Title
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Publication Date
1950-11-22

UCRL 670 Rev.
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November 22, 1950

Berkeley, California

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ABSTRACT

A number of new neutron deficient isotopes of astatine have been identified in the mass number range 200-209 following the irradiation of bismuth with high energy helium ions. Their alpha decay properties fall in line with predictions for isotopes in this region with <126 neutrons, that is, the alpha energies increase with decrease in mass number. Because of the complexity of the isotopic mixtures, half-lives and mass number assignments were made in most cases through the identification of decay products of lower atomic number. The decay properties as now known are summarized in Fig. 1.

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INTRODUCTION

As part of the program in this laboratory to determine and correlate radioactive properties of the heavy elements, a study was undertaken of the isotopes of astatine which can be prepared by the irradiation of bismuth with high energy helium ions. Of particular interest in the case of astatine isotopes is the characterization of those with less than 126 neutrons since it has been shown[1] that there are abrupt changes in the trends of alpha decay properties in crossing this region. The well known isotope At^{211} is the one with 126 neutrons[2] and the present study includes identification of new isotopes tentatively assigned to mass numbers as low as 201. All of the astatine isotopes discussed here are unstable toward electron capture and the difficult problem of assigning partial half-lives for that mode of decay and for alpha emission is still in an unsatisfactory state.

Some of the energies and half-lives found in the present study have been referred to briefly in another publication.[1] The present picture of all nuclei in this region is shown as a segment of an "isotope chart" (Fig. 1) in which are indicated half-lives, observed modes of decay and alpha energies for the new and previously reported isotopes of astatine. Some isotopes of polonium, bismuth, lead, and thallium are also entered because these will be referred to in the discussion of isotopic assignments of the astatine isotopes.

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[1] Perlman, Ghiorso, and Seaborg, Phys. Rev. 77, 26 (1950).

[2] Corson, Mackenzie, and Segrè, Phys. Rev. 58, 672 (1940).

METHODS

The most feasible method for preparing astatine isotopes in the mass number region in question is the irradiation of bismuth (Bi^{209}) with helium ions of 60 Mev and greater. At these energies a complex mixture of activities is invariably encountered and genetic relationships with previously known activities must be relied upon for the most part in making isotopic assignments. The variation of projectile energy is of some importance in these studies since the order of appearance of new activities with successive increase in energy sets the order of mass numbers.

Most of the irradiations in the 184-inch cyclotron were made with the undeflected beam striking an internal probe target in which strips of bismuth metal were clamped to a water-cooled copper block. In some cases bismuth oxide in aluminum foil envelopes was bombarded similarly. For the short-lived activities, powdered bismuth metal or oxide was bombarded in a special stainless steel tube which is drawn out of irradiation position through a pneumatic tube directly into the chemistry laboratory. This pneumatic tube target allows one to begin chemical separations within about 20 seconds after the beam is turned off.

For either type of target arrangement, energies were changed by radial displacement of the target permitting selection of helium ion energies up to the maximum of 380 Mev. In all irradiations, energies were such that the particular bismuth samples used could be considered to be "thin targets."

Chemical Procedures

Besides the mixture of astatine isotopes, each target contained in high yield isotopes of polonium, bismuth, lead, and thallium; and in lower yield, spallation products further removed from bismuth, and bismuth fission products. The methods of identifying the astatine isotopes varied for different species

and will be discussed for the individual cases but some general remarks can be made to give reason for the chemistry employed. The general procedure was to obtain a pure astatine fraction without carrier so that alpha particles could be identified according to energy and half-life with the alpha pulse analyzer[3] and then to remove from this fraction periodically such polonium, bismuth, and lead isotopes as had grown through electron capture and alpha particle decay. The identification of the growth of known daughter activities with particular astatine activities was the principal method employed for making mass number assignments. Since the astatine isotopes in question have half-lives of the order of an hour down to a few minutes, rapid chemical procedures were required.

The method developed for removal of pure astatine consisted of its extraction, presumably while in the zero oxidation state, into diisopropyl ether (DIPE). The bismuth target was dissolved in such a way as to end up with a solution in concentrated hydrochloric acid to which ferrous sulfate was added to make sure that the astatine was reduced to the zero state and this solution was contacted with DIPE. The DIPE solution was washed with dilute sulfuric acid or hydrochloric acid, and so far as could be told by absence of polonium and bismuth alpha activity, the astatine was pure. Samples of the DIPE solution could then be evaporated on platinum or stainless steel discs for radiation measurement.

A solution containing pure astatine isotopes in the mass number range in question begins to grow successively polonium and lower element daughters

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[3]Ghiorso, Jaffey, Robinson, and Weissbourd, National Nuclear Energy Series, Plutonium Project Record, Vol. 14B, (The Transuranium Elements: Research Papers," Paper No. 16.8 (McGraw-Hill Book Co., Inc., New York, 1949).

principally by electron capture decay. In an experiment to identify astatine isotopes through genetic relationships, the astatine is first purified, allowed to stand for an interval of the order of the half-life of the parent, the daughter elements removed and separated from each other, and the decay characteristics of each followed. This "milking" process is repeated on the parent solution at equal time intervals.

The polonium, bismuth, and lead may be removed periodically by adding to the DIPE solution one-tenth volume of 20 percent tributyl phosphate (TBP) in isobutyl ether and extracting into a 2M nitric acid - 4M hydrochloric acid aqueous solution. These elements leave the organic phase quantitatively in only about one minute contact time while the astatine remains quantitatively in the organic layer. The polonium can then be separated from bismuth and lead by extracting into TBP solution after destroying the nitrate ion and making the aqueous solution 6M HCl. (The behavior of polonium in TBP extraction from HCl and HNO_3 solutions has been investigated by others in this laboratory.)[4] The bismuth and lead are separated by precipitating the bismuth as BiOCl and the lead as $PbSO_4$.

For very rapid separation of astatine from the bismuth target, a different method was used which gives astatine of somewhat uncertain purity but which was considered adequate for determination of short-lived alpha emitters. The basis for the method is the distillation of astatine from molten bismuth. The bismuth target is dropped into a stainless steel crucible fitted on top with a water-cooled steel finger to which a collecting platinum disc is clamped. When the bismuth is kept slightly above its melting point (as measured by a thermocouple fitted into a well in the crucible) within a few

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[4] D. G. Karraker and D. H. Templeton, University of California Radiation Laboratory Declassified Report UCRL-640 Revised (September, 1950).

seconds astatine distills onto the collecting plate. Polonium does not distill in appreciable quantities until considerably higher temperatures are reached. Using the vacuum carrier system to deliver the target, this procedure permits samples to be in the alpha pulse analyzer within 90 seconds after the cyclotron beam is shut off.

In some instances recoil methods were used to separate the alpha decay daughters. The astatine, plated on a silver foil, was placed in a vacuum chamber with a collecting plate maintained at a few hundred volts negative potential. Some astatine volatilizes across the gap and contaminates the bismuth daughters caught by alpha particle recoil. To remove this, some sulfuric acid is placed on the platinum collecting plate which is heated until the H_2SO_4 is fumed off. This step converts the bismuth to its sulfate which remains on the plate when flaming it to remove the astatine.

RESULTS

In all irradiations the previously known isotopes of astatine, 7.5-hour At^{211} and 8.3-hour At^{210}, could be observed. At^{211} is identified readily, using an alpha pulse analyzer, by the characteristic twin alpha particle peaks:[2] that of the alpha decay of At^{211} itself (5.89 Mev) in 40 percent of the events, and a high energy peak (7.43 Mev) which is the alpha particle of Po^{211} (AcC') from the 60 percent electron capture branching of At^{211}. The other isotope, At^{210}, decays by electron capture with 8.3-hour half-life[5] and no observable alpha branching. Its presence may be determined quantitatively by counting the alpha particles of the daughter, Po^{210}, after decay of the parent.

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[5] E. L. Kelly and E. Segrè, Phys. Rev. 75, 999 (1949).

The other astatine isotopes observed in these studies have not been reported previously aside from mention of two of them in the Table of Isotopes.[6] In discussing some of these, excitation functions will be of value and such curves over a limited energy range (60-95 Mev) are shown in Fig. 2. As will be noted, no attempt has been made to define the curves accurately, but as they stand they are helpful in making mass number assignments and in visualizing the mixture of activities encountered in this energy range. The curve for At^{211} as shown is a segment of that obtained by Kelly[7] and At^{211} was used as a monitor to which the other isotopes were normalized; that is, all yields determined for a given sample were measured relative to the At^{211} in that sample.

At^{209}

An activity assigned to At^{209} is characterized by a half-life of 5.5 ± 0.3 hours and an alpha particle of 5.65 Mev. It is estimated that it decays with ~5 percent alpha branching and ~95 percent electron capture.

The assignment to At^{209} is based on several pieces of evidence. One point concerns its relationship in Fig. 2 to At^{208} assigned with some confidence through its genetic relationship[8] with Po^{208}. As seen, the yield of the activity assigned to At^{209} falls off at energies where At^{208} is still climbing. While attention is focused on the excitation curves, it may be mentioned that no At^{209} could be identified below 55 Mev but this is not to be interpreted as the threshold. The reason the threshold cannot be determined is because of the rapidly climbing yield of At^{211} with decrease in energy

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[6] G. T. Seaborg and I. Perlman, Rev. Mod. Phys. 20, 585 (1948).

[7] E. L. Kelly, University of California Radiation Laboratory Unclassified Report UCRL-277 (January, 1949).

[8] Templeton, Howland, and Perlman, Phys. Rev. 72, 758 (1947).

and the tail of its 5.89 Mev alpha group obscures the 5.65 Mev group of At^{209}. The pulse analysis of the astatine fraction from the irradiation of bismuth with 65 Mev helium ions is shown in Fig. 3. The energy band was spread out to cover only about 2/3 Mev over the entire register bank so the high energy group accompanying At^{211} (7.43 Mev Po^{211}) was not registered. Only the two groups are seen because At^{210} and At^{208} decay almost entirely by electron capture and inappreciable quantities of At^{207} are formed at this energy (compare with Fig. 2). The At^{209} peak is smaller than that of At^{211} while the cross section for formation is shown larger in Fig. 2 because At^{209} is assumed to have only 5 percent alpha branching while that for At^{211} is 40 percent.

The half-lives of the alpha particle groups cannot be resolved with any accuracy by gross alpha counting, but with the pulse analyzer the decay of the two peaks may be followed separately. The decay observed in this manner is plotted in Fig. 4 from which the value 5.5 ± 0.2 hours is obtained. The two limits shown denote the uncertainty in resolution of the two alpha peaks of Fig. 3 and are felt to be the extreme deviations introduced from this source.

With some knowledge of the half-life, two other checks of the isotopic assignment become possible. These are the identification of electron capture and alpha decay daughters and the observation that amounts which grow in during successive time intervals fall off with the half-life of the parent. The electron capture product[5] is Po^{209} which because of its long half-life, estimated to be about 200 years, makes accurate measurement difficult with the amounts of At^{209} which could be prepared. Nevertheless, Po^{209} was definitely identified and the proper half-life for At^{209} reproduced. The particular astatine sample was prepared at 120 Mev, and at approximately 5-hour intervals an aliquot was purified of polonium and plated on a disc

where it was allowed to undergo complete decay. The resulting polonium activities were analyzed according to energy and a typical plot is shown in Fig. 5. The Po^{208} peak resulted from the decay of At^{208} to be discussed below and the Po^{210} came from the decay of 8.3-hour At^{210}. The energies shown for Po^{208} and Po^{209} are probably more accurate than those which have been previously reported. Other astatine isotopes formed in the bombardment were either too short-lived or their polonium daughters were too short-lived to be seen under the conditions of the chemical separations. The amounts of Po^{209} which grew during each period could be calculated from the pulse analysis curves. In order to overcome variations in chemical yield, the data for Po^{210} were adjusted to the 8.3-hour half-life of its parent and other yields were normalized to them. These curves are shown in Fig. 6 in which a 5.7-hour half-life is found for At^{209}. This is in excellent agreement with the half-life obtained by following the decay of the alpha particle peak at 5.65 Mev considering the uncertainties in resolving the weak Po^{209} peaks. The alpha branching of At^{209} was calculated from the ratio of its alpha particles to those of the Po^{209} by assuming the Po^{209} half-life to be 200 years as estimated from yield considerations by Kelly and Segrè.[5] It is from this calculation that the alpha branching was found to be 5 percent.

The alpha decay daughter can be used in a similar manner as the electron capture daughter to determine mass number and half-life of the parent. The alpha decay product is Bi^{205} shown by Karraker and Templeton[4] to be an electron capture activity with 14.5-day half-life. The Bi^{205} was separated in two ways: by chemical separation from the astatine and other decay products, and by collecting the recoils from the alpha decay. In both cases the ~14-day period was identified without difficulty. Decay curves of the parent determined by yields of Bi^{205} gave for two experiments 5.4 hours and 6.2 hours

which is considered satisfactory agreement.

At^{208}

This isotope formed by the a,5n reaction had no discernible alpha decay, but the limits of detection are poor particularly if its energy is close to that of At^{209}. It was detected at 55 Mev, the lowest energy used in these studies, and at higher energies through its electron capture decay daughter, Po^{208}. Its excitation function (Fig. 2) agrees with this assignment in that it appears at lower energies than an activity assigned to At^{207} and does not drop off in yield as fast as does At^{209}.

It has not been possible to resolve the radiation of At^{208} from the complex mixture so that its half-life could be determined only by successive removal and yield measurement of the Po^{208} daughter. Fig. 6 shows a plot of such data in which a 5.9-hour half-life for the parent is noted. Another similar experiment indicated a half-life of 6.7 hours. For the present, we will assume the half-life to be 6.3 ± 0.5 hours.

As mentioned, no alpha particles attributable to At^{208} have been noted. If the alpha energy falls in a gap between others present, the alpha branching could be as low as 1 percent, but if the alpha group is obscured by the other isotopes present, it could be considerably higher, say 10 percent. No experiments were done to measure the alpha decay daughter, 12-hour Bi^{204}, which could shed some light on the alpha branching.

It is interesting to note that Hyde, Ghiorso, and Seaborg[9] have reported another set of properties for At^{208}. Their activity arose from the alpha decay of Fr^{212} and had a 1.7-hour half-life and alpha particle of 5.65 Mev. The evidence for mass number assignments for the two activities are fairly

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[9]Hyde, Ghiorso, and Seaborg, Phys. Rev. 77, 765 (1950).

convincing and we shall assume that they are isomers of At^{208}. It is not surprising that only one isomer should be seen from the alpha decay of Fr^{212}, but we would expect both to be formed in appreciable yield in the bombardment of bismuth. However, if the 1.8-hour isomer were formed in lower yield than the 6.3-hour period, it might not have been picked up through the Po^{208} daughter and its alpha particles would have been submerged in those of At^{209} which has the same energy. As mentioned below, there is some scanty evidence that there is some activity at 5.65 Mev with shorter half-life than that of At^{209}.

At^{207}

At 75 Mev a new activity appeared having a half-life of about 2 hours and this has been assigned to At^{207} formed by the a,6n reaction (see Fig. 2). An alpha pulse analysis of astatine prepared at 85 Mev is shown in Fig. 7 in which a new group at 5.75 Mev has appeared. In Fig. 8 are plotted the decay data of the individual peaks of Fig. 7 from which it is seen that the 5.75 Mev group decays with a 2.0-hour half-life. It will be noted that the early points of the 5.65 Mev peak indicate a short-lived component at this energy. This may be the 1.8-hour isomer of At^{208} reported by Hyde, Ghiorso, and Seaborg and formed in sufficiently favorable yield to make its appearance.

Along with the excitation function, the identification of the alpha decay and electron capture decay daughters have served to assign the mass number 207 to this activity. In one experiment, bismuth recoils were caught over two time intervals and after decay (of 12-hour Bi^{203}), 52-hour Pb^{203} was identified and the decrease in yield corresponded to a half-life for the parent of somewhat under 2 hours. To obtain larger amounts of Pb^{203} in order to prove its identity, chemical separation of combined bismuth, lead, and polonium was made from a sample of astatine prepared at 110 Mev. These

fractions were removed at 2-hour intervals, allowed to decay for two days, the lead fraction removed and the 52-hour decay period of Pb^{203} followed. The data are shown as one of the sets in Fig. 9, and in view of the errors which could be introduced by variations in the chemical yields, the best line of 1.9 hours is considered an excellent and perhaps fortuitous check. A polonium fraction removed in a similar experiment was followed for decay[8] of the 5.7-hour Po^{207}, and its yield went down with a 1.7-hour half-life. The most reliable half-life measurement is that obtained by following the 5.75 Mev peak on the pulse analyzer rather than the more complex procedures involving chemical separations just discussed.

No serious attempt has been made to determine the degree of alpha branching of At^{207}. The best estimate from the alpha particles of At^{207} and the yield of Po^{207} is 10 percent alpha branching. This involves considerable uncertainty because of the unknown counting efficiency of the Po^{207} radiation. The cross sections for At^{207} in Fig. 2 are based on 10 percent alpha branching.

At^{206}

The same experiment (110 Mev helium ions) in which the astatine fraction yielded Pb^{203} indirectly from the alpha decay of At^{207}, the polonium fraction[8] showed the presence of 9-day Po^{206} from the electron capture decay of At^{206}. Other polonium isotopes, Po^{210} and Po^{208}, were also present. Fig. 9 shows that the yield of Po^{206} goes down with a half-life of 2.6 hours for the parent, At^{206}. No radiations directly attributable to At^{206} could be observed because of the complex mixture of other activities.

At^{205} and At^{204}

At higher bombardment energies other astatine isotopes were formed. These were, of course, farther from beta stability and would be expected to

have shorter half-lives toward electron capture decay. In addition, the alpha energies would be expected to become progressively higher, and consequently the half-lives would become shorter.[1]

Using 150 Mev helium ions, the astatine fraction was subjected to chemical separations in which polonium fractions were removed at short intervals, each polonium fraction was allowed to decay for five hours, and then the bismuth fraction was removed and its decay followed. It was the object of this experiment to find the half-lives of the At^{205} and At^{204} grandparents of 14-day Bi^{205} and 12-hour Bi^{204}. The bismuth decay curves were resolved and the yields plotted as Fig. 10 in which it is seen that half-lives of about 25 minutes are indicated for both At^{205} and At^{204}. Alpha pulse analysis of another higher energy bombardment showed a single peak at 5.90 Mev with this half-life. Considerable further work would have to be done to establish to which mass number the 5.90 Mev alpha particle belongs or whether indeed it may have two components which cannot be resolved.

For the present, we shall attribute the alpha particle, which was found to decay with a 25-minute half-life, to At^{205} and leave the At^{204} with its 25-minute half-life and no alpha particles indicated. The arguments are not very strong for this assignment over the reverse and have to do with the generally shorter half-lives for alpha decay of the odd-even nuclei as compared with the odd-odd ones of the same or similar decay energy. For example, the alpha particles of At^{211}, At^{209}, and At^{207} are seen; those of At^{210}, At^{208} (one of the isomers), and At^{206} are not. The argument is admittedly weak.

At^{203} and Lighter Isotopes

An irradiation with 275 Mev helium ions produced still other astatine isotopes. This bombardment and others at higher energies were made with

pneumatic tube targets in order that the short half-lives might be seen. Fig. 11 shows the alpha pulse analysis of the astatine fraction in which new groups at 6.10 and 6.35 Mev appeared. The decay curves of these peaks are plotted in Fig. 12 along with part of that of 23-minute At^{205}.

Since these new activities first appeared at higher energies than At^{205} and At^{204}, it is necessary to assign them lower mass numbers. Their alpha energies are in conformity with this assignment. For the present we shall assume the 7-minute 6.10 Mev group to be At^{203} and designate the 6.35 Mev group with 1.7-minute half-life as $At^{<203}$. None of the decay products of these activities have been examined.

Using the full energy helium ions of the 184-inch cyclotron (380 Mev), other short-lived activities appeared. One, which we shall designate $At^{<202}$, has a 43-second half-life and alpha particles of 6.50 Mev.

Other alpha particle groups of lower energy and half-lives in the range 1-3 minutes were also observed. Although one or more of these may be astatine isotopes, their energies and half-lives are such that they could be polonium daughters of short-lived astatine isotopes, or polonium contamination carried in the extremely rapid chemical procedure.

ACKNOWLEDGMENTS

We wish to express our appreciation to J. T. Vale and the other members of the 184-inch cyclotron operating group for making the irradiations used in these studies. This work was performed under the auspices of the U. S. Atomic Energy Commission.

Fig. 1. Isotope chart of thallium-astatine region.

Fig. 2. Rough excitation functions of the astatine activities produced with 60-100 Mev helium ions on bismuth. (The points observed have been normalized to fit the excitation function of Kelly[2] for At^{211}.)

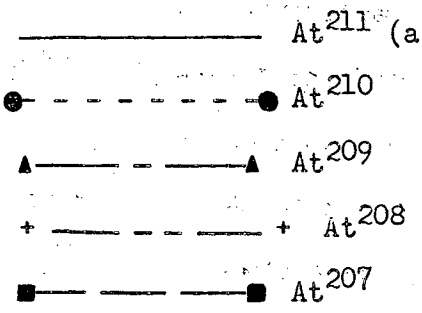

Fig. 3. Alpha particle spectrum from alpha pulse analysis of astatine made with 65 Mev helium ions on bismuth.

Fig. 4. Decay curves of At^{211} and At^{209} from data obtained by successive pulse analyses (see Fig. 3).

● 5.89 Mev group

▲ Total activity under 5.65 Mev peak

x Activity under 5.65 Mev peak after subtracting a maximum possible tailing from At^{211}

Fig. 5. Alpha particle spectrum of polonium activities remaining after decay of astatine produced with 120 Mev helium ions on bismuth. (Broken line is on ten-fold expanded ordinate scale.)

Fig. 6. Half-lives for At^{209} and At^{208} determined by yields of polonium daughters.

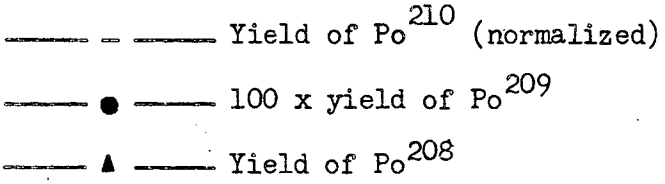

Fig. 7. Alpha particle spectrum of astatine prepared with 85 Mev helium ions on bismuth.

Fig. 8. Decay curves of At^{211}, At^{209}, and At^{207} from data obtained by successive pulse analyses (see Fig. 7).

Fig. 9. Yields of Pb^{203} and Po^{206} observed by "milking" astatine for lead and polonium at 2-hour intervals (astatine produced by 110 Mev helium ions on bismuth).

● Yields of 52-hour Pb^{203} indirectly from alpha decay of At^{207}

x Yields of 9-day Po^{206} from electron capture decay of At^{206}

Fig. 10. Yields of Bi^{204} and Bi^{205} separated from polonium fractions which were in turn separated from an astatine sample prepared with 150 Mev helium ions on bismuth.

Fig. 11. Alpha pulse analysis of astatine prepared with 275 Mev helium ions on bismuth.

Fig. 12. Decay of the alpha groups shown in pulse analysis of Fig. 11.

——●—— $At^{<203}$ 6.35 Mev α

— — — ▲ At^{203} 6.10 Mev α

- - - - -■ At^{205} 5.90 Mev α

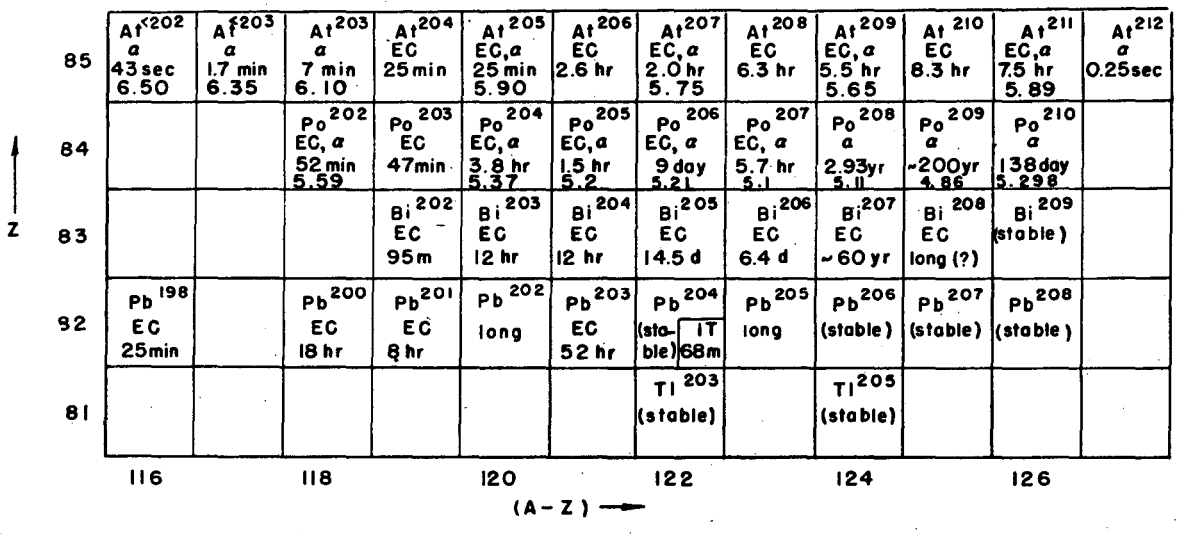
85
84
83
82
81
Z
At202 α 43 sec 6.50
At203 α 1.7 min 6.35
At203 α 7 min 6.10
At204 EC 25 min
At205 EC, α 25 min 5.90
At206 EC 2.6 hr
At207 EC, α 2.0 hr 5.75
At208 EC 6.3 hr
At209 EC, α 5.5 hr 5.65
At210 EC 8.3 hr
At211 EC, α 7.5 hr 5.89
At212 α 0.25 sec
Po202 EC, α 52 min 5.59
Po203 EC 47 min
Po204 EC, α 3.8 hr 5.37
Po205 EC, α 1.5 hr 5.2
Po206 EC, α 9 day 5.21
Po207 EC, α 5.7 hr 5.1
Po208 α 2.93 yr 5.11
Po209 α ~200 yr 4.86
Po210 α 138 day 5.298
Bi202 EC 95 m
Bi203 EC 12 hr
Bi204 EC 12 hr
Bi205 EC 14.5 d
Bi206 EC 6.4 d
Bi207 EC ~60 yr
Bi208 EC long (?)
Bi209 (stable)
Pb198 EC 25 min
Pb200 EC 18 hr
Pb201 EC 8 hr
Pb202 long
Pb203 EC 52 hr
Pb204 (stable) IT 68 m
Pb205 long
Pb206 (stable)
Pb207 (stable)
Pb208 (stable)
Tl203 (stable)
Tl205 (stable)
116
118
120
122
124
126
(A - Z)

FIG. 1

MU 1018

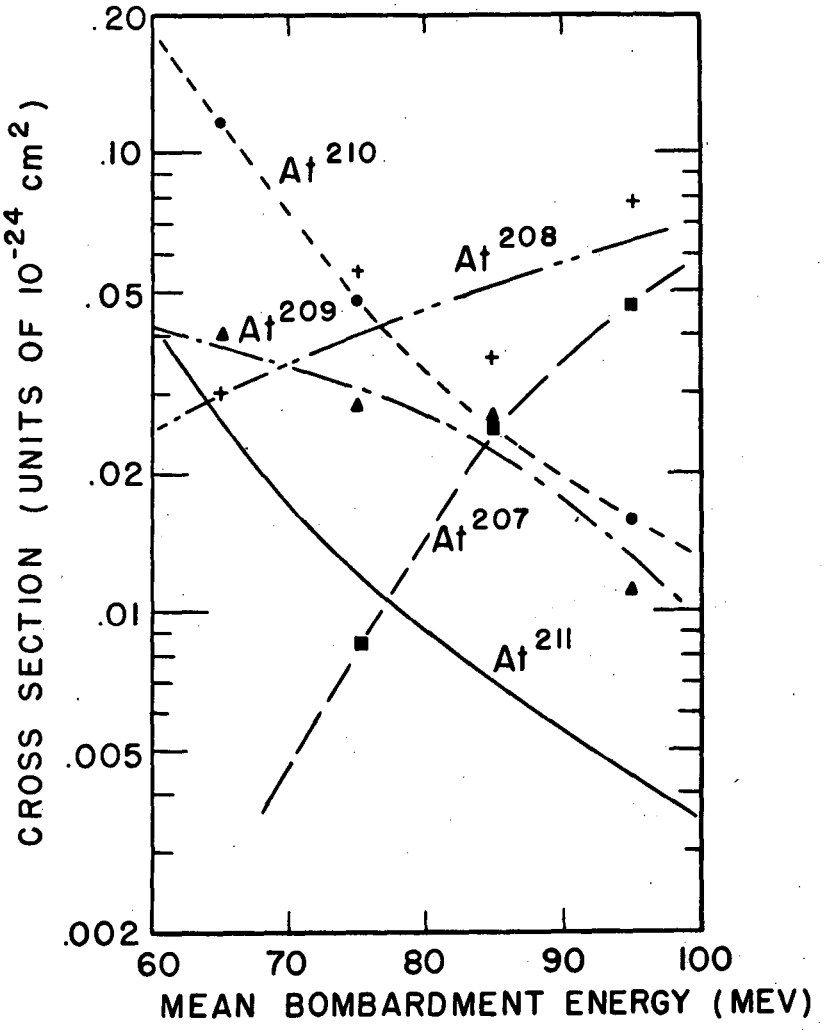
.20
.10
.05
.02
.01
.005
.002
CROSS SECTION (UNITS OF 10^{-24} cm^2)
At^{210}
At^{208}
At^{209}
At^{207}
At^{211}
60
70
80
90
100
MEAN BOMBARDMENT ENERGY (MEV)

FIG. 2

MU 1019

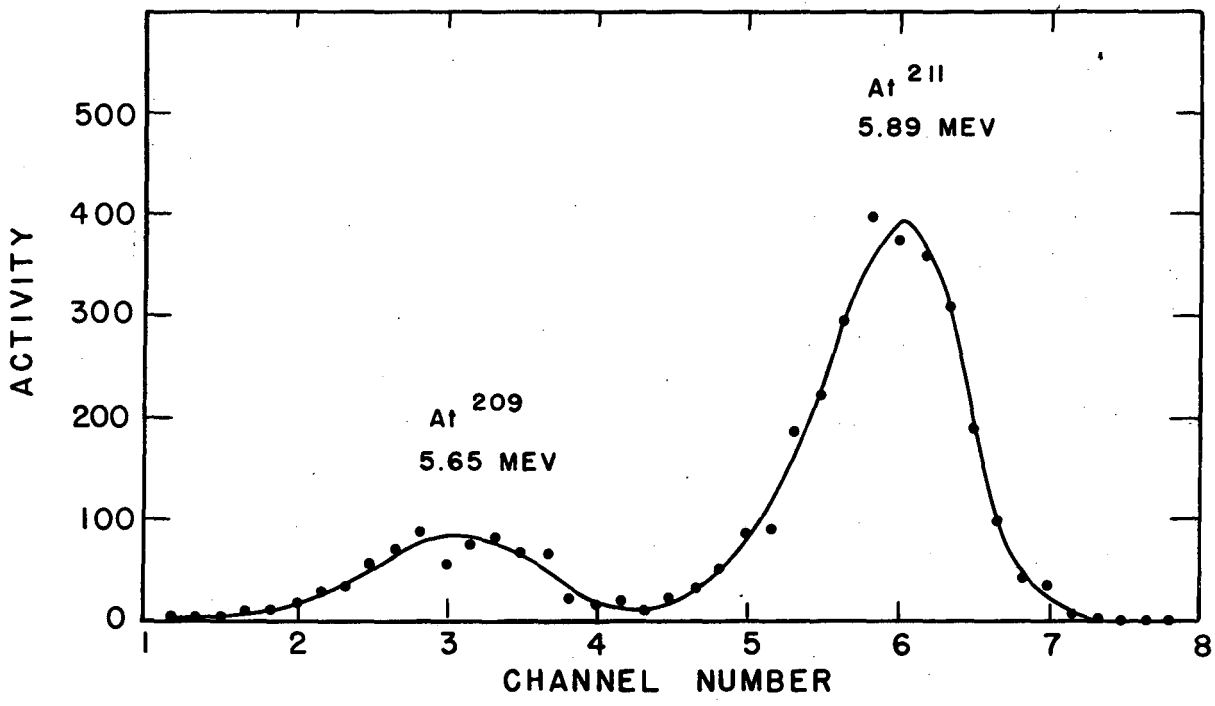
At 211
5.89 MEV
At 209
5.65 MEV
ACTIVITY
500
400
300
200
100
0
1
2
3
4
5
6
7
8
CHANNEL NUMBER

FIG. 3

MU 1020

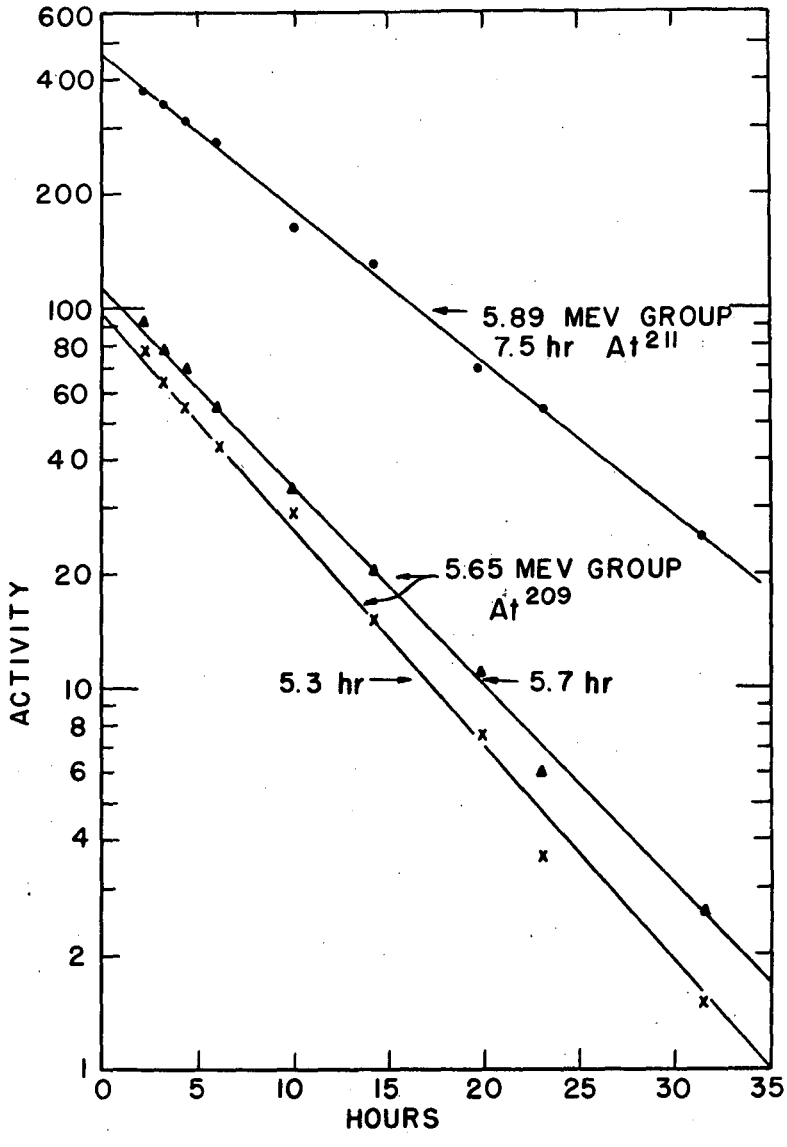
600
400
200
100
80
60
40
20
10
8
6
4
2
1
ACTIVITY
0
5
10
15
20
25
30
35
HOURS
5.89 MEV GROUP
7.5 hr At 211
5.65 MEV GROUP
At 209
5.3 hr
5.7 hr

FIG. 4

MU 1021

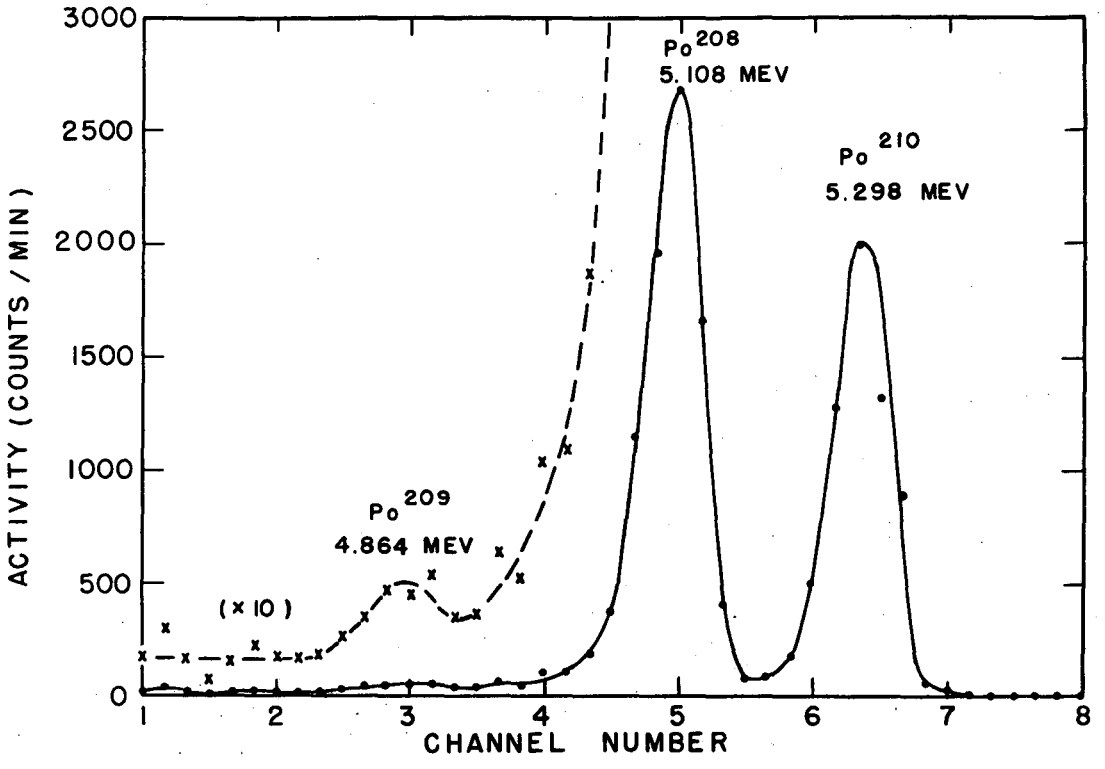
3000
2500
2000
1500
1000
500
0
ACTIVITY (COUNTS / MIN)
Po 208
5.108 MEV
Po 210
5.298 MEV
Po 209
4.864 MEV
(× 10)
1
2
3
4
5
6
7
8
CHANNEL NUMBER

FIG. 5

MU 1022

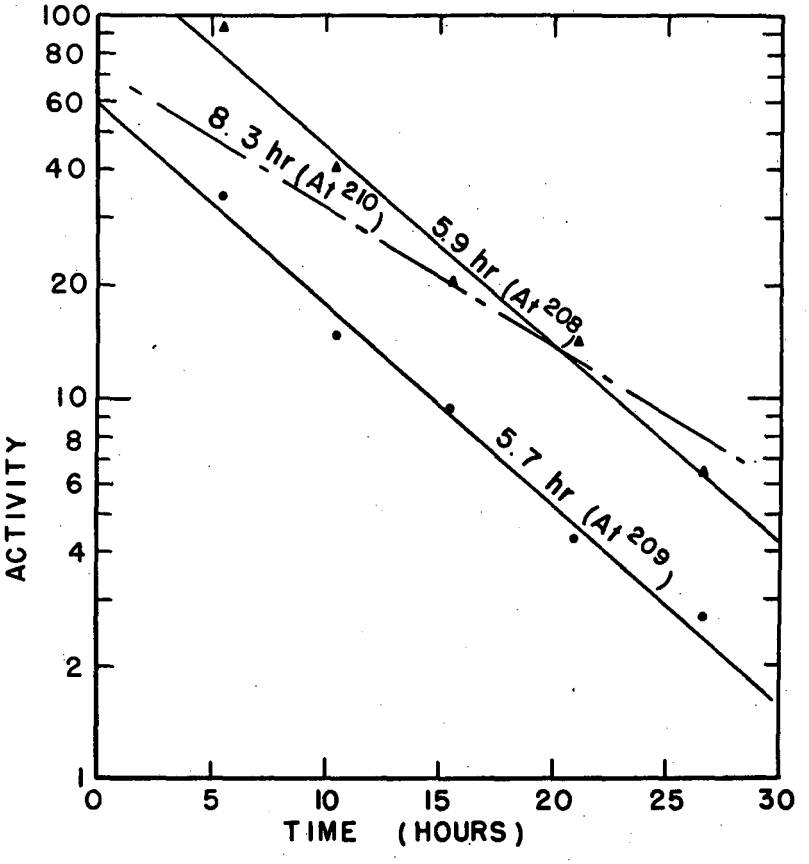
100
80
60
40
20
10
8
6
4
2
1
ACTIVITY
0
5
10
15
20
25
30
TIME (HOURS)
8.3 hr (At 210)
5.9 hr (At 208)
5.7 hr (At 209)

FIG. 6

MU 1023

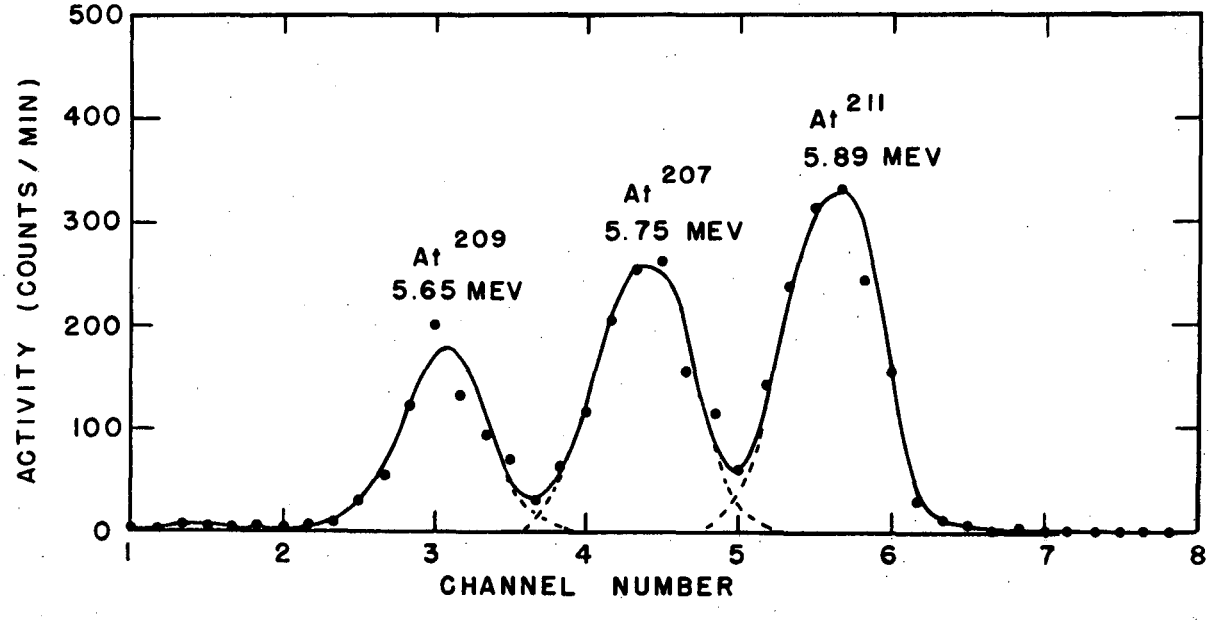
500
400
300
200
100
0
ACTIVITY (COUNTS / MIN)
1
2
3
4
5
6
7
8
CHANNEL NUMBER
At 209
5.65 MEV
At 207
5.75 MEV
At 211
5.89 MEV

FIG. 7

MU 1024

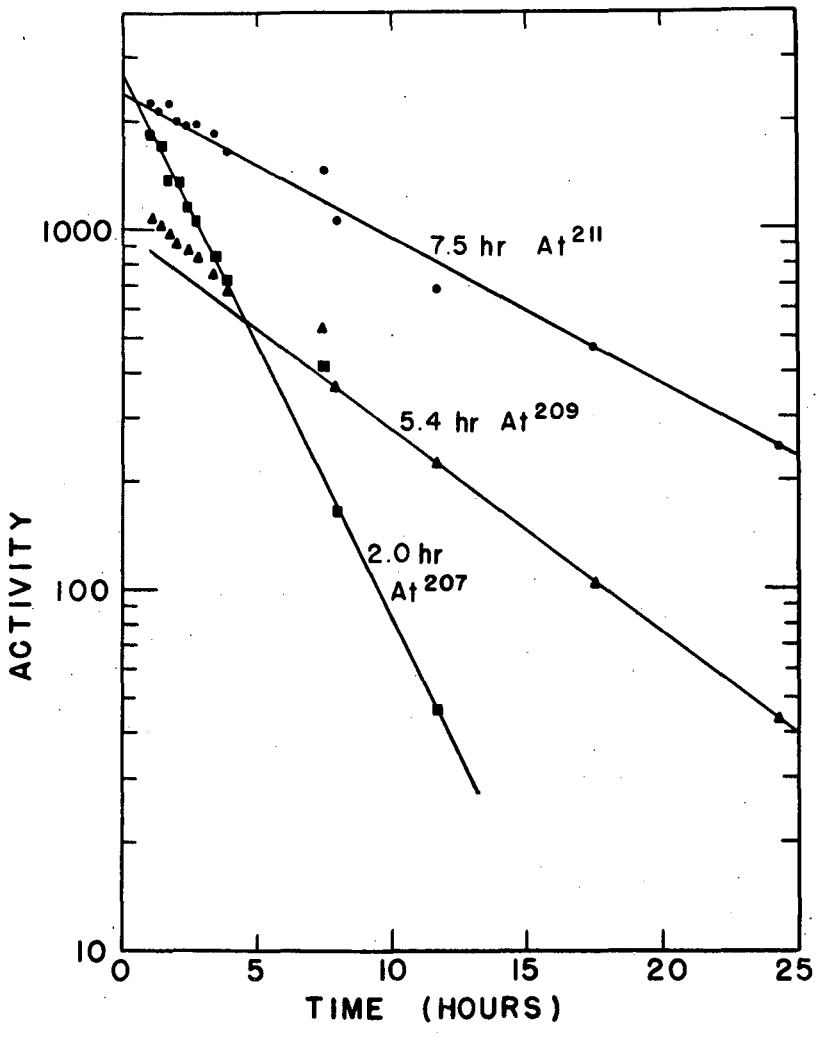
1000
100
10
ACTIVITY
0
5
10
15
20
25
TIME (HOURS)
7.5 hr At211
5.4 hr At209
2.0 hr
At207

FIG. 8 MU 1025

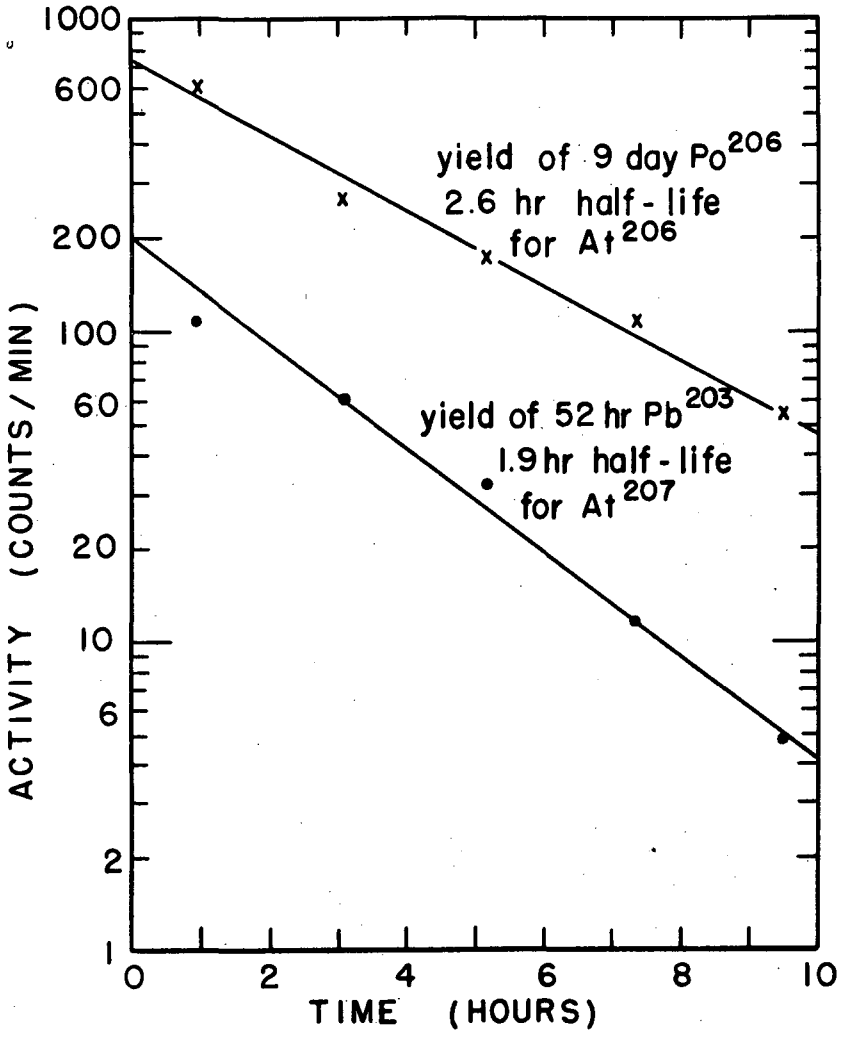
1000
600
200
100
60
20
10
6
2
1
ACTIVITY (COUNTS / MIN)
0
2
4
6
8
10
TIME (HOURS)
yield of 9 day Po206
2.6 hr half-life
for At206
yield of 52 hr Pb203
1.9 hr half-life
for At207

FIG. 9 MU 1026

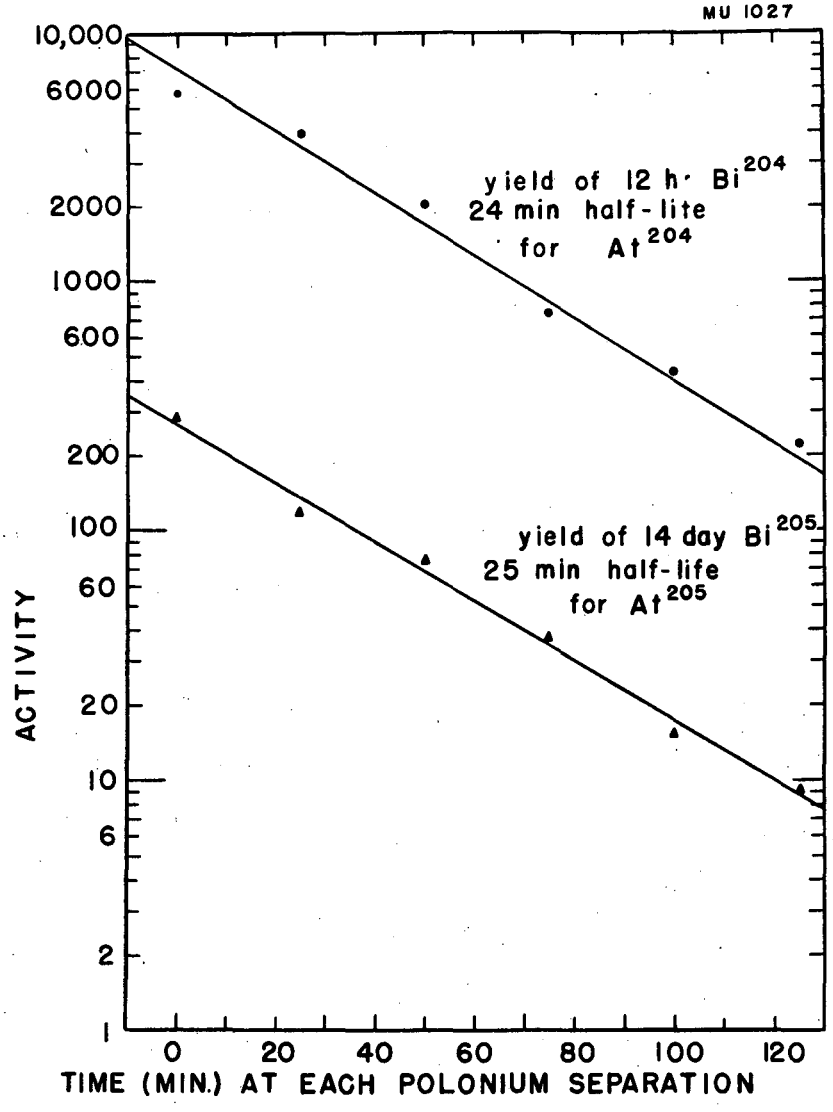
MU 1027
10,000
6000
2000
1000
600
200
100
60
20
10
6
2
1
ACTIVITY
yield of 12 h Bi 204
24 min half-lite
for At 204
yield of 14 day Bi 205
25 min half-life
for At 205
0
20
40
60
80
100
120
TIME (MIN.) AT EACH POLONIUM SEPARATION

FIG. 10

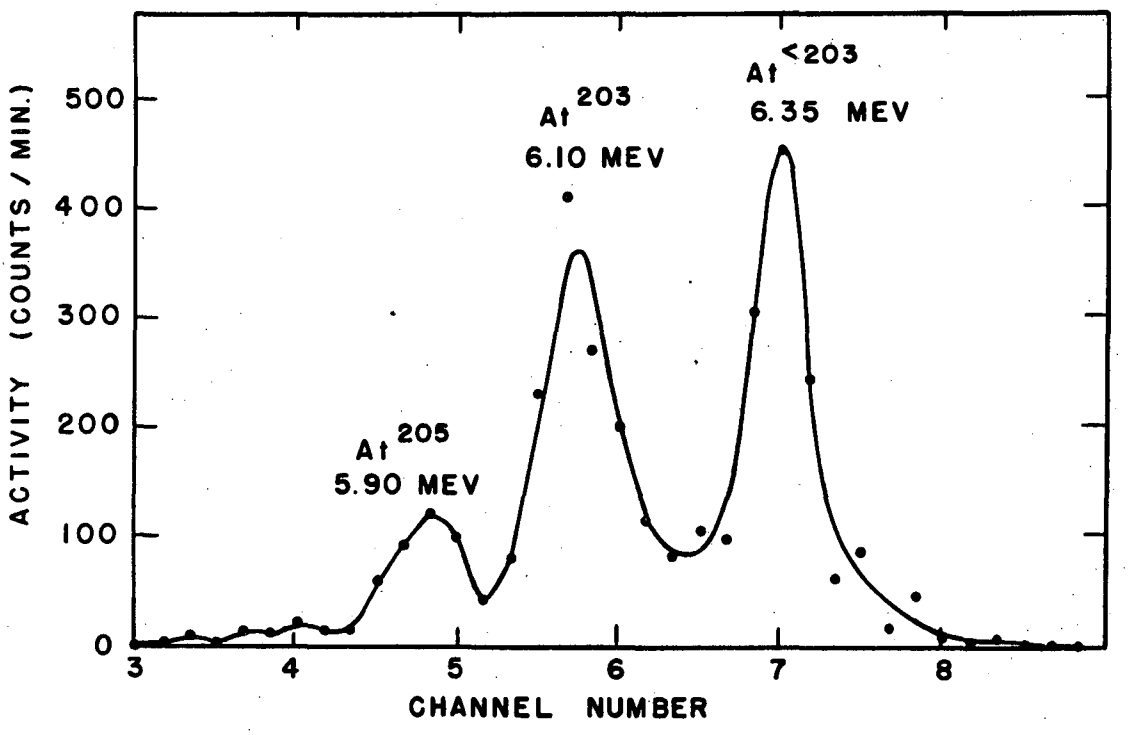

FIG. II

MU 1028

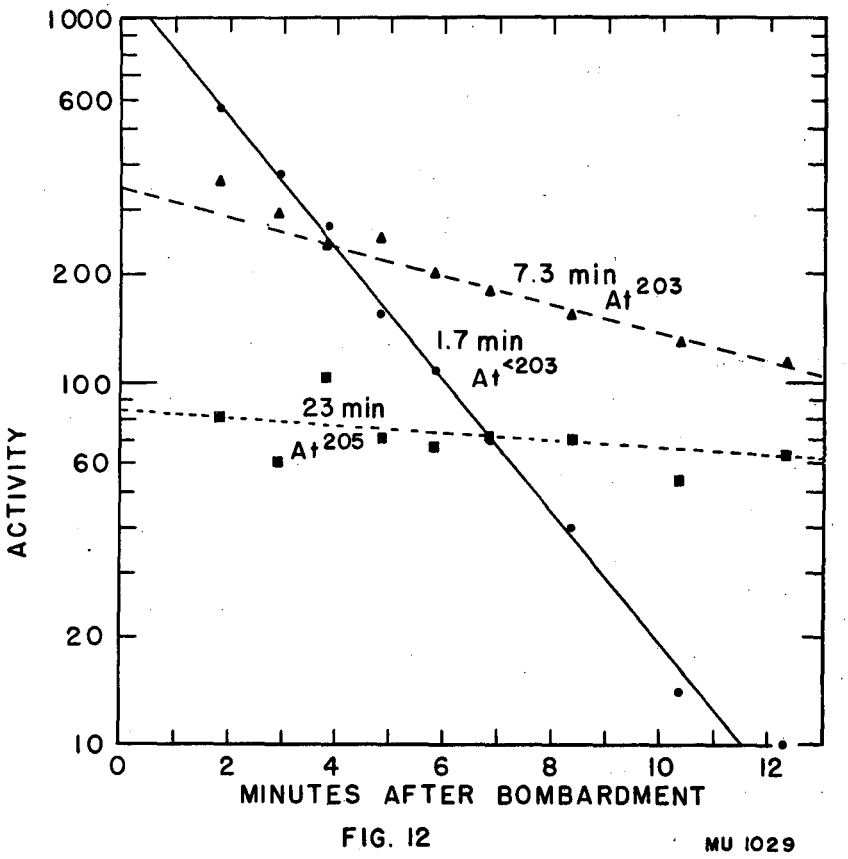

FIG. 12

MU 1029