energy has been observed but not identified further.

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Radiation Laboratory, Department of Physics
University of California, Berkeley, California

II. INTRODUCTION

A great amount of work has been done on the measurement of the properties of various alpha particle emitters, and also on the investigation of the various nuclear reactions by which they can be produced.[1, 2] In particular, reactions involving bismuth as the target element have been intensively studied.[3, 4, 5] On the other hand, reactions involving lead as the target material have not been as thoroughly investigated, in part because of the difficulties inherent in working with a mixture of several isotopes. This paper reports the investigation of some rather short-lived alpha emitters which are produced when lead is bombarded with alpha particles of from 20 to 40 Mev.

In these experiments it has been found that the half-life of Po^{211}, for many years quoted in the literature as 5×10^{-3} seconds, is in reality 0.52 seconds. An isomer of Po^{211}, hitherto unobserved, has been identified, and several reactions for producing Bi^{211} and the two states of Po^{211} have been studied. In addition, a group of long range (9 Mev) alpha particles has been observed to result from bombardment of lead with alpha particles.

Initially it was observed by M. Weissbluth* that, upon bombardment of lead with 38 Mev alphas from the sixty inch cyclotron at the University of California Crocker Radiation Laboratory, one alpha activity with half-life of a few tenths of a second, one with about half a minute and one of several minutes half-life were produced.

* Private communication.

An examination of the possible products of such a bombardment showed that any of the following might conceivably have been made, as shown in the isotope chart, Fig. 1: Polonium isotopes ranging from Po^{211} (from the α,n reaction on Pb^{208}) to Po^{204} (from the α,4n reaction on Pb^{204}) and bismuth isotopes from Bi^{211} (from α,p on Pb^{208}) to Bi^{204} (from α,p3n on Pb^{204}). The reason for the restriction to reactions involving the emission of four particles or less is that the threshold for five particle emitting reactions is about 40 Mev. Actually, exploratory experiments showed that all three activities could be produced at least as low as 24 Mev, thus ruling out also the emission of either three or four particles, as shown in Table 1, and narrowing the range of possible products. Although several reactions involving the emission of two protons or an alpha from the compound nucleus are energetically possible, these were not considered inasmuch as the large barrier penetration factors would lead to quite small cross-sections and also since these would all give rise to lead isotopes among which there are no known alpha emitters. Among the possible products, the alpha emitters known before this investigation were listed in the NBS Bulletin on Nuclear Data[8] as having the characteristics shown in Table 2.

The procedure followed in determining the reactions involved was as follows. First, some exploratory experiments were made which showed that the half-second activity had an alpha energy of about 7.5 Mev and that all three activities were produced over a wide range of bombarding energies. Next, actual yields were measured for the production of each activity from ordinary lead at several bombarding energies, and simultaneously somewhat more exact measurements of the

Thresholds for Reactions Possibly Occurring

When Pb^{208} is Bombarded

With 40 Mev Alpha Particles

(Masses of the heavy elements are taken from Reference 6. (These results agree within a few tenths of an Mev with values calculated from Reference 7.))

Isotope	Mass	Emitted Particles' Mass	Sum	Difference from Pb^{208} + α	Threshold (Mev)
Pb^{208}+α			212.05212		
Po^{212}	212.06123		212.06123	911	8.5
Po^{211}	211.05917	(n)1.00893	212.06890	1598	14.9
Po^{210}	210.05504	(2n)2.01786	212.07290	2078	19.3
Po^{209}	209.05384	(3n)3.02679	212.08063	2851	26.5
Po^{208}	208.05100+	(4n)4.03572	212.08672+	3460+	32.2+
Po^{207}	207.05037+	(5n)5.04465	212.09502+	4290+	39.9+
Bi^{211}	211.06037	(p)1.00812	212.06849	1637	15.2
Bi^{210}	210.05630	(pn)2.01705	212.07335	2123	19.8
Bi^{209}	209.05225	(p2n)3.02598	212.07823	2611	24.3
Bi^{208}	208.05036	(p3n)4.03491	212.08527	3315	30.8
Bi^{207}	207.0488+	(p4n)5.04384	212.09272+	4060+	37.8+

+ designates an unknown amount of energy involved in K-capture.

Table 1.

Alpha Emitters known prior to this Investigation among the Possible Products of Bombardment of Lead with 38 Mev Alphas

(Data taken from Reference 8)

Bi^{210} (Radium E);
4.85 day β^-; K. Siegbahn, H. Slätis; Arkiv. Mat. Astron. Fysik 34A, No. 6 (1946)
Rare α branching; E. Broda, N. Feather: Proc. Roy. Soc. A 190, 20 (1947)
α energy 5.02 Mev; Neuman and Perlman; Unpublished data (1949)

Bi^{211} (Actinium C)
2.16 minute α; Int. Rad. Stds. Comm. Rep't; Rev. Mod. Phys. 3, 427 (1931)
α energies of 6.272 (20%) and 6.618 (80%)
Rutherford and Williams; Proc. Roy. Soc. A 133, 351 (1931)
Rosenblum, Guillot and Perey; Comptes Rendus 202, 1974 (1936)
Holloway and Livingston; Phys. Rev. 54, 18 (1938)

Po^{205}
1.5 hour α; α energy 5.2 Mev; Karraker and Templeton; Unpublished (1949)

Po^{206}
9 day K-capture and α; α emission 10%; A energy 5.2 Mev
Templeton, Howland and Perlman; Phys. Rev. 72, 758 (1947)

Po^{207}
5.7 hour K-capture; α about 0.01%; α energy 5.1 Mev
Templeton, Howland and Perlman; Phys. Rev. 72, 758 (1947)

Po^{208}
3.0 year α; Kelly and Segrè; Phys. Rev. 75, 999 (1949)
α energy 5.14 Mev; Templeton, Howland, Perlman; Phys. Rev. 72, 758 (1947)

Po^{209}
about 200 year α; α energy 4.95 Mev; Kelly and Segrè; Phys. Rev. 75, 999 (1949)

Po^{210} (Radium F)
138 day α; Beamer and Easton; J. Chem. Phys. 17, 1298 (1949)
α energy 5.30 Mev; Holloway and Livingston; Phys. Rev. 54, 18 (1938)
W. Y. Chang; Phys. Rev. 69, 60 (1946)

Po^{211} (Actinium C')
5×10^{-3} sec. α [changed to 0.52 sec. by this paper]
Int. Rad. Stds. Comm. Rep't; Rev. Mod. Phys. 3, 427 (1931)
α energy 7.43 Mev; Lewis and Bowden; Proc. Roy. Soc. A 145, 235 (1934).

Table 2.

half-lives were made. After this, lead targets enriched in various isotopes were bombarded to determine the cross-section variation as a function of isotopic concentration at several energies. At this point it became evident that the particular nuclide involved in all three cases was Pb^{208} and from half-life and excitation function the longest-lived activity was probably Actinium C (Bi^{211}). From excitation function the shortest activity (half-second) appeared to be the result of an α,n reaction, which would give Po^{211}. The approximate energy for the half-second activity was in agreement with this, but the half-life of Po^{211} (Actinium C') was found never to have been measured, so the next step was the measurement of the decay constant of Po^{211} as it occurs in the decay of At^{211}. This showed a half-life of 0.52 seconds, as opposed to the 5×10^{-3} seconds predicted from the Geiger - Nuttall law. Thus the short-lived activity was clearly Po^{211} from the α,n reaction on Pb^{208}.

Following the determination of the Actinium C' half-life a series of chemical separation experiments was run which showed that the longest-lived activity was bismuth and the intermediate one was polonium. This fact coupled with the lack of variation in relative yield with changes in isotope concentration at low (19 Mev) bombarding energy indicated that the 1/2-second and 25 second activities probably resulted from an α,n reaction on the same lead isotope, and hence were isomeric. At the same time the half-lives of the two longer-lived groups were accurately determined as 2.2 minutes and 25 seconds, respectively. This confirmed the assumption that the long-lived activity resulted from the reaction $Pb^{208}(\alpha,p)Bi^{211}$.

The final stages included the accurate measurement of the alpha decay energy associated with the 25 second decay period and the investigation of other reactions (bombardment of bismuth with protons, alphas and deuterons) by which the 25 second activity could be produced. In the course of these energy measurements a 9 Mev alpha group of unknown origin was found.

III. CROSS-SECTION MEASUREMENTS

A. Experimental details

The experimental arrangement used in measuring the cross-sections for production of these activities at various energies can be divided into three sections: Beam collimating and measuring system, ionization chamber for observing the resulting activity and the recording and control system. Each of these is treated separately below.

1. Beam Collimating and Measuring System. This system is substantially the same as that described by E. L. Kelly and E. Segrè.[5] It is shown coupled to the ionization chamber in Fig. 2, and 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 (of the order of 2000 gauss) the pipe is provided with three sylphon joints, one at each end and one at the middle to allow the slits to be oriented properly to pick up the maximum beam 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.

Immediately behind the second slit is a wheel which can be rotated to place any one of twenty absorbers in the beam path. The absorbers used were punched from aluminum foils whith a die whose area was known to five parts in a thousand, and the foils were then weighed to 0.1 mg in order to determine their density. The wheel was enclosed in a vacuum tight casing which opened into the pipe.

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 current was measured by means of a D.C. amplifier to be described below.

Use of this system reduced the useable deflected beam by about a factor of one hundred from that available at the exit port (from 10^{-5}, 10^{-6} to 10^{-7}, 10^{-8} amps), thus in order to measure the cross-sections at low energy (21 Mev or less) more beam was needed. This was obtained by using a shorter pipe and discarding the foil wheel. The beam was allowed to pass through a window at the back end of this shorter pipe and traverse 10 cm of air before entering the front window of the ionization chamber to traverse the target and enter the Faraday cup. The necessary absorbers were placed behind the window on the pipe. Using this arrangement as much as one quarter of the deflected beam passed through the target.

2. Ionization chamber. The ionization chamber used was basically a parallel plate chamber with a Frisch grid. A schematic drawing of the chamber is shown as Fig. 3 and photographs are shown in

Fig. 4. 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 a portion 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 drive rod. The transit time from one position to the other was about 0.1 second. The 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. The principal dimensions and arrangement of electrodes are shown in Fig. 3.

Electron collection was employed and the grid to plate voltage ratio used was such as to eliminate electron collection at the grid.[9] In order to obtain fast rising pulses the chamber was filled with a mixture of about 95 percent argon and 5 percent CO_2.[10] 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 pounds per square inch, gauge pressure.

The pulses were amplified by a pre-amp and amplifier system having a rise time of about 0.1 micro-seconds. The pre-amp was operated in the fringing magnetic field of the cyclotron, where the intensity was about a thousand gauss. At first the iron tube shields

previously employed when the pre-amp had been operated in smaller fields were used, but without much success. The final setup had no magnetic shielding, but utilized instead the fact that the 6AK5's used 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 unchanged when the cyclotron magnet was turned off or on.

The target changer built into the chamber could be loaded with five targets in addition to the one originally placed in the holder, thus making six different samples available without opening the chamber. Once a target had been replaced it could not, however, be returned to the holder without disassembling the chamber.

A collimated Po^{210} alpha 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.

Some difficulty was experienced initially in finding a material to insulate the actual target holder from the piston and drive rod assembly. The material had to be a very good insulator and at the same time able to withstand the severe mechanical shock which occurred when the holder was shot back and forth. The material finally used was Teflon, which satisfied the requirements completely.

3. Recording and Control System. The principal element of the control system was a time motor which, in sequence, turned on the beam current recorder, opened the air supply to drive the target into the beam, shifted the valves to drive the target back into the

counting position, turned off the cyclotron and turned on the scaler. The duration of the bombardment could be pre-set for between one-half and two seconds, or controlled manually to allow for longer bombardments.

The recording system was built around a Brush Recorder. This consists of two, fast, recording galvanometers mounted to write side by side on a single paper tape. The available paper speeds were 0.5, 2.5, and 12.5 cm per sec. The usual procedure was to amplify the Faraday cup current with a D.C. amplifier also made by the Brush Instrument Company and to feed this as the input to one pen and the output from the pulse amplifier, scaled down by a factor of 4, 16 or 64, to the other pen. In addition a signal was supplied to the latter pen to indicate the time at which the target entered and left the beam.

4. Targets. The fact that ordinary lead is composed of a mixture of four isotopes meant that, in order to determine the cross-sections for production of each of the unknown activities several samples of different isotopic concentration had to be used. Those actually employed were ordinary lead, radiogenic lead, lead enriched in 208 and lead enriched in 207. The compositions of these are given in Table 3.

Table 3

Isotopic Concentrations in Lead Samples Used

	Ordinary	Radiogenic	Enriched in 207	Enriched in 208
%204	1.3	0.07	0.6	0.2
%206	25.2	93.3	7.4	1.9
%207	21.1	6.0	60.0	7.8
%208	52.4	0.6	30.0	90.3

The ordinary lead targets were made by evaporating a thin layer of lead onto one mil aluminum in a high vacuum chamber. The aluminum disks were cleaned with acetone and alcohol and then weighed to 0.01 mg on an assay balance. They were then placed in the evaporation tank at a distance of about 18 inches from the filament from which the lead was evaporated. After the evaporation the disks were weighed again to determine the amount of lead deposited. The samples used in measuring the cross-sections were about 0.3 mg per cm^2 thick while those used in the energy measurements were between 0.08 and 0.09 mg per cm^2.

Since several grams of radiogenic lead were on hand a standard electroplating solution containing an excess of lead over the amount to be plated out was used. The lead was plated on copper, and showed a fairly uniform appearance, although not quite as good as the evaporated targets. The sample used was 0.5 mg per cm^2.

Only a very small amount of the enriched Pb^{207} and Pb^{208} were available and thus the method used for plating the radiogenic lead was not easily applicable. The technique used was to dissolve the Pb in a warm HNO_3 solution to prevent the lead from depositing at the cathode and then plate out PbO_2 on platinum or rhodium foils at the anode for the targets. The material was not deposited quite as uniformly as in the method for plating the radiogenic lead, and it had a strong tendency to flake if the foils were flexed even slightly. A few drops of dilute Zapon solution were applied to the surface after plating and weighing and this eliminated the flaking trouble.

In some parts of the experiment bismuth foils were needed, also. These were prepared in exactly the same way as the ordinary lead targets, by evaporation.

B. Results

Several series of measurements were made, including the bombardment of all four types of lead samples (Table 3) with alphas and the bombardment of bismuth with alphas, protons and deuterons, all at several energies below the maxima available from the sixty inch cyclotron (40 Mev alphas, 20 Mev deuterons and 10 Mev protons). The data were treated as outlined in the Appendix (Section VIII) to yield typical decay curves. The curves were then peeled back and the component for each half-life was extrapolated to the time of the end of the bombardment to determine the amount of each which had been produced.

Absolute cross-sections were determined using the formula:

$$\sigma_j = \frac{\lambda_j N_{0j} A q}{\rho_s L I \varepsilon (1-e^{-\lambda_j T})}$$

In this σ_j is the desired cross-section in cm^2, λ_j is the decay constant in sec^{-1}, N_{0j} the total number of nuclei whose decay could be detected, A is the atomic weight, ρ_s the surface density (gm/cm^2) of the target material and L is Avogadro's number. q is the charge on each bombarding particle, I is the average current and T is the duration of the bombardment. Actually I is defined by

$$I(1-e^{-\lambda_j T}) = \lambda_j e^{-\lambda_j T} \int_0^T i(t) e^{\lambda_j T} dt$$

ε is the efficiency of the counter. This was taken to be 50 percent since the corrections for absorption in the target and for back-

scattering, as calculated from the equations given by Rossi and Staub,[10] proved to be less than one percent.

Inasmuch as the samples made by electroplating were not completely uniform in density, the cross-sections quoted here are those determined from evaporated natural lead targets. These have been calculated to give the cross-section for production of each activity from alpha particle bombardment of pure Pb^{208}, using 52 percent as the abundance of this isotope in natural lead[2] and are listed in Table 4. Bombarding energies were calculated from the Al range-energy curves of Arom, Hoffman and Williams.[11]

Various miscellaneous cross-sections are listed in Table 5. This includes limits on the cross-section for production of each of the three activities from alpha bombardment of radiogenic lead (93 percent Pb^{206}) and from proton bombardment of bismuth. These limits, taken in conjunction with the data in Table 4, rule out the possibility that the activities involved could arise from isotopes of mass number less than 210. The deuteron on bismuth cross-sections make it improbable that mass numbers of 210 are involved also. Table 5 shows, in addition, cross-sections for formation of the 25 sec. activity from bombardment of bismuth with alphas. These were measured by bombarding thick (about 15 mg/cm^2) bismuth targets and calculation the cross-sections relative to those for production of At^{211} as determined by E. L. Kelly and E. Segrè.[5] Correction was made for the difference in counting efficiency for the various ranges of alpha particles involved.[10] The significance of these cross-sections as compared with those in Table 4 will be discussed in Section VII.

Finally, in order to obtain quantities independent of the fluctuations in distribution of the target material in the case of the electroplated enriched isotope targets the relative yields for two activities (always involving the 25 sec. activity) were determined as shown in Table 6. Once the 2.2 minute and 0.52 sec. activities had been identified this information could be used (Section VII) to aid in identifying the reaction involved in production of the 25 second decay period. At each energy the ratios quoted involved bombardment with approximately constant current for the same length of time (30 seconds) for each target.

Table 4

Cross-Sections in Millibarns (10^{-27} cm^2) for Alpha Particle Bombardment of pure Pb^{208} (using 52% as concentration of Pb^{208} in natural lead) to produce the activity indicated.

Bombarding Energy (Mev)	0.52 second	25 second	2.2 minute
18	2.6	0.01	<0.01
20	14.8	0.17	<0.01
21-1/2	95; 80	2.3	<0.01
23	46.1	4.6	0.01
24-1/2	30.4	5.5	0.07
26	24.7	4.7	0.11
27	12.8; 10.4	3.4; 2.0	0.54
28	9.6		
30-1/2	8.2		
33-1/2	5.9		
36	5.2		
37-1/2	4.8		
39	4.1	2.2; 2.4	3.8; 3.6

Table 5

Cross-Sections in Millibarns (10^{-27} cm^2)
for Production of the Activity Indicated.

Bombarding Particle	Energy (Mev)	Target	0.52 sec.	25 sec.	2.2 min.
Alpha	31	Bi		<0.1	
Alpha	33	Bi		0.3	
Alpha	34	Bi		0.4	
Alpha	35-1/2	Bi		0.6	
Alpha	39	Bi		1.2	
Protons	10	Bi	<0.05	<0.05	<0.05
Alpha	39	Radiogenic Pb	<0.1	<0.1	<0.1
Deuterons	19	Bi	<0.1	<0.003	
Deuterons	15	Bi	<0.07	<0.001	
Deuterons	12	Bi	<0.02	0.01	

Table 6

Relative Yields from Alpha Particle Bombardments
of Lead Targets.

Bombarding Energy (Mev)	Ratio Tabulated	Value for Nat'l Pb	Pb enriched in 207	Pb enriched in 208
35	N_{130}/N_{25}	2.4	2.0	2.2
20	$N_{0.52}/N_{25}$	3.3	3.8: 3.4	
18	$N_{0.52}/N_{25}$	9.6	10.0: 10.5	

IV. MEASUREMENT OF ACTINIUM C' HALF-LIFE

After the cross-section measurements had been made it became apparent that the short-lived activity had an excitation function like that for an α,n reaction on Pb^{208}. In addition, the rough energy measurement had shown that these were about 7.5 Mev alphas. Both these pieces of evidence pointed out Po^{211} as the product, however the half-life measured here (0.6 ± 0.1 sec.) was not at all in agreement with that listed in existing tables (5×10^{-3} sec.). An examination of the literature finally showed that the quoted value had merely been estimated from the Geiger-Nuttall law many years ago. At this point it was obviously necessary to measure the decay constant by some experiment independent of the production from lead.

A convenient source of Polonium 211 for this experiment was At^{211}. This decays both by direct alpha emission to Bi^{207} and by K-capture to Po^{211}. The alpha branching ratio is 0.40 and the half-life is 7.5 hours[4]. The energy of the At^{211} alpha (5.9 Mev) is sufficiently different from the 7.43 Mev of the Po^{211} alpha to make discrimination by means of range relatively simple. At first glance two methods of approach presented themselves. One was to measure delayed coincidences between the X-rays accompanying the K-capture and the subsequent alpha emission from the Po^{211}. This would be applicable if the half-life were of the order of a hundredth of a second or less. The other was to try to find a suitable method for separating the polonium from the astatine rapidly. As it turned out, a separation procedure, suggested by A. Ghiorso*, was available, so this method was tried.

---

* Private communication.

The separation process was based on the fact that while polonium will stick to platinum at a dull red heat, the astatine evaporates off quite easily.

The experimental arrangement consisted of a platinum filament about one centimeter wide and five centimeters long inserted in an electrical circuit which could, by means of a motor driven switch, provide reproducible current pulses of about one twentieth of a second duration. Two different thicknesses of platinum were used (1.2 mil and 0.7 mil) in order to detect any possible effect due to different heating times. The filament was mounted on a sliding holder in order that it could be positioned either over or away from 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 At^{211} alphas. The counter output was amplified and fed to a scale of 64 or 1000 from which output pulses were recorded on the moving tape of a Brush Recorder.

The astatine was made by bombarding a thick bismuth target with alphas from the 60-inch cyclotron. The beam energy was reduced to about 28 Mev with aluminum absorbers in order that no At^{210} would be formed to give rise to a Po^{210} background. The bismuth was then heated in a vacuum and the evaporating astatine was caught in a liquid air trap. The astatine 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 filament 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 using the method described in the Appendix (Section VIII) and the resulting half-life was determined to be 0.52 ± 0.01 seconds. A section of the Brush Recorder tape for one run is reproduced in Fig. 5 and the results of two runs are plotted in Fig. 6.

The disagreement between this value and that estimated from the Geiger-Nuttall law, while large, is not particularly surprising in view of the behavior of other nuclei having values of Z and N in the vicinity of 82 or 126[1, 12].

A thorough investigation[1] of the characteristics of the many known alpha emitters shows that there are certain regularities present. In particular, for nuclei of even Z and even N, with $Z \geq 86$ and $N \geq 130$ the relationship between decay energy and half-life is a very smooth one. Kaplan[13] has shown, in fact, that if the Gamow barrier penetration theory is used in the form given by Preston[14] to calculate the nuclear radius of the daughter from the known Z,

decay energy and half-life of these nuclei, then the radii of the daughters fit to within a few percent the relationship: $1.57A^{1/3} \times 10^{-13}$ cm.* Using this expression for the radius in Preston's formula[14] one obtains for the calculated half-life of Po^{211} the value 8.4×10^{-4} sec.

One point to be remembered, however, is made clearly by Perlman, Ghiorso and Seaborg[1]. Namely that, in general, alpha decay of nuclei having either odd Z or N or both is forbidden relative to that of their even-even neighbors. The Geiger-Nuttall law as stated for the Actinium Series should contain an average correction for this fact since its empirical basis is a group of odd-even and even-odd nuclei, thus accounting for the discrepancy between the old predicted value of 5×10^{-3} and the calculated one of 8×10^{-4} seconds.

A second consideration is that in the vicinity of Z = 82 and N = 126 the degree of forbiddenness increases, and the even-even nuclei themselves fail to agree with predictions based on the simple $A^{1/3}$ radius relationship. Presumably this second effect is due at least in part to an actual shrinkage in the nuclear radius below the $A^{1/3}$ value, due to the strong binding in the closed neutron and proton shell configurations. This effect makes the half-life of Po^{210} about 30 times as long as the simple theory would predict and in Po^{209} the two effects make the half-life about 150 times as long as would be expected.

Thus the fact that the Po^{211} half-life is observed to be 620 times as large as predicted fits roughly with the pattern of its

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* Perlman and Ypsilantis[12], using a more approximate form of the theory find $r = 1.48A^{1/3} \times 10^{-13}$ cm.

neighbors and can be attributed to its even-odd character and the proximity of its daughter (Z = 82, N = 125) to the closed shells at Z = 82 and N = 126 where an actual shrinkage in nuclear radius is to be expected.

The possibility that the 25 second activity might be isomeric with the 0.52 second activity indicated that additional runs should be 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, without correction for the losses at this rate, of 465,000 Po^{211} 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 counts per minute, with no sign of any 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 secular equilibrium with the parent At^{211}. Thus the ratio of 25 second to total Po^{211} activity at zero time would be identical with the fraction of the At^{211} K-captures going to the state having the 25 second half-life, i.e. less than 10^{-4}.

V. CHEMICAL SEPARATION EXPERIMENTS

These experiments were made in order to determine the element to which each of the two longer activities should be assigned. It could be assumed that after a bombardment the heavy elements present

in the target would be lead, bismuth and polonium. Two different separations were made. In the first, polonium was extracted from the combination and the twenty-five second activity was observed to go with the polonium fraction. In the second, bismuth and polonium together were separated from the lead, and in this case both the 130 second and the 25 second activities were in the bismuth-polonium portion.

In both methods the target material 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 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 target used is shown in Figs. 7 and 8. In this assembly the target material 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 the Brush Recorder described in Section III.

The analysis for polonium[15a] was fairly simple. The lead carbonate was dissolved in hot, six normal HCl containing 1.0 mg per liter of Bi as a holdback. A piece of silver foil was inserted in

the solution and stirred in it for about one minute, after which it was removed, washed with 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 sec. activity following a 30 second bombardment at about 2 microamperes of 30 Mev alphas.

The separation of polonium and bismuth from lead[16] went as follows. The $PbCO_3$ 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 1 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 proportional 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[15b] 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 by Prodinger's method[16].

The data obtained from the polonium extractions showed the half-minute activity clearly. This allowed an opportunity for an accurate determination of the half-life of the half-minute mode of decay, which turned out to be 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 2.2 minute activity. Thus this experiment indicated that the 25 second decay period should be assigned to some isotope of polonium, 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 bismuth isotope, and the agreement between the observed half-life and that known for Bi^{211} (Actinium C) (Table 2) indicated that this reaction could definitely be assigned as $Pb^{208}(\alpha,p)Bi^{211}$.

VI. ENERGY MEASUREMENTS

It was naturally desirable to learn the energies of the alpha particles emitted by the various isotopes involved in this experiment. In the first place this could aid in identifying some products and, in the case of previously unknown products, this would be a valuable

additional piece of information.

The equipment used was the argon filled parallel plate ionization chamber, with Frisch grid, described in Section III, A, 2. The target holder was driven back and forth with argon in order to avoid the possibility of introducing small amounts of oxygen into the chamber.

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 driven 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 of from 5 ft. per sec. to 1-1/2 in. per sec., in order that speeds appropriate to the level of activity would be available. The film was processed in a portable developing tank, using D-19 developer and Kodak Rapid Fixer. After drying, the film was viewed using a micro-film viewer, and the pulse heights were measured. Typical pulses are shown in Fig. 9.

The linearity of the response of the electronic system was checked by applying voltage pulses to the grid of the chamber and photographing the resulting display on the oscilloscope face. The pulse amplitudes were increased in even steps and the results given in Fig. 10 show that the output actually varied in somewhat non-linear fashion. Since the response was strictly linear over this

region when the pre-amp was not in the magnetic field of the cyclotron, it is believed that the field was responsible for the apparent change in amplifier response. 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 of chamber, the 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 a particular pulse height were known. However, since three well defined alpha groups were readily available it was possible to construct directly a pulse height versus energy curve covering the necessary energy range as shown in Fig. 11. The three groups used were Po^{210} (5.30 Mev), At^{211} (5.9 Mev) and Po^{211} (as it occurs following the At^{211} K-capture) (7.43 Mev). The pulse height distributions for these three calibrating points are shown in Figs. 12 and 13. The shape of the pulse height vs. energy curve agreed within the experimental error with the pulse height vs. pulse generator setting 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 (Section III, A. 4) with 22 Mev alphas for thirty 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 130 second activity is formed, but the pulses were recorded on the Brush Recorder tape as a check and subsequently it was

determined that less than 5 percent of the counts could have been associated with the longer decay period. Fig. 14 shows the pulse height distribution for this case, with peak at 62.0. Referring to Fig. 11 the resulting energy is 7.14 ± 0.05 Mev, which indicates that the 25 second activity decays from the lower state of Po^{211} and that the 0.52 second decay occurs from a Po^{211} state which is excited by 0.3 ± 0.05 Mev.

This same pulse height distribution, illustrated in Fig. 14, shows some additional interesting features: The presence of one alpha group with energy about 9 Mev and possibly one at about 8-1/2 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 of the order of 10^{-2} second much less a lifetime long enough to allow its observation as long as half a minute after its production. This group may be the same as that reported[17] to occur somewhere in the natural decay chain following Actinium B. Below the principal peak there is a possible group at 5.9 Mev (pulse height 53) and one at about 5.3 Mev (pulse height 48-1/2). The latter one is most probably due to Po^{210} from the α,n reaction on Pb^{207}. The 5.9 Mev is just the energy for At^{211} decay, but the cross-section for formation of this using 22 Mev alphas on bismuth is rather small. In turn this would necessitate that over 15 percent of the Pb be Bi, and this is not possible. There is the possibility that this group, being only about 1 percent of the total intensity, could be the low energy counterpart of the 6.34 Mev alpha group reported[18] as occurring

in the decay of the 0.52 second Po^{211}. The evidence at this point is, however, inconclusive because of the high background in this energy range. Further consideration of the possible existence of low energy groups will have to await an increase in the resolving power of the equipment used, or the application of a different method.

Another set of energy measurements was made at an earlier stage in this experiment. In that case the electronic equipment was almost identical with that used in the more recent measurements. The chamber was a parallel plate one, with grid. The target material was permanently mounted on the high voltage electrode, and the beam traversed the active volume of the chamber during the bombardment period. Only Po^{210} alphas and the pulse generator were used for calibration purposes. The pulse generator vs. pulse height curve was quite linear (the pre-amp was located in a weaker part of the cyclotron magnetic field) but the use of only one point, at 5.3 Mev, to set the energy scale decreased the reliability of the measurements in the 7 Mev range. At that time two peaks were observed, separated by about 0.3 Mev, the upper one being estimated as 7.6 $\pm$ 0.2 Mev and belonging to the 1/2 second activity. It was this energy and the α,n type excitation function which made it advisable to look for the AcC' half-life in the 1/2 second range. Once it was determined from half-life considerations that the 1/2 second decay period actually did belong to Po^{211} (as it occurs in the decay of At^{211}) then the upper peak could be used as a calibration point at 7.43 Mev and this gave 7.15 $\pm$ 0.1 for the alpha energy associated with the 25 second activity.

These measurements showed a distribution above the principal peak which was very similar to that observed in the later runs, showing a definite peak at about 9.1 Mev and a possible peak at about 8.3 Mev. Since in both cases the statistics in the region above the main peak were poor, not too much faith can be placed in the exact values. However, it is certain that these 9 Mev alphas exist, since in no other case (Po^{210} or astatine pulse heights) are any pulses of this height observed.

VII. CONCLUSIONS

This section is divided into the following parts:

A. Bismuth 211

B. Polonium 211 ($T_{1/2}$ = 0.52 sec.)

C. Polonium 211 ($T_{1/2}$ = 25 seconds)

D. Comparison of Po^{211} states, spin assignments

E. Long Range Alpha Particles

The first three summarize the concrete information which is obtainable from the experiments discussed in Sections III, IV, V, and VI. This concerns the half-lives, energies, identification and excitation functions of the three activities studied. Parts D and E set forth conjectures which can be made with regard to spin assignments for the two states of Po^{211} and the origin of the long range alpha particles. The arguments in these latter two parts will naturally be subject to revision if more contributing material should become available.

A. Bismuth 211

This bismuth isotope was identified by chemical separation (Section V) and by measurement of its half-life, which agreed to within the experimental error with the previously measured value (Table 2).

The production of this activity from Pb^{208} by an (α,p) reaction was observed and a rough excitation function was measured (Table 4). In theory the difference between these cross sections and those for the (α,n) reaction should be accounted for primarily by the fact that the outgoing proton will be influenced by the coulomb barrier. Unfortunately, in the region in which barrier penetration calculations could be made the (α,p) cross-sections were too small to allow observable production. Between proton energies of 8 and 12 Mev (bombarding energies from 23 to 27 Mev, barrier is about 13 Mev) the proton energy is above 1/2 of the proton barrier energy, and the WKB approximation can not be applied to the barrier problem. In this latter region, the data in Table 4 shows that the ratio of (α,p) to (α,n) cross-section changes a little more slowly than $e^{-\frac{Zze^2}{\hbar v_p}}$. At energies well above the barrier the two cross sections [(α,p) and (α,n)] as would be expected, are of about the same magnitude.

B. Polonium 211 (0.52 second)

This is one of the least studied of the naturally occurring radioactive nuclei. The existence of this isotope as an alpha emitting beta decay daughter of AcC was first inferred by analogy with the cases of RaC → RaC' and ThC → ThC' by E. Marsden and his co-

workers. They tested their hypothesis and found the long range alpha group now associated with this nuclide. This was reported in 1914 by Marsden and Perkins[19]. In the same article a 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.

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 in 1931[20]. They obtained a mean range of 6.506 cm. This was corrected by Holloway and Livingston[21] to a value of 6.555 cm.

In 1940 Corson, MacKenzie and Segrè[4] found AcC' 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.[20], as corrected by Holloway and Livingston[21].

The work reported in the present paper includes the measurement of the half-life of this activity by actually separating it chemically from the parent At^{211} and observing its decay as described in Section IV. As has been stated previously this was determined to be 0.52 seconds instead of the 0.005 seconds previously estimated. The measured energy was in agreement with the previously determined 7.43 Mev.

The direct production of Po^{211} from an α,n reaction on Pb^{208} has also been observed for the first time and a rough excitation function for this reaction is presented in Table 4. 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 excitation functions have been made in this portion of the periodic table, although the $Bi^{209}(\alpha,n)At^{212}$ may be available in the near future.

Assuming that an (α,n) reaction should have a cross-section which behaves in a way similar to a (p,n), one can compare this with the results of Kelly[22] 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.

One method of comparison with theory is to use the total cross-section for alpha bombardment as given by Weisskopf[23]. 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 (α,2n) and (α,p) reactions. Comparison above this region is not possible since the (α,2n) and (α,3n) cross-sections are not known. The comparison at the low energy end is shown in Fig. 15 in which the solid lines are the theoretical total cross-sections[23], using $r_oA^{1/3}$ as the nuclear radius where $r_o = 1.5 \times 10^{-13}$ cm in one case and $r_o = 1.3 \times 10^{-13}$ cm in the other. It is seen that the experimental points indicate rough agreement with a value of $r_o = 1.4 \times 10^{-13}$ cm. This value is close to the value $r_o = 1.43 \times 10^{-13}$ cm found in a similar way by Kelly[22] for $Bi^{209} + \alpha$ based on excitation functions for the α,2n and α,3n reactions.

C. Polonium 211 (25 seconds)

In addition to the 0.52 second Po^{211} discussed above, this experiment has been concerned with a 25 second alpha emitter, chemically identified as polonium (Section V). In view of the fact that the half-lives and energies of all the possibly produced polonium alpha emitters are known, it seems that this activity must be isomeric with some previously observed nuclide. The following argument, based on the lack of variation in 25 second to 0.52 second yield ratio with change in isotopic concentration, indicates that the 25 second activity should be assigned to Po^{211}.

Consider two targets, a and b, each of thin lead, but having different percentages of the various stable isotopes. If one of these is bombarded with a constant 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:

$$\delta = \frac{N_{0.52}}{N_{25}} = \frac{0.52}{25} \frac{\sigma_{0.52}}{\sigma_{25}} \frac{P_{208}}{P_x} \frac{(1-e^{-\lambda_{0.52}T})}{(1-e^{-\lambda_{25}T})}$$

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. λ and σ are the appropriate decay constants and cross-sections. If the other target is bombarded at constant current for the same length of time at the same energy then the ratio of the δ's will be

$$\gamma = \frac{\delta_a}{\delta_b} = \left(\frac{P_{208}}{P_x}\right)_a \left(\frac{P_x}{P_{208}}\right)_b$$

The two targets under consideration are (a) natural lead and (b) lead

enriched in Pb^{207}. Based on the isotope percentages listed in Table 3 the following calculations can be made:

If $x = 208$ then $\left(\frac{P_{208}}{P_x}\right)_a = \left(\frac{P_{208}}{P_x}\right)_b = 1$ and $\gamma = 1$

If $x = 207$ then $\left(\frac{P_{208}}{P_x}\right)_a = \frac{52.4}{21.1} = 2.48$; $\left(\frac{P_{208}}{P_x}\right)_b = \frac{30.0}{60.0} = 0.50$ and $\gamma = 4.96$

If $x = 206$ then $\left(\frac{P_{208}}{P_x}\right)_a = \frac{52.4}{25.2} = 2.08$; $\left(\frac{P_{208}}{P_x}\right)_b = \frac{30.0}{7.4} = 4.28$ and $\gamma = 0.49$

Based on the averages of the experimental results (relative yields) shown in Table 6 we find at 18 Mev $\gamma = \frac{11.5}{10.2} = 1.13$ and at 20 Mev $\gamma = \frac{3.3}{3.6} = 0.92$ both essentially one within the accuracy of these runs. The end result of the argument given above is to show rather definitely 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 α,2n reaction. Taken with the chemical identification of the 25 second activity as polonium, this means that the best assignment of the 25 second decay is to Po^{211}, isomeric with 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 be an excited state lying at least 1.9 Mev above its ground state. This would require at least a sixth order transition to the ground state if it were the only available level, and from what is known of nuclear energy levels in this region there would in such an energy range be several other levels to which jumps could be made, not all of which could also be highly forbidden. Thus again the only possible assignment consistent with the chemical identification as polonium is to Po^{211}.

The alpha particle energy for this activity, as set forth in Section VI above, is 7.14 Mev. This means a total decay energy of 7.28 Mev as compared with 7.57 for the 0.52 second activity. This means that the 25 second decay is retarded relative to the decay of an even-even nucleus of radius $1.57A^{1/3} \times 10^{-13}$ cm by a factor of 3350 while the 0.52 second lags by only 820 (using Preston's equations[14]).

The $Pb^{208}(\alpha,n)Po^{211}$(25 second) has an excitation function which is depressed considerably below that for the more normal appearing excitation function for the 0.52 second activity at the low energy end and then 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. Another explanation for the small cross-section relative to that for the 0.52 second Po^{211} would be to assume that most of the states lying close above these had spins near that of the 0.52 second isomer, and thus when excitation was not high the chances of cascading into the 0.52 second state would be greater.

The 25 second Po^{211} has also been produced by bombardment of Bi^{209} with alphas. Here the reaction would be an (α,pn) if our assignment is correct. A theoretical treatment of the probability of decay of the compound nucleus by emission of a proton and a neutron relative to that for decay by emission of two neutrons is not a simple one. Part of the difficulty is that in the two neutron case a particular neutron can go out with any energy below the maximum

available, with no hindrance, while the exit of a low energy proton is much impeded by the coulomb barrier. Thus if the first particle boiled off is a neutron with a relatively large share of the available energy then the probability that this particular event will be a 2n rather than a pn is enormously increased. Thus the (α,pn) to $(\alpha,2n)$ ratio will involve the barrier transmission for all proton energies from zero to the excitation energy, while only the maximum barrier transmission, occurring at the full excitation is involved in the (α,p) reaction. This effect will tend to make the ratio of $\sigma(\alpha,pn)$ to $\sigma(\alpha,2n)$ much smaller than the $\sigma(\alpha,p)$ to $\sigma(\alpha,n)$ ratio to the same excitation energy of the compound nucleus. This relative effect is actually observed. A similar, qualitative argument can be made for the $\alpha,p2n$ vs. $\alpha,3n$ cross-sections, however, which produces the same result, thus this portion of the work makes no contribution to the identification of the 25 second activity as Po^{211} rather than Po^{210}.

D. Comparison of the two Po^{211} States, Spin Assignments

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 any more than a lower limit on the half-life for such a transition. Neither of the two spins has been measured directly, nor is there any beta decay data linking either state to some other nucleus of known spin. The information available concerns (1) alpha decay to a nucleus of known spin,

(2) gamma decay energy and limit on half-life, and (3) relative cross-sections for production of the two states. Each of these will be discussed in turn below, but all merely set the order of magnitude of the spin difference between the two states, and indicate which state has the higher spin. This information can then be correlated with the predicted levels from the one-particle (shell) model of the nucleus[24] and spins tentatively assigned which are compatible with both the theory and the information available. These topics will be discussed in detail in the following order:

1. Excitation energy
2. Alpha decay
3. Decay of upper to lower state
4. Relative cross-sections
5. Shell model and spin assignments

1. Excitation energy. In general our discussion must be based on the difference between the two observed alpha decay energies. How we can correlate them with the actual energy difference between the two Po^{211} states will depend on the states of Pb^{207} which are available as terminations for these two alpha decays.

The energy levels of Pb^{207} have been studied previously in several ways. Harvey and others at Massachusetts Institute of Technology[25] have investigated the proton and triton spectra from the reactions $Pb^{206}(d,p)Pb^{207}$ and $Pb^{208}(d,t)Pb^{207}$. They find that the first excited state lies at 0.61 Mev above ground and the next at 0.95 Mev, but their resolving power is not sufficient to allow detection of a level

within about 0.05 Mev of ground. Neumann and Perlman[18] have presented a level scheme based on the fine structure of the Po^{211} alphas (as they occur in the decay of At^{211}) and on the conversion electron spectrum from the Bi^{207} -Pb^{207} K-capture. Their first three excited states are at 0.54, 0.88 and 1.06 Mev. There is one electron group at 0.049 Mev, indicating a gamma of either 0.137 or 0.064 (depending on whether K or L conversion is assumed), which is not assigned, but may occur in a transition between two excited states, although none of the differences correspond to this energy. The breadth of the principal alpha peak (at 7.43 Mev alpha particle energy) is such that a 0.1 percent peak at 7.14 Mev indicating presence of the 25 second alpha decay state or a small peak slightly above the principal one would not have been observed, thus the previously deduced limit on K-capture into the 25 second state is not contradicted, nor is the possibility that the most probable decay goes to a level slightly above ground in Pb^{207}, with a highly prohibited decay with slightly higher energy to the ground state. In addition to the above experiments, E. C. Campbell and M. Goodrich[26] have observed a 0.9 second gamma emitter following irradiation of Pb with slow neutrons in a pile at Oak Ridge. This isomer is assigned to Pb^{207} by Goldhaber and Sunyar[27] with transitions of 1050 followed by 520 Kev based on unpublished supporting evidence found by M. H. L. Pryce. These levels are compatible with some of those found in the alpha decay fine structure observations.

The implications are then that e_1 in Fig. 16 must be, say, 0.05 Mev or less. The possibility that the 25 second state could lie such

that $e_2 > 0.3$ is very small since then the direct alpha decay to the ground state would be so favored by the greater available energy that no reasonable spin assumption could account for the long life of this state. Thus, from knowledge that the Pb^{207} levels are widely spaced we are led to the conclusion that both the 25 second and 1/2 second states decay to the ground state of Pb^{207} or to some previously unobserved level quite close to it. This means in turn that the 1/2 second state lies approximately 0.3 Mev above the 25 second one.

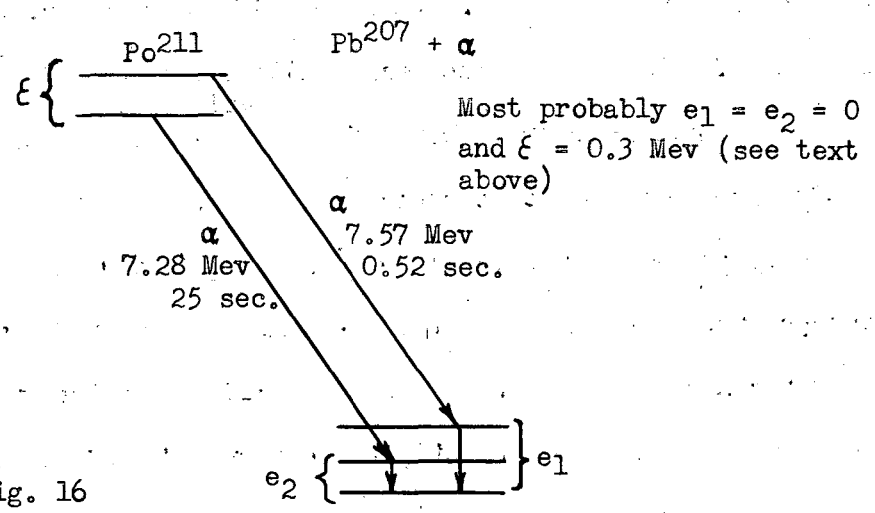


Fig. 16

2. Alpha decay. Observation of alpha half-lives and energies[1] shows that if a nuclear radius of $r = 1.57\ A^{1/3} \times 10^{-13}$ cm[13] is used in the decay formula of Preston[14] with the observed alpha decay energy corrected for the recoil of the product nucleus then the calculated decay constant for 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. In these cases $\lambda^{calc}/\lambda_{obs}$ is greater than unity, indicating that the actual decay is inhibited in some way relative

to the regular decay of the even-even nuclides. Several factors contribute to this retardation. One is the relative difficulty in forming an alpha particle from a nucleus in which there are unpaired nucleons in the uppermost energy states. Another is the fact that in many cases there is an angular momentum change involved, which introduces a centrifugal barrier into the problem in addition to the coulomb one. In the cases near the closed shells it is thought that there is an actual decrease in the nuclear radius below the $A^{1/3}$ law, which would account for the retardation in the decay of even-even nuclides such as Po^{210}.

In the case of Po^{211}, since from Part D,1 of this section 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 $A^{1/3}$ law prediction. Applying the most rigorous available development of the barrier penetration theory including angular momentum change[14] using the observed energies and several assumed radii (from 1.27 to 1.47 $A^{1/3} \times 10^{-1/3}$ cm) it is found that the prohibition of the 25 second relative to that of the 0.52 second decay is accounted for by assuming an angular momentum change of 5 or 6 units for the 25 second and 0 or 1 for the 0.52 second activity. This in turn implies (from the Pb^{207} spin of 1/2) that the spin of the 25 second state is large (9/2 to 13/2) while the spin of the 1/2 second state is small (1/2 to 3/2). These calculations do not single out a well-defined number for the nuclear radius unless some assumption is made with regard to the retardation due to even-odd nuclear character, but indicates that

values between 1.3 and 1.4 $A^{1/3} \times 10^{-13}$ cm are the most acceptable.

3. Decay of Upper to Lower State. Since we have concluded that the 0.52 second state most probably lies above the 25 second state by about 0.3 Mev then it is possible to make an estimate of the probability of decay of the upper to the lower state. This can then be compared with the upper limit placed on the probability of this transition by the lack of presence of 25 second alphas following separation of Po from At, (See Section IV). Using an energy of 0.3 Mev and the approximate formula of Bethe as given by Segrè and Helmholz,[28] the value of λ_γ can be calculated for various orders of transition, Λ, where Λ = the multipole order, 1, for electric and the multipole order plus one for magnetic transitions. Such values of λ_γ are for the gamma transition alone and include no allowance for internal conversion transitions, which, for large Z and a high order transition, would play a considerable part. The actual decay constant for the transition from the upper to the lower state is $\lambda = \lambda_\gamma + \lambda_c = \lambda_\gamma(1 + \alpha)$. Theoretical calculations of α for K shell conversion in electric dipole transitions have been made for $h\nu = 0.3$ Mev and Z = 83 by Hulme[29]. He found α_K(dipole) = 0.03. Similar calculations by Taylor and Mott[30] for the quadrupole case give α_K(quad) = 0.11. Taylor and Mott quote experimental results from the work of Ellis and Aston on RaB which give, for $h\nu = 0.3$ Mev, a value of 0.18. (Note - these values have been changed from those in the original articles to take care of the fact that in their notation the ratio of number of electrons to the number of gammas is $\alpha/1-\alpha$ while ours is simply α). Segrè and Helmholz[28] quote formulae of Dancoff and Morrison for both electric and magnetic multipole

conversion. These are relativistically correct, but involve the assumption that the electron binding energies are small compared with the decay energy. These formulae are not particularly useable in this range (primarily because of the large Z) but they may serve as a guide in estimating the order of magnitude of the conversion effect. For electric quadrupole and dipole they differ from the values of Mott, Taylor and Hulme by factors of from 2 to 4. In addition to the K conversion one should also consider L shell conversion in this range. Values of N_K/N_L for electric transitions have been taken from a graph by Hebb and Nelson published by Segrè and Helmholz[28]. The values for the decay constants using the above formulae and graphs are shown in Table 7. These values should be taken merely as indicative and, particularly in view of the neglect of the L and higher conversion, and the approximate nature of the formulae, may be off by several factors of ten.

Table 7

Order	Type	Conversion	Decay Constant
3	elect	K and L	2.7×10^{5}
3	mag	K	7.6×10^{4}
4	elect	K and L	4.1
4	mag	K	0.42
5	elect	K and L	1.1×10^{-4}
5	mag	K	2.3×10^{-6}
6	elect	K	1.2×10^{-10}
6	mag	K	1.2×10^{-11}

Keeping the necessary precautions in mind it can be seen that the $\Lambda = 6$ (or above) transitions and possibly the $\Lambda = 5$ transitions could be compatible with the upper limit of 10^{-4} which is placed on λ by the experiments of Section IV.

A recent article by Goldhaber and Sunyar[27] tabulates and classifies a large number of isomers, and, judging from the assignments made there, the limits given above are rather conservative. In that article the 394 Kev Pa^{234} isomer, with partial half-life for decay to its ground state of 5.7×10^4 seconds is assigned as an electric 2^4 pole while Hg^{199}, 368 Kev, $T_{1/2} = 2.6 \times 10^3$ seconds and Hg^{197}, 164 Kev, $T_{1/2} = 3.0 \times 10^5$ seconds are both assigned as magnetic 2^4 pole transitions. On this basis it would seem that the Po^{211} isomer could be an electric or magnetic 2^4 or any transition of higher order.

<u>4. Relative Cross-Sections</u>. In Part B of this section the excitation function for the production of the 1/2 second activity by an α,n reaction is discussed, while Part C covers the cross-sections for formation of the 25 second activity and sets forth some possible reasons for the fact that formation of the 1/2 second state is more probable than formation of the 25 second state at low energies. The strongest of these is that the centrifugal barrier reduces the probability of barrier penetration by high angular momentum alphas in this region in which the cross-section is still strongly limited by the coulomb barrier also. Thus, since most of the states formed apparently cascade easily into the 0.52 second state then it can be assumed that it has a low spin as compared with the 25 second state.

5. Spin Assignments and Nuclear Shell Model. At this point we should examine the statements made in connection with the one-particle model of the nucleus, particularly as developed by Mayer[24] using the assumption of strong j-j coupling. This theory gives an explanation of the magic numbers, and predicts the various nuclear spins properly in most instances for even-odd and odd-even nuclides. Goldhaber and Sunyar,[27] 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.[24] In the region in which we are interested (127 neutrons - beginning of new shell) the only statement of level order in Mayer's paper does not include the splitting due to the spin - orbit coupling, but gives as the order: $1i_{11/2}$, $2g_{9/2}$, $2g_{7/2}$, $3d_{5/2}$, $3d_{3/2}$, $4s_{1/2}$, etc. One of the fundamental assumptions made by Mayer is that levels within one shell, which arise from adjacent orbital levels in the square well approximation in such a way that spin - orbit coupling tends to bring their energy closer together can, and often will, cross. Specific examples given by Mayer include the $d_{3/2}$ - $s_{1/2}$ and $g_{7/2}$ - $d_{5/2}$ levels. Thus it is possible that some order such as: $1i_{11/2}$, $2g_{9/2}$, $3d_{5/2}$, $4s_{1/2}$, $2g_{7/2}$, $3d_{3/2}$, etc., might exist, even possibly with the $1i_{11/2}$ and the $2g_{9/2}$ interchanged. One thing is certain, and that is the prediction that all the levels should have even parity.

Applying this to Po^{211} and accepting Goldhaber and Sunyar's assignment[27] of electric 2^4 pole transitions, then the possible transitions which would lead to the appropriate half-life for gamma

decay involve angular momentum changes of 4 or more units. This would make available only transitions between the levels $s_{1/2}$ - $g_{9/2}$, $s_{1/2}$ - $i_{11/2}$, and $d_{3/2}$ - $i_{11/2}$. The third of these is the least probable, since it is known that there is a large energy difference (due to the postulated spin - orbit coupling) between the $d_{5/2}$ and the $d_{3/2}$ levels, and thus the $d_{3/2}$ state would be depleted rapidly by a magnetic dipole transition to the $d_{5/2}$ state. This leaves the two involving the $s_{1/2}$, with the $s_{1/2}$ - $i_{11/2}$ as the more logical.

This assignment agrees with a large angular momentum change (5 units) for the 25 second alpha decay and a small one (1 unit) for the 0.52 second decay, since it is most probable that both alpha decays go to the $p_{1/2}$ ground state of Pb^{207}. Agreement is also good for the assumption that the additional centrifugal barrier inhibits formation of the 25 second relative to the 1/2 second activity at the low energy end of the excitation function.

The only objection to this assignment arises in connection with the K-capture in At^{211}, which favors the 0.52 second state quite strongly (see Section IV). According to the shell model the odd proton (85th) in At^{211} should be in an $h_{9/2}$ state, as is known to be the case for the 83rd proton in Bi^{209}. This would presumably give the At^{211} a spin of 9/2, and consequently the K-capture would be favoring a large spin change in preference to a small one. However, in Na^{23} which should have a $(d_{5/2})^3$ configuration the spin is 3/2 rather than 5/2 and similarly Mn^{55} which has a spin of 5/2 is in an $(f_{7/2})^5$ state. Goldhaber and Sunyar[27] interpret this as a breakdown of the rule that j-j coupling of an odd

number of nucleons of equal j leads to a spin j as the lowest state. This breakdown is attributable to taking into account the finite range of the forces involved. Thus, in the absence of an experimental determination of the spin of At^{211} it is not felt that this objection should be given too much weight.

E. Long Range Alpha Particles

At the present time very little is known of the long range alpha particles reported in Section VII.

The first question that can be discussed concerns the validity of the measurements themselves. The fact that the pulses have been observed whenever a pulse height analysis has been made shortly after a bombardment of lead with alphas indicates that the experiment is reproducible. The possibility that the pulses arise somewhere in the equipment, rather than from actual alphas in the chamber is ruled out by the fact that the pulses do not appear when other targets (Pt and Bi) are substituted for the Pb. Examination of the shapes of the pulses shows that they can not result from coincidences between pairs of pulses. This is borne out also by the lack of appearance of such pulses when other targets are in use, even when the counting rates are higher than those with which the high pulses were observed. Thus it seems an inescapable conclusion that there are alphas of about 9 Mev actually traversing the chamber as long as a minute after the conclusion of the bombardment, without a high counting rate of such particles at any earlier time.

This then indicates that they are associated with a decay period of longer than a few seconds, and thus, in view of their high energy they must occur in cascade with some other activity produced by alpha bombardment of Pb. The parent state must then lie 9 Mev plus its own decay energy above the final product, and its own decay energy must be such as to allow it to have a half-life in excess of ten seconds. This condition can be written as $M_Z^A + E^* > M_{Z-2 \pm 1}^{A-4} + M_{He} + 9$ Mev, using atomic masses and with E^* as the excitation energy of the parent state. In addition, in order that direct alpha decay of the parent with too short a half-life will not occur, there cannot be too much energy available, certainly not more than 8 Mev. This imposes the additional restriction: $M_Z^A + E^* < M_{Z-2}^{A-4} + M_{He} + 8$ Mev. Combining these two relationships gives: $M_{Z-2}^{A-4} + M_{He} + 8 > M_{Z-2 \pm 1}^{A-4} + M_{He} + 9$ Mev. In mass units this gives (with 1 Mev = 0.00107 mass units) $M_{Z-2}^{A-4} > M_{Z-2 \pm 1}^{A-4} + 0.00107$.

Within the range of possible products for which the data is available only four satisfy the above relationship, none satisfying it with $E^* = 0$. In each case, with $E^* > E^*_o$, there will be two other processes competing with the one leading to the 9 Mev alpha. These are gamma decay of the parent from its excited state to its ground state with energy $E^* > E^*_o$, and direct alpha decay of the parent with E'_α $E'_{\alpha o}$. These various quantities are given in Table 8. The Po^{209} parent is rather definitely ruled out by the high available energy for direct alpha decay, as well as the high excitation energy. The Bi^{210} and Pb^{209} are acceptable from the

Table 8

Parent	9 Mev Alpha Emitter	E_o^* (Mev)	$E'_{\alpha o}$ (Mev)
Bi^{211*}	Po^{211*}	0.78	7.53
Bi^{210*}	Po^{210*}	2.43	7.3
Po^{209*}	Bi^{209*}	2.94	7.9
Pb^{209*}	Bi^{209*}	3.73	7.39

alpha decay point of view, but a very high order transition would be necessary to keep the excited state alive for the appropriate length of time. This leaves the Bi^{211} parent as the most reasonably acceptable, although the alpha decay has somewhat more available energy than is compatible with the probable half-life. Further experiments will be necessary to check this hypothesis.

VIII. APPENDIX: TREATMENT OF BRUSH RECORDER DATA

The number of counts occurring in an interval, t, starting at t_a is given by the well-known expression:

$$N_a = mt + \sum N_{0j} e^{-\lambda_j t_a}(1 - e^{-\lambda_j t})$$

where m is a continuous counting rate from background or activities of half-life long compared to those being investigated, and the j refers to the various activities of interest.

Usually one of two cases can be conveniently exploited. The first possibility, $\lambda t \ll 1$, in which case $N_a = \left[m + \sum \lambda_j N_{0j} e^{-\lambda_j t_a}\right] t$ and the various values of N_a/t can be plotted on semi-log paper against t_a to find both the zero time activity and the half-life. The second possibility is to make t the same for all the various

observations, in which case $N_a = mt + \sum N_{0j}(1 - e^{-\lambda_j t})e^{-\lambda_j t_a}$. Here again the slopes give the λ_j, but the intercepts of the component curves give $N_{0j}(1 - e^{-\lambda_j t})$. Neither of these methods uses to the fullest the data as displayed on the Brush Recorder tape, since interpolation between the marks on the tape is necessary.

Two methods were devised which used the actual distances along the tape, measured to the point of occurrence of a particular scaler output pulse from some appropriate zero. The two systimes, both using integral forms of the decay equation, are described below. Both methods use the fact that the number of counts between some time taken as zero and any subsequent time, t_α, is:

$$N_\alpha = mt_\alpha + \sum N_{0j}(1 - e^{-\lambda_j t_\alpha}).$$

Method 1 uses the fact that there exist times t_β and t_γ such that $e^{-\lambda_j t_\beta}$ and $e^{-\lambda_j t_\gamma} \ll 1$ then

$$N_\beta = mt_\beta + \sum N_{0j} \quad \text{and} \quad N_\gamma = mt_\gamma + \sum N_{0j}$$

from which

$$M = \frac{N_\gamma - N_\beta}{t_\gamma - t_\beta} \text{ and } \sum N_{0j} = N_\gamma - \frac{N_\gamma - N_\beta}{t_\gamma - t_\beta} t_\gamma = \frac{N_\beta t_\gamma - N_\gamma t_\beta}{t_\gamma - t_\beta}.$$

We then define

$$S_\alpha^1 \equiv \frac{N_\beta t_\gamma - N_\gamma t_\beta}{t_\gamma - t_\beta} + \frac{N_\gamma - N_\beta}{t_\gamma - t_\beta} t_\alpha - N_\alpha .$$

If all the N_α are integral multiples of a particular scaling factor, k, then

$$N_\alpha = \alpha k, \; N_\beta = \beta k, \; N_\gamma = \gamma k$$

and

$$S_\alpha \equiv \left(\frac{\beta t_\gamma - \gamma t_\beta}{t_\gamma - t_\beta}\right) + \left(\frac{\gamma - \beta}{t_\gamma - t_\beta}\right) t_\alpha - \alpha \quad .$$

The two constants $\frac{\beta t_\gamma - \gamma t_\beta}{t_\gamma - t_\beta}$ and $\frac{\gamma - \beta}{t_\gamma - t_\beta}$ are easily computed, α is simply the number of the pulse and t_α is proportional to the distance along the tape. S_α can thus be tabulated easily and plotted against t_α on semi-log paper to give the usual decay curve, since S_α satisfies

$$S_\alpha = \sum \frac{N_{0j}}{k} e^{-\lambda_j t_\alpha} \quad .$$

This can be separated into components having slope λ_j and intercepts $\frac{N_{0j}}{k}$.

Method 2 is derived from the basic equation in such a way that the time intervals are measured from the end of the tape back toward the time of bombardment. Taking $t_\gamma > t_\alpha$ then

$$N_\gamma - N_\alpha = m(t_\gamma - t_\alpha) + \sum N_{0j}(e^{-\lambda_j t_\alpha} - e^{-\lambda_j t_\gamma})$$

$$= m(t_\gamma - t_\alpha) + \sum N_{0j}\, e^{-\lambda_j t_\gamma}(e^{-\lambda_j (t_\alpha - t_\gamma)} - 1)$$

define $\quad t_\emptyset \equiv t_\gamma - t_\alpha \quad$ and $\quad N_\emptyset \equiv N_\gamma - N_\alpha$

then

$$N_\emptyset = mt_\gamma + \sum N_{0j} e^{-\lambda_j t_\gamma} (e^{\lambda_j t_\emptyset} - 1) \quad .$$

If m is calculated, then $N_\emptyset - mt$ can be plotted against $t_\emptyset$ and for $e^{\lambda_j t_\emptyset} \gg 1$ will have a form adaptable to separation into component activities with slopes λ_j and values at $t_\emptyset = t_\gamma$ which are simply N_{0j}, the total number of counts of the jth activity. As in Method 1 it is convenient to introduce a scaling factor in order to make the numerical work simpler.

Both of these methods utilize the exact time of occurrence of the pulse from the scaler, thus exploiting the Brush recorder tape display to the fullest. The one disadvantage is that counting must be continued uninterrupted throughout the period being used, which must be long compared to the longest-lived activity under consideration.

IX. ACKNOWLEDGEMENTS

This work was guided from the start by Prof. E. Segrè. In addition many helpful discussions were held with Drs. O. Chamberlain, C. Wiegand and E. L. Kelly.

Particular thanks are due to Dr. R. F. Leininger for his direct aid in the chemical separation experiments described in Sections IV and V as well as for advice and assistance throughout the remainder of the work.

T. J. Thompson, F. Vaughan and G. Fischer rendered able assistance in preparing for and carrying out the many cyclotron bombardments.

Thanks are also due to Dr. J. G. Hamilton, Mr. T. Putnam, Mr. B. Rossi and the sixty-inch cyclotron crew for their considerable cooperation and assistance.

A portion of this work was carried out while the author was an Atomic Energy Commission Pre-Doctoral Fellow.

X. REFERENCES

1. I. Perlman, A. Ghiorso and G. T. Seaborg; Phys. Rev. 77, 26 (1950).
2. G. T. Seaborg and I. Perlman; Rev. Mod. Phys. 20, 585 (1948).
3. J. M. Cork; Phys. Rev. 70, 563 (1946).
4. D. R. Corson, K. R. MacKenzie and E. Segrè; Phys. Rev. 58, 672 (1940).
5. E. L. Kelly and E. Segrè; Phys. Rev. 75, 999 (1949).
6. M. O. Stern; Aug 15, 1950 (privately distributed revision of Rev. Mod. Phys. 21, 316, (1949)).
7. A. H. Wapstra; Physica 16, 33 (1950).
8. Nuclear Data; National Bureau of Standards Bulletin Number 499.
9. O. Bunemann, T. E. Cranshaw and J. A. Harvey; Canadian Journal of Research, Sec. A, 27, 191 (1949).
10. B. Rossi and H. H. Staub; Ionization Chambers and Counters: Experimental Techniques, McGraw Hill Book Co., 1949.
11. W. A. Aron, B. G. Hoffman, F. C. Williams; Range - Energy Curves (Second Revision, 1949), UCRL-121 and AECU-663).
12. I. Perlman and T. J. Ypsilantis; Phys. Rev. 79, 30 (1950).
13. I. Kaplan; Phys. Rev. 81, 962 (1951).
14. M. A. Preston; Phys. Rev. 71, 865 (1947).
15. W. W. Meinke; Chemical Procedures Used in Bombardment Work at Berkeley, (UCRL-432)
    a. page 84-1 (under remarks)
    b. page 83-1.
16. Wilhelm Prodinger; Organic Reagents used in Quantitative Inorganic Analysis, Elsevier Publishing Co., 1940.

17. M. Curie and W. A. Lub; Jour de Phys et le Rad. 4, 513, (1933).

18. H. M. Neumann and I. Perlman; Phys. Rev. 81, 958 (1951).

19. E. Marsden and P. B. Perkins; Phil. Mag. 27, 690 (1914).

20. Lord Rutherford, C. E. Wynn-Williams and W. B. Lewis; Proc. Roy. Soc., A, 133, 351 (1931).

21. M. G. Holloway and M. S. Livingston; Phys. Rev. 54, 18 (1938).

22. E. L. Kelly; PhD thesis, University of California, 1951.

23. V. F. Weisskopf and others; Lecture Series in Nuclear Physics, MDDC 1175, U. S. Government Printing Office, Dec. 1947.

24. M. G. Mayer; Phys. Rev. 78, 16 (1950).

25. J. A. Harvey; MIT Progress Report, ONR - NP - 1586, April 1, 1950.

26. E. C. Campbell and M. Goodrich; Phys. Rev. 78, 640 (A) (1950).

27. M. Goldhaber and A. W. Sunyar; Phys. Rev. 83, 906 (1951).

28. E. Segrè and A. C. Helmholz; Rev. Mod. Phys. 21, 271 (1949).

29. H. R. Hulme; Proc. Roy. Soc. 138, 643 (1932).

30. H. M. Taylor and N. F. Mott; Proc. Roy. Soc. 138, 665 (1932).

130						
129		RaC″ 1.32m β^-1.80	AcB^{211} 36.1m β^-0.5,1.4 γ 0.8	ThC^{212} $\alpha\gamma\beta^-$ 60.5m α6.054 β^-2.20	A α 3.2×10^{-6}S α 8.3	
128		A β^- <1h	RaD^{210} 22y β^-0.025 γ 0.047	AcC^{211} A$\alpha\gamma\beta^-$ 2.16m α6.619	ThC′^{212} 2.6×10^{7} α8.776	
127		ThC″^{208} 3.1m β^-1.82 γ2.62	A β^- 3.3h β^-0.68	RaE^{210} 5.0D β^-1.17 $\alpha\times10^{-6}$,4.83	AcC′^{211} 5×10^{-3}S α7.434	A α 0.2 S
126		AcC″^{207} 4.76m β^-1.47	Pb^{208} 52.38% 0	Bi^{209} 100% 3.8 $\frac{9}{2}$	Po^{210} 138.0D α 5.298 γ0.8	Aα,K α -5.94
125	A β^- 5.5 m β^-1.62	B β^- 4.23m β^-1.6	Pb^{207} 21.11% 0.6 $\frac{1}{2}$	K$\gamma\beta$e ~10^4 Y	Cα 200yrs. α 4.90	AK γ 8.3h γ 1.0
124	Hg^{204} 6.7%	Tl^{205} 70.54% 1.45 $\frac{1}{2}$	Pb^{206} 25.16% 0		A α 3 Y α5.14	
123	C $\beta^-\gamma$ 51.5 D β^-<0.3	B β^- 3.5y β^-0.87	CIT,γe 68 m γ1.1	BKe$^-$ 6.4 D γ 0.93	AKα 5.7h α5.1(10^{-4}) γ 1.3	
122	Hg^{202} 29.6%	Tl^{203} 29.46% 1.45 $\frac{1}{2}$	Pb^{204} 1.3% / BIT 68m γ1.0	BKe$^-\gamma$ 10-15h	AK$\alpha\gamma$ 9D α 5.2(0.1)	
121	Hg^{201} 13.2% $\frac{3}{2}$	BKγe$^-$ 13D γ 0.4	K 52h γ0.27,0.45	BKe$^-\gamma$ 12h γ0.2		
120					α 5.5(10^{-6})	
119	Hg	Tl	Pb	Bi	Po	At
118						
117						
116						
	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At

211

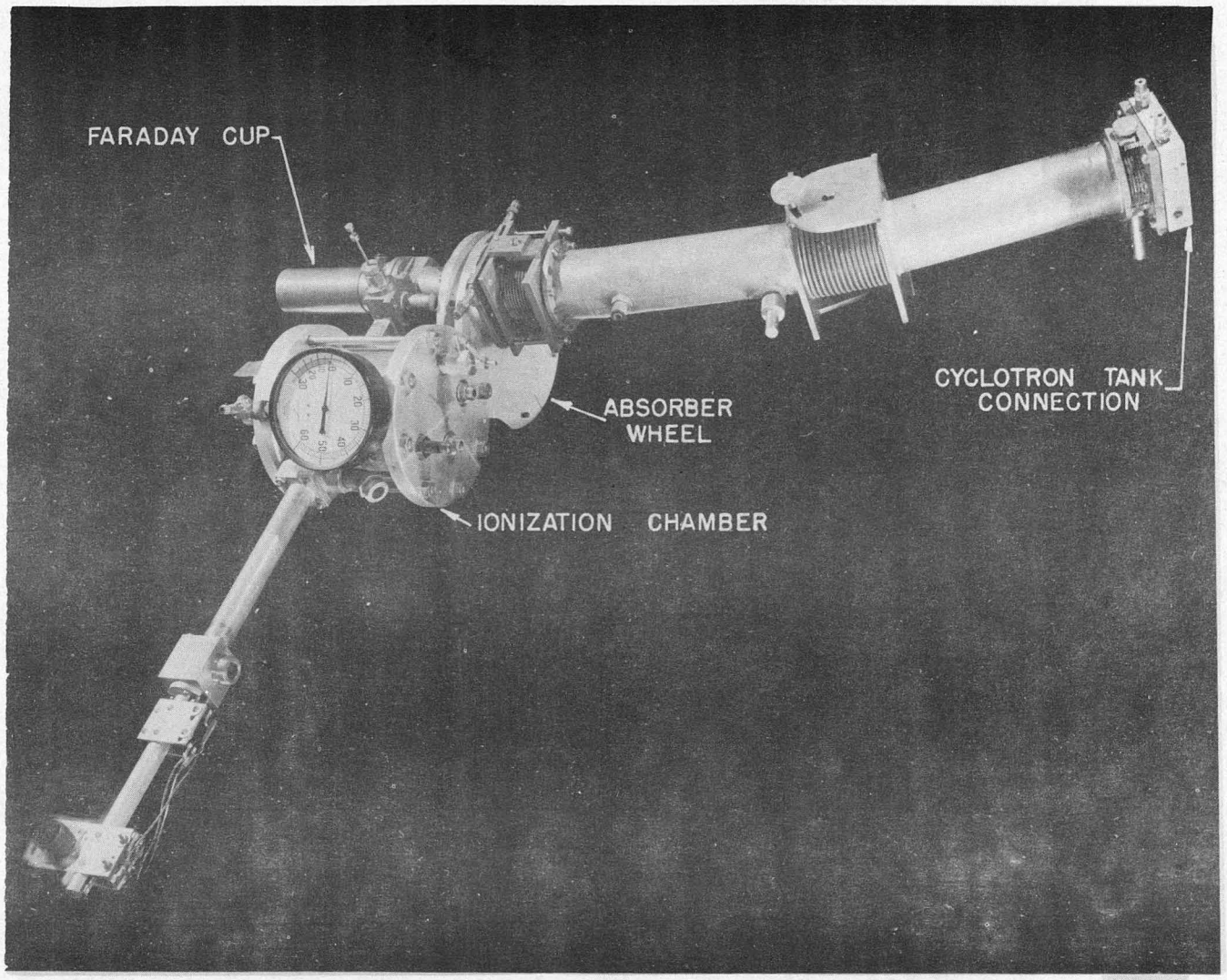
209

207

FIG. 1

ISOTOPE CHART

MU 2608


FARADAY CUP
ABSORBER WHEEL
IONIZATION CHAMBER
CYCLOTRON TANK CONNECTION

ZN98

Fig. 2

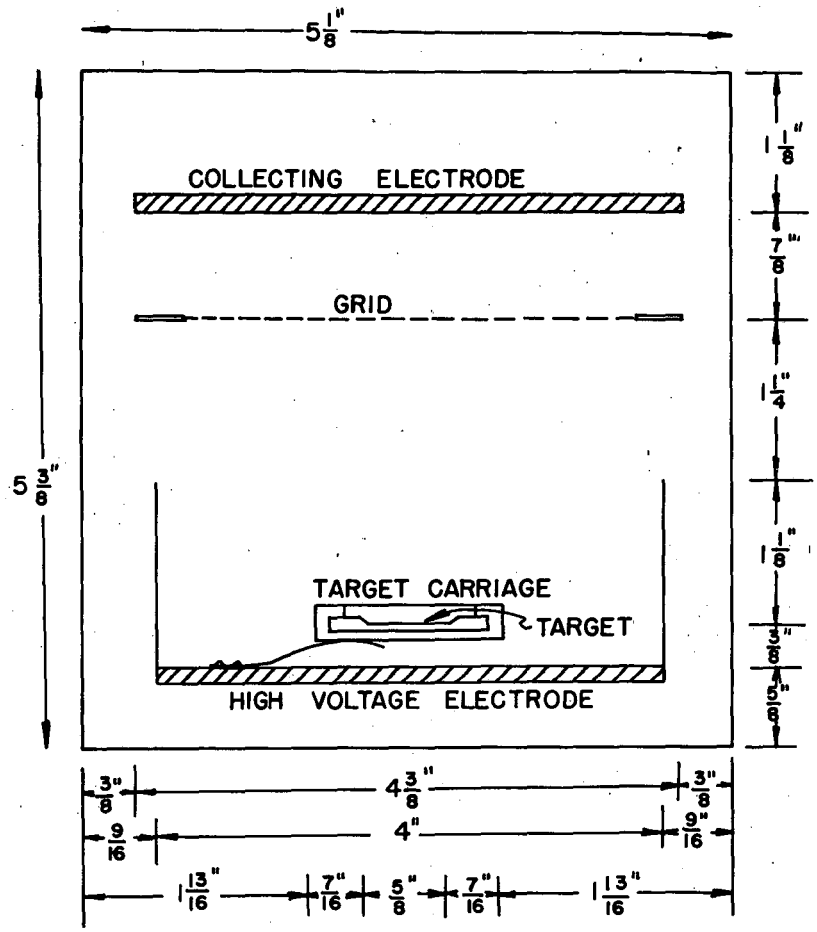


FIG. 3
SCHEMATIC DIAGRAM OF IONIZATION CHAMBER

MU 2609

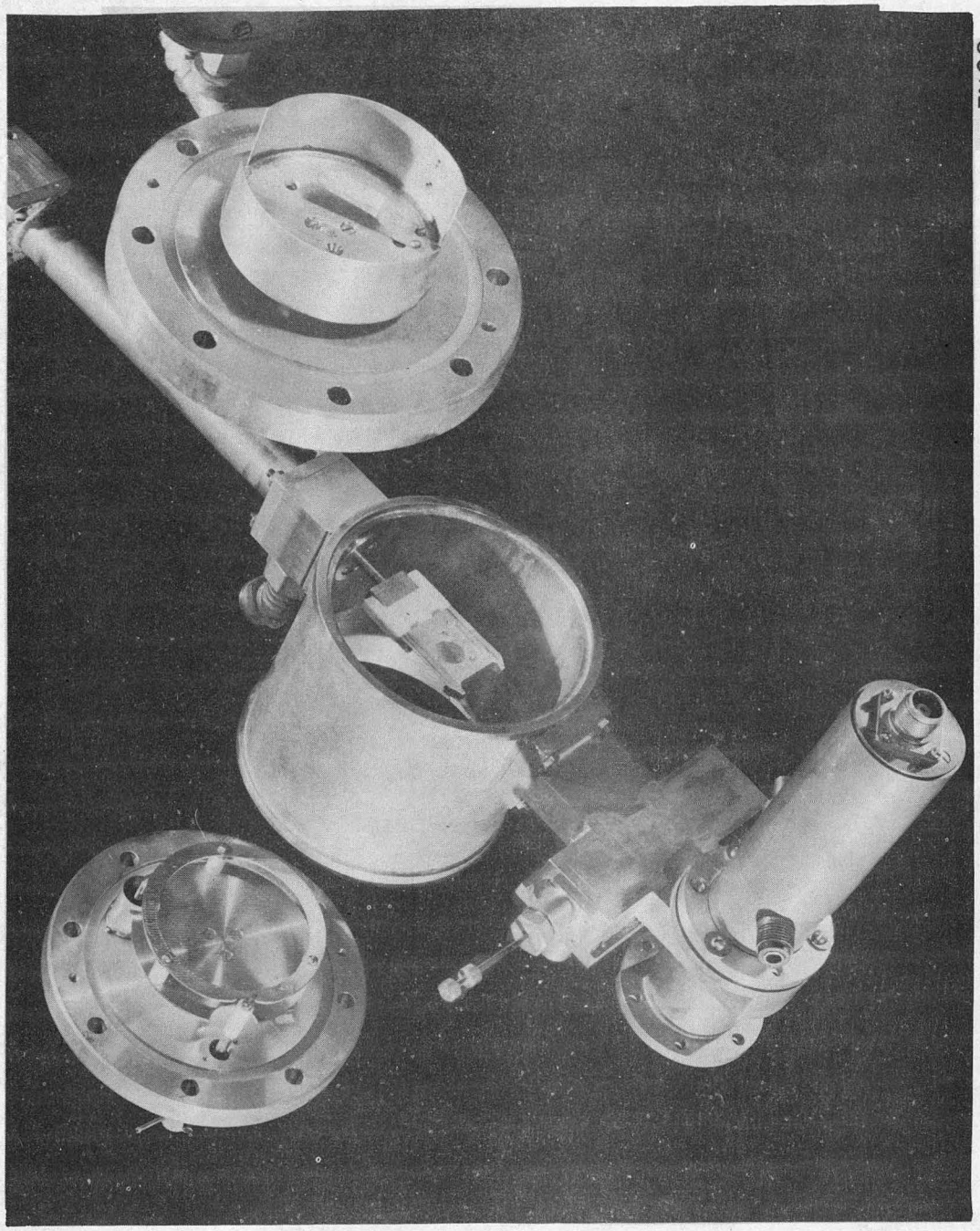


Fig. 4

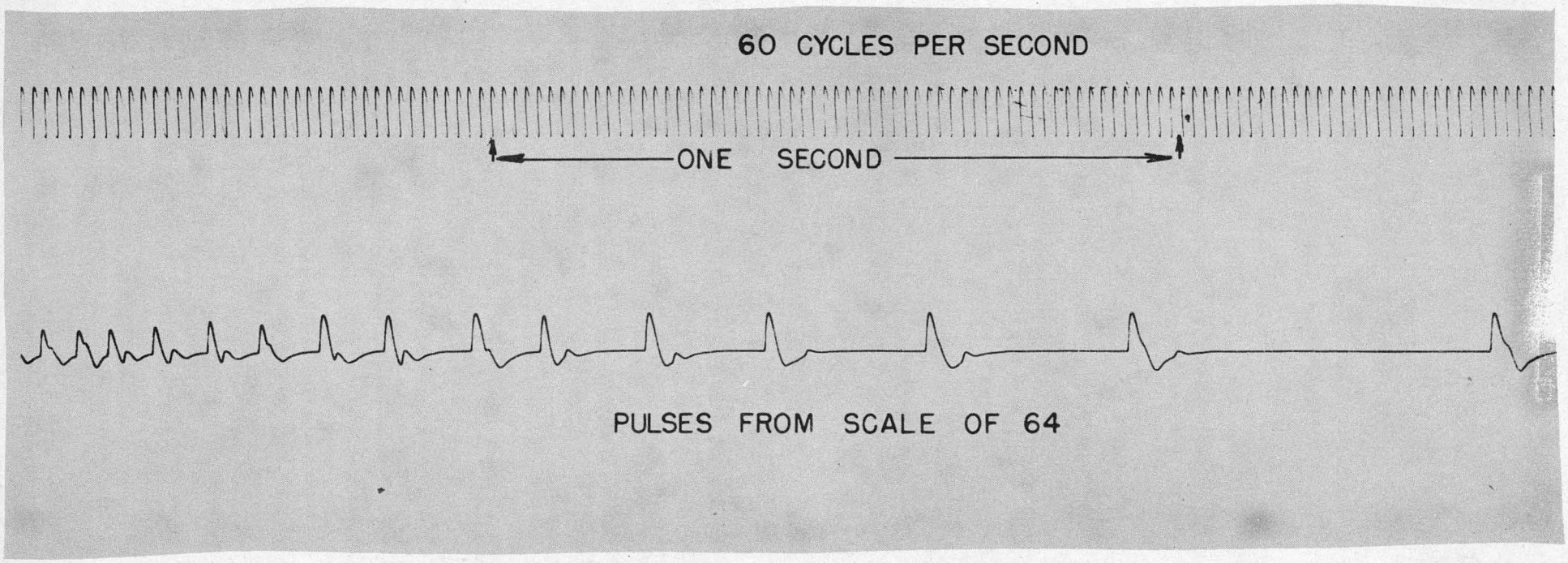


Fig. 5

ZN101

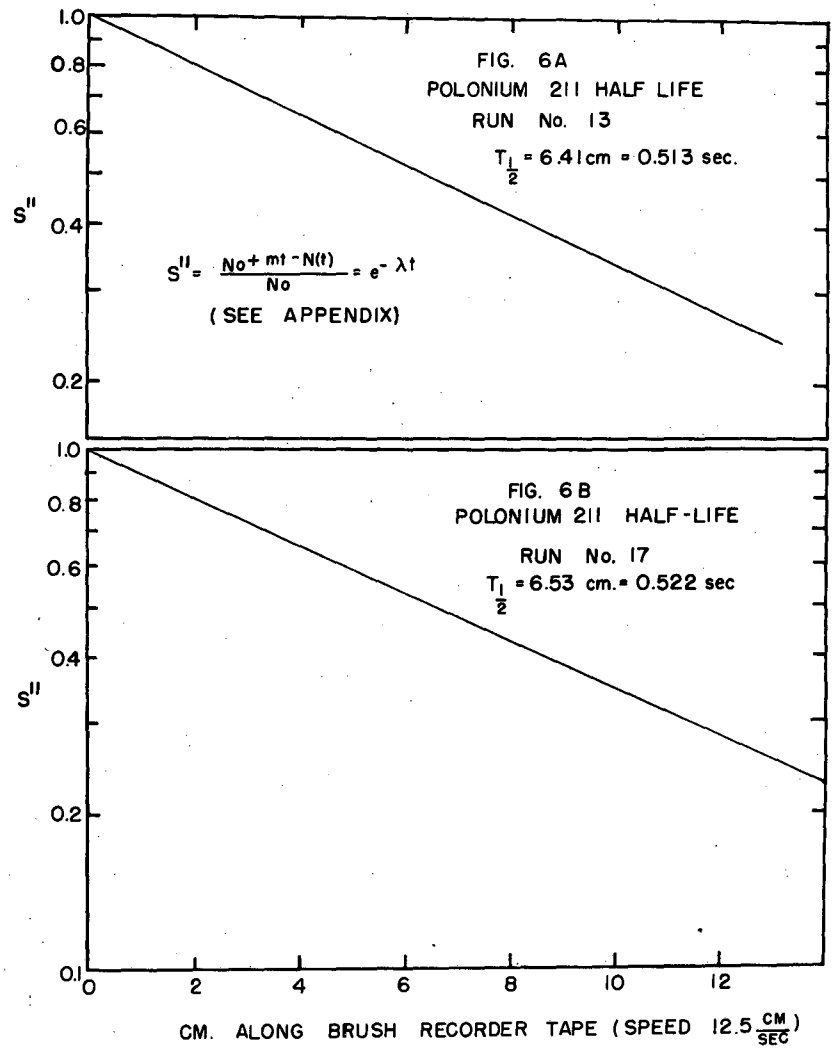


FIG. 6A
POLONIUM 211 HALF LIFE
RUN No. 13
$T_{\frac{1}{2}}$ = 6.41cm = 0.513 sec.
$S'' = \frac{No + mt - N(t)}{No} = e^{-\lambda t}$
(SEE APPENDIX)
FIG. 6B
POLONIUM 211 HALF-LIFE
RUN No. 17
$T_{\frac{1}{2}}$ = 6.53 cm. = 0.522 sec
S''
1.0
0.8
0.6
0.4
0.2
0.1
0
2
4
6
8
10
12
CM. ALONG BRUSH RECORDER TAPE (SPEED 12.5 $\frac{CM}{SEC}$)

MU 2610

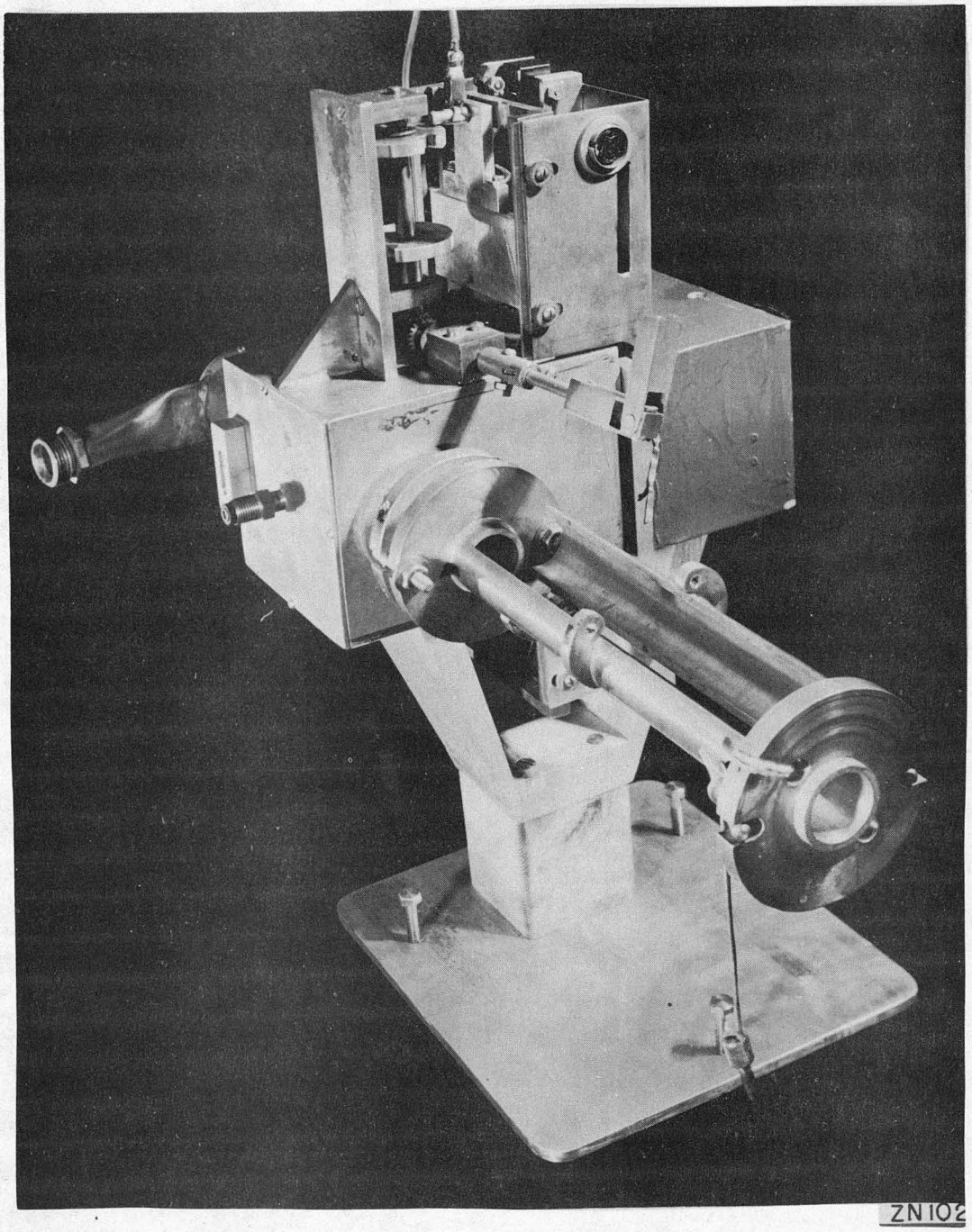


Fig. 7

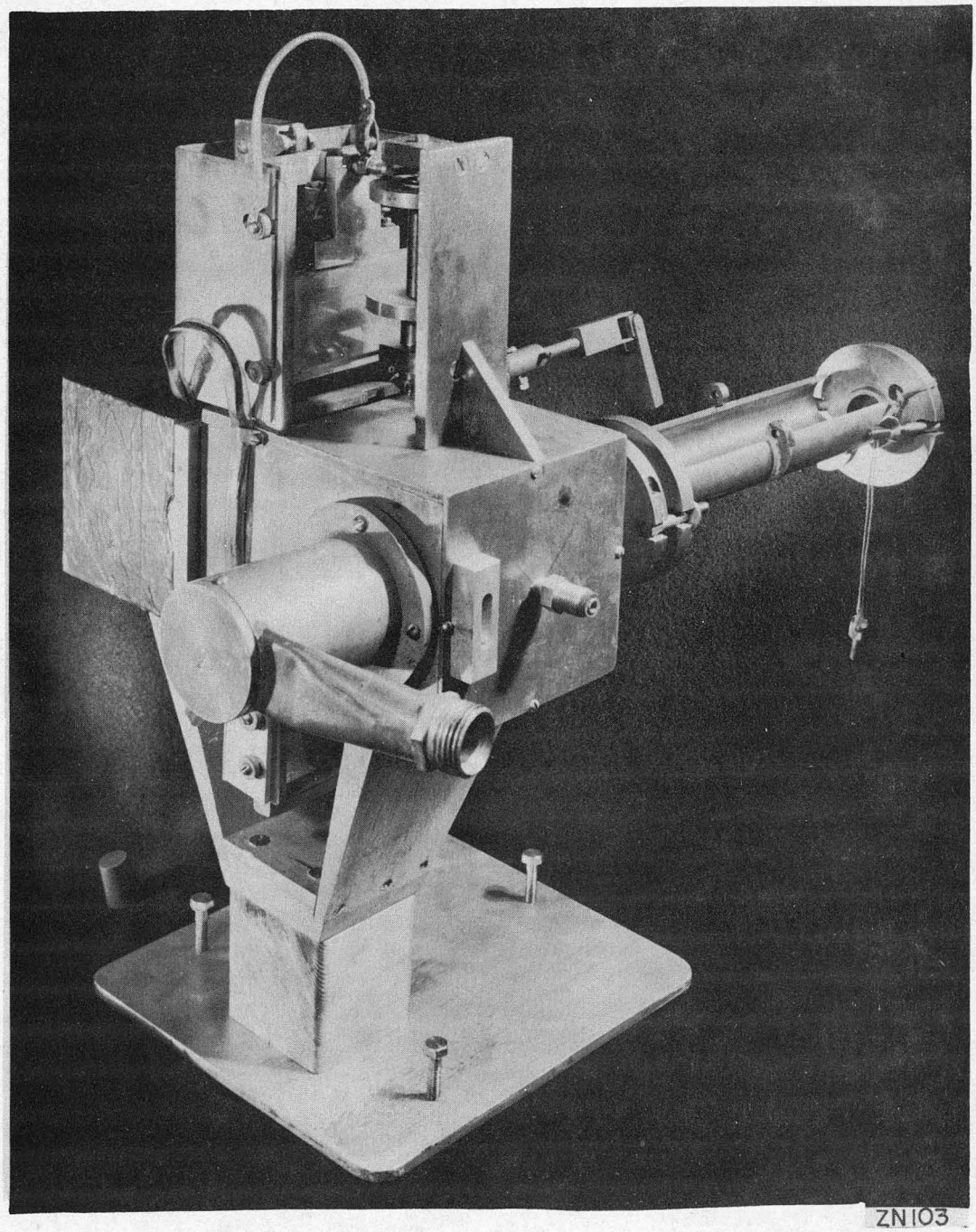


Fig. 8

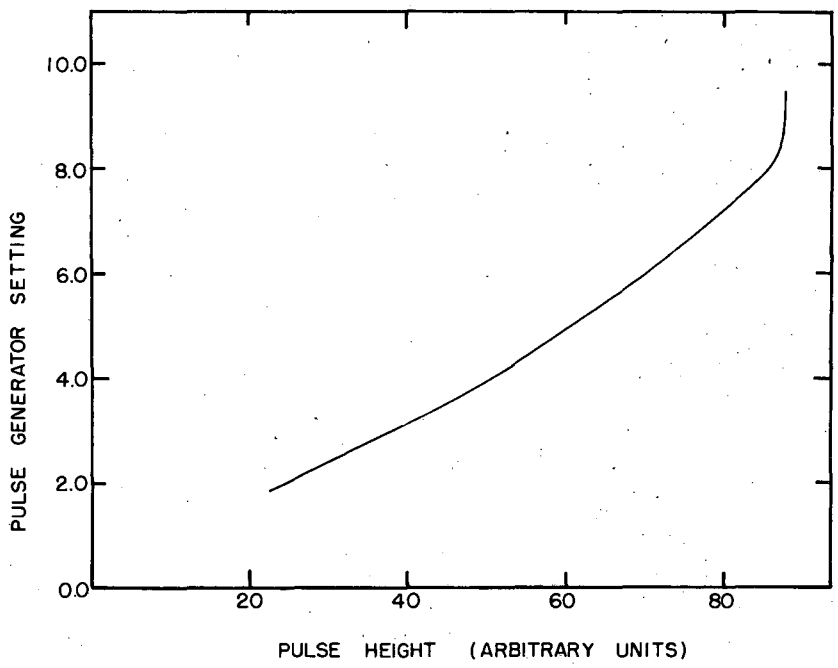


FIG. 10
PULSE GENERATOR SETTING vs. PULSE HEIGHT

MU 2611

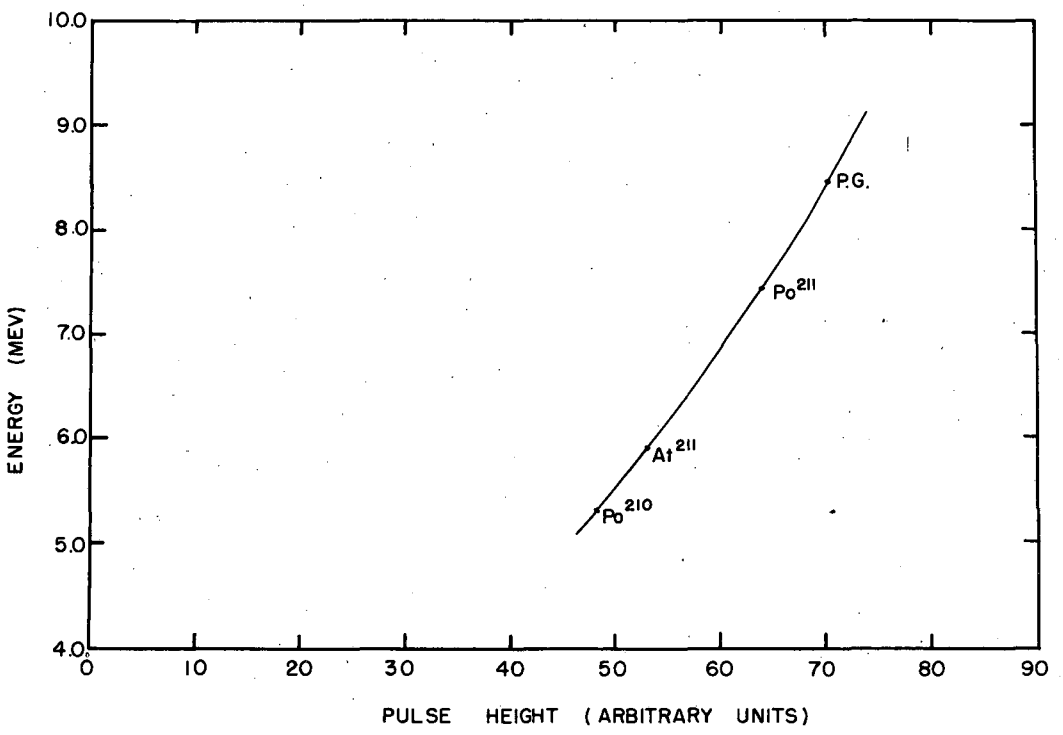


FIG. II
ENERGY vs. PULSE HEIGHT

MU 2612

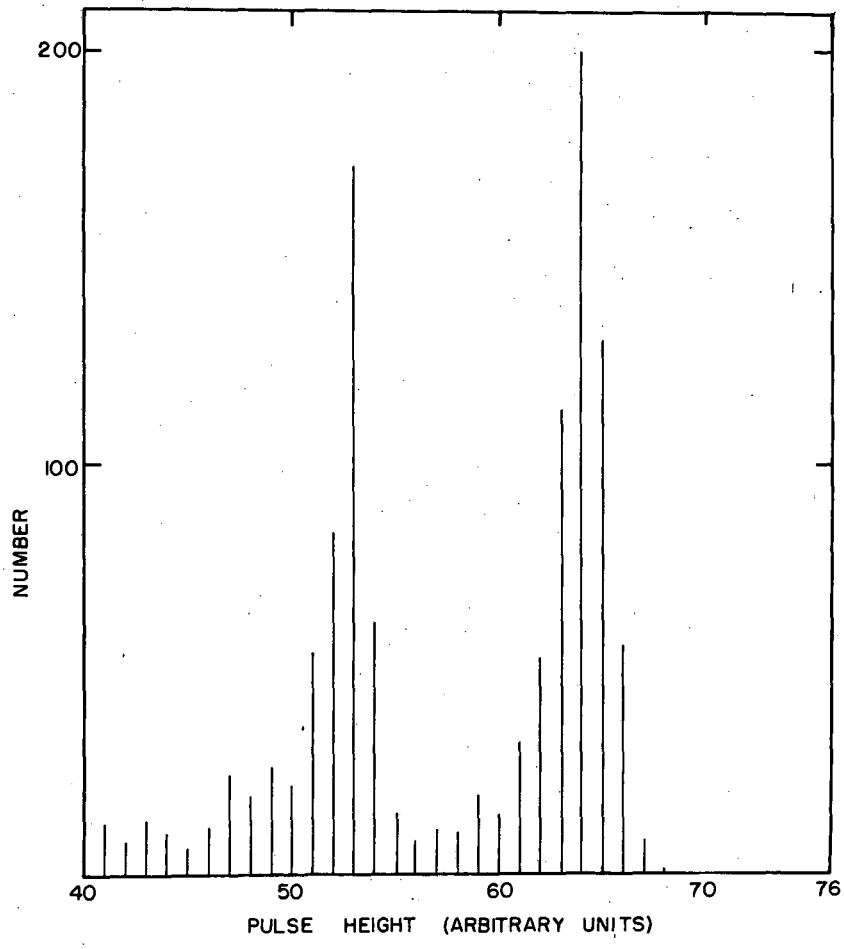


FIG. 12
ASTATINE PULSE HEIGHT DISTRIBUTION

MU 2613

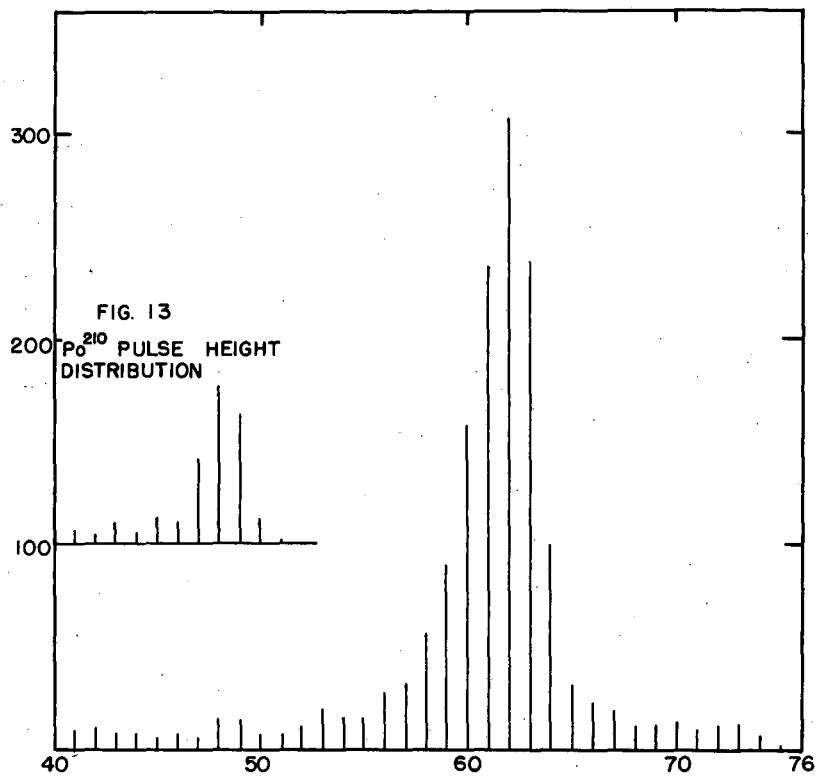


FIG. 14

PULSE HEIGHT DISTRIBUTION IN INTERMEDIATE LIVED ACTIVITY. (NO PULSES OBSERVED ABOVE 75)

MU 2614

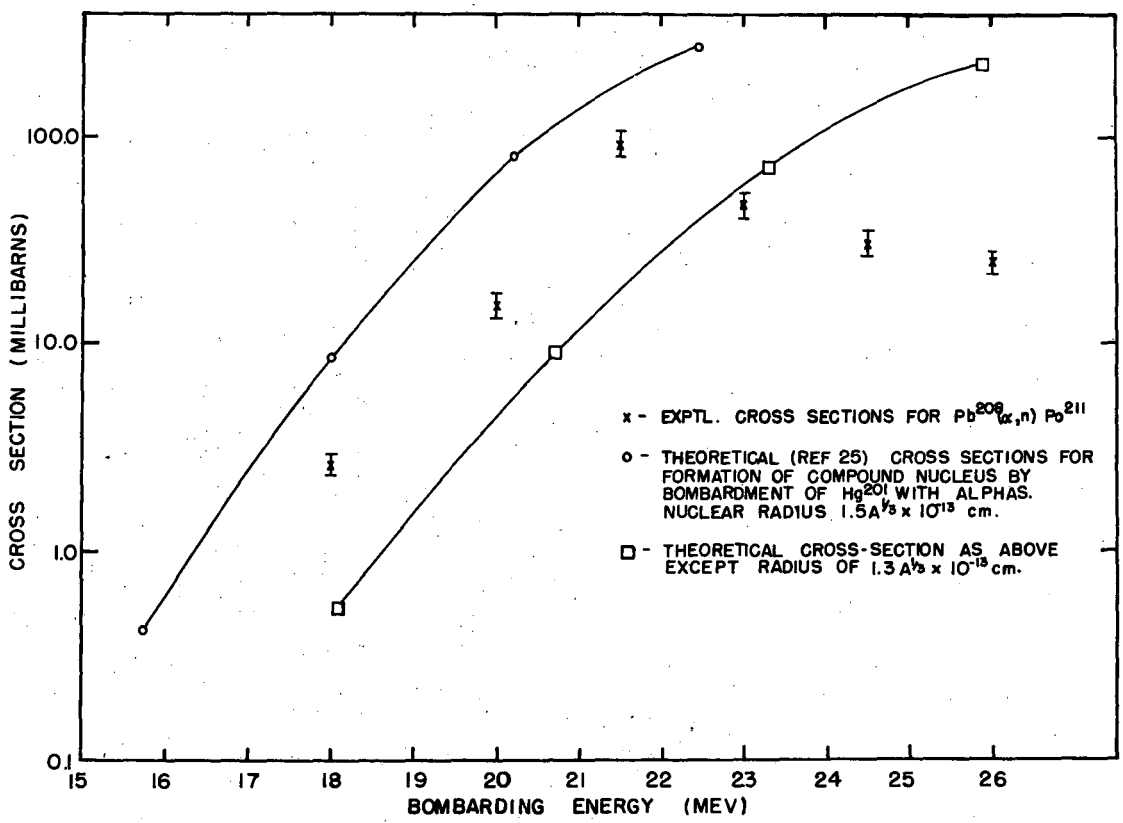


FIG. 15

MU 2615