Some Excitation Functions of Bismuth

E. L. KELLY AND E. SEGRÈ
Radiation Laboratory, Department of Physics, University of California, Berkeley, California
(Received December 17, 1948)

Excitation functions have been measured, using a 38-Mev alpha-beam and a 19-Mev deuteron beam for the following reactions: Bi(α,2n)At^{211}, Bi(α,3n)At^{210}, Bi(d,p)RaE, Bi(d,n)Po^{210}, and Bi(d,3n)Po^{208}. The results are summarized in Figs. 4 and 5 and Tables I and II. A new isotope of astatine, At^{210}, has been identified; this isotope has a half life of 8.3 hr., decaying by K-capture to Po^{210} with the emission of a 1.0-Mev gamma-ray and a few conversion electrons.

BISMUTH has long been a favorite element for excitation function work. This is due in part to the fact that bismuth has a single stable isotope, is abundant, and is easily evaporated to form thin uniform films. Also, many of the products of bismuth bombarded with deuterons or alphas are alpha-active, which is convenient for determination of absolute counting rates. Early investigators[1–3] in this field had available deuterons up to 9-Mev energy. In later work deuterons up to 14 Mev[4] and alphas up to 28-Mev energy[5] were used. In spite of the excellence of the work that already had been done on bismuth, the availability of the 19-Mev deuteron beam and the 38-Mev alpha-beam of the 60-in. Crocker Radiation Laboratory cyclotron made further work seem worth while. The method used in the present work is the well-known stacked foil technique with some improvement in the definition of the energy and the measurement of the beam current. A stack of aluminum foils, each having a thin film of evaporated bismuth on one side, was exposed to the collimated beam of the Crocker 60-in. cyclotron. The stack was not thick enough to stop the beam which was caught in a Faraday cup, amplified, and fed into a recording milliameter. The mean range of the cyclotron beam was found by determining the amount of aluminum absorber required to reduce the beam intensity to one-half. The activity induced in the bismuth films was counted by means of a parallel plate ionization chamber. Figure 1 gives a schematic diagram of the apparatus used for the bombardments. Tables I and II and Figs. 4 and 5 give the final results, i.e., the cross sections for the various processes as a function of the energy of the bombarding deuteron or alpha-particle.

[1] D. G. Hurst, R. Lantham, and W. B. Lewis, Proc. Roy. Soc. **174**, 126 (1940).
[2] J. M. Cork, J. Halpern, and H. Tatel, Phys. Rev. **57**, 348 (1940); **57**, 371 (1940).
[3] R. S. Krishnan and E. A. Nahum, Proc. Roy. Soc. **A180**, 321 (1942).
[4] J. M. Cork, Phys. Rev. **70**, 563 (1946).
[5] D. R. Corson, K. R. MacKenzie, and E. Segrè, Phys. Rev. **58**, 672 (1940).

EXPERIMENTAL DETAILS

The aluminum foil used as backing for the evaporated bismuth, and for the energy determination absorbers, was punched on a die whose area was accurately measured. The dimensions of several foils were also measured with a traveling microscope. The areas of the various foils agreed to better than 3 parts in a thousand. Each backing foil, which was 0.001 inch thick, was thoroughly cleaned in CCl_4 and absolute alcohol, and weighed on an assay balance to the closest 0.01 mg. Next, the foils were placed in a high vacuum chamber and bismuth evaporated onto them to the desired thickness. (Most runs were made with 1 to 1.5 mg cm^{-2} of bismuth.) The foils were then reweighed and the thickness of bismuth determined with an estimated accuracy of 1 part in 200 or better.

The raw beam of the 60-in. Crocker cyclotron had enough inhomogenity in energy so that a better definition of the energy was required. This was obtained with a collimation system which consisted of the deflector channel of the cyclotron and the $\frac{1}{8}$-inch slit shown in Fig. 1. Because of the fringing magnetic field of the cyclotron, this collimation system served as a velocity selector producing a beam of very homogeneous energy. Tests of energy *versus* deflector voltage showed a dependence of 0.04 Mev per kilovolt on the deflector. In practice the deflector voltage was held constant within 2 kilovolts for the entire run. Since this collimation reduced the primary beam intensity by a factor of approximately one hundred (from 10^{-5}–10^{-6} to 10^{-7}–10^{-8} amp.) a sensitive beam current integrator was necessary. The current to the Faraday cup of Fig. 1 (10^{-7} to 10^{-8} amp.) was amplified to 1 milliampere by a modified version of the current amplifier described by Vance,[6] and recorded on an Esterline Angus recording milliameter. The integrated beam current was found by planimetering the area under the trace. The trace of each run was planimetered by two people, and the agreement was 1 part in 200 or better. Allowance was made for the peculiar form of the Esterline Angus trace.

[6] A. W. Vance, Rev. Sci. Inst. **7**, 489 (1936).

The range of the collimated beam was determined in a manner similar to that described by Wilson.[7] The foil wheel shown in Fig. 1 contained aluminum absorbers differing in thickness by approximately 1 mg cm^{-2}. Each of these absorbers in turn was placed in the path of the beam, while the amount of beam current stopped and the amount transmitted were determined simultaneously by current amplifiers.[6] This gave the fraction of the total beam current transmitted for various thicknesses of aluminum absorber. From this data the mean beam range was at once determined. The position of the foil wheel could be changed by remote control, and since the stacked bismuth foils were contained in the wheel it was possible to determine the beam range, bombard the stacked bismuth foils, and redetermine the beam range without turning off the cyclotron. The range data for a typical run are plotted in Fig. 2. It will be noted that there was little change in the beam range during the run. The straggling of 1.1 percent compares favorably with the theoretical minimum of 0.9 percent given by Livingston and Bethe.[8] The range in aluminum was converted to energy using the table of Smith.[9]

The activity induced in the bismuth films was followed by counting each sample in a parallel plate ionization chamber having a depth of 1.5 cm and filled with argon at a pressure of 1.7 atmospheres. The pulses from electron collection in the chamber were fed into a preamplifier and then into an amplifier whose time of rise was 0.2 microsecond. The amplified pulses were discriminated and counted on a 256 scaling circuit and mechanical register. The counter was checked against a standard alpha-particle source (a thin uranium sample electro-deposited on platinum) at the beginning and end of each counting period, and was found to remain constant to one percent over the entire period of 2 years during which these studies were made. The background was 1 to 2 counts per minute. The counting rate of the uranium alpha-standard as a function of discriminator bias is shown in Fig. 3. The counting efficiency at the operating bias of 14 has been taken to be 0.50. This round number takes into account the absorption in the sample itself and the back-scattering from the support.

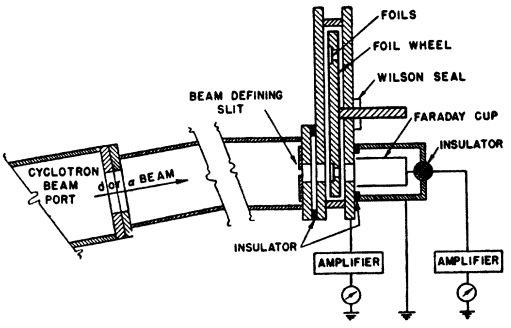

FIG. 1. Schematic diagram of the collimating tube, foil holder, and current amplifiers. This apparatus connects directly to the cyclotron tank and becomes therefore an integral part of the cyclotron vacuum system, obviating the need for any windows or separate pumps.

The possibility of error in the beam current measurements as a result of gas ionization or secondary electron emission was investigated. The space around the Faraday cup and the foil wheel was connected to the cyclotron tank during normal operation, as shown in Fig. 1. Since the pumping speed of the opening of the defining slits was small, a leak in this region could cause a substantial increase in pressure with a resulting increase in gas ionization along the path of the beam between the slits and the Faraday cup. Any selective collection of these gas ions would, of course, introduce an error. To test this effect, the pressure in the region of the Faraday cup was gradually increased until the cyclotron tank pressure showed a 50 percent increase. At this juncture the pressure in the region of the Faraday cup was approximately 10 microns of mercury, but no evidence of gas ionization was observed on the beam current meters. Since in normal operation no observable change in cyclotron tank pressure was produced by our apparatus, this source of error must be ruled out. The effect of possible secondary emission of electrons is also ruled out. The fringing magnetic field of the cyclotron is 2500 gauss in the region where the Faraday cup was located. The resulting curvature in the path of any secondary electron formed by the beam striking the bottom of the Faraday cup would be more than sufficient to prevent the escape of the electron.

Bi(α,2n) AND Bi(α,3n) EXCITATION FUNCTIONS

At bombarding alpha-energies below 29 Mev the only alpha-particle activity observed in the bombarded bismuth was that of At^{211}, which has a half-life of 7.5 hr. At higher bombarding alpha energies another alpha-activity was observed after the 7.5-hr. activity had died out. This was found to be due to Po^{210}. No other alpha-activity was detected. This made the separation of activities extremely simple. Alpha-counts 5 or 6 days after bombardment gave only the Po^{210} activity; correcting this for decay and subtracting from alpha-counts made within 24 hours after bombardment, we obtained the activity resulting from At^{211}, which could then easily be extrapolated back to the time of the end of bombardment. This method of sepa-

[7] R. R. Wilson, Phys. Rev. 60, 749 (1941).
[8] M. Stanley Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 285 (1937).
[9] J. H. Smith, Phys. Rev. 71, 32 (1947).

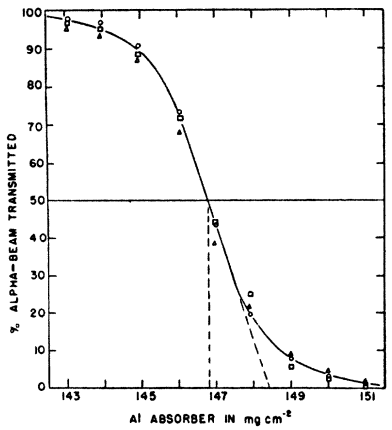

FIG. 2. The percent of the α-beam transmitted by the Al absorber plotted as a function of the absorber thickness. The three sets of points represent data taken before bombardment, at the middle of bombardment, and after bombardment of the bismuth foils. The straggling, given by the difference between the extrapolated range and the mean range divided by the mean range, is 1.1 percent.

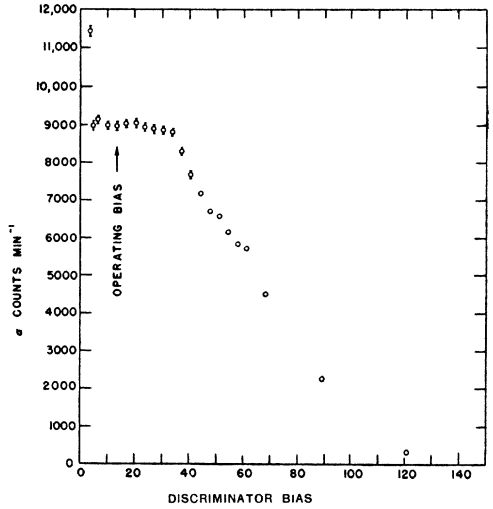

FIG. 3. Counts per minute of the thin U α-standard plotted as a function of the pulse discriminator bias voltage. The operating bias was kept constant to within 2 units.

rating the activities was quick and accurate.* The question immediately arose, however, as to the origin of the Po^{210}. Careful investigation, which will be discussed in detail later, showed that the Po^{210} came from the Bi(α,3n) reaction producing At^{210} which in turn decays to Po^{210} by orbital electron capture, with a half-life of 8.3 hr. Thus the At^{210} which had no alpha-activity decayed to an alpha-emitter which was readily counted on an absolute scale. The results of three runs were analyzed in this way and reduced to absolute cross section *versus* energy of the bombarding alphas. One run was made with bismuth films of 0.3 mg cm^{-2}, one with 1.5 mg cm^{-2}, and one with 2.0 mg cm^{-2}. When the results of these runs were first compared, a dispersion of a few percent was found, which was felt to be outside the experimental error. After thorough checking, this dispersion was tentatively laid to the inaccuracy in the stopping power ratio of bismuth to aluminum, which had been extrapolated from the value for gold given by Bethe.[8] A subsequent experimental determination of this stopping power ratio removed the apparent dispersion. The results of the three runs are shown in Fig. 4 and Table I.

Bi(d,p), Bi(d,n), AND Bi(d,3n) EXCITATION FUNCTIONS

The activities resulting from deuterons on bismuth are more difficult to separate than those from alphas on bismuth. Early work has established the production of RaE(Bi^{210}) and Po^{210} from the Bi(d,p) and Bi(d,n) reactions. Recent work[10] shows that the Bi(d,2n) reaction is not ordinarily observed and that the only alpha-activity at these energies, other than that due to the Bi(d,n) and Bi(d,p) reactions, is due to the Bi(d,3n) reaction which results in Po^{208} with a half-life of about 3 years. This is in agreement with the results of two deuteron on bismuth runs made by the authors.

For the separation of the Po^{210} with a 140-day half-life, the Po^{208} with a 3-year half-life, and the RaE, which goes by 5-day β-decay to Po^{210}, the following procedure was adopted.** Each sample was alpha-counted within several hours after bombardment and daily for a week; each sample was counted again after 2 months when all of the 5 day RaE had decayed into Po^{210}, and thereafter once every 3 months for a year. In order to determine the Po^{208} half-life, ten samples were analyzed by trial and error into 140-day Po^{210} and Po^{208}, such that when the Po^{210} activity was subtracted, the resulting activity fell on a straight line on semilog paper. The slope of this line gave the Po^{208} half-life. The result was 3.0 ± 0.2 years where the error given is based on internal consistency only. Each bombarded sample was then analyzed by the same method except that the resulting activity after Po^{210} subtraction was required to fit a straight line with a slope corresponding to a half-life of 3.0 years. This yielded the Po^{208} activity, which was extrapolated back to the time of the end of bombardment, and the total Po^{210} activity which was also extrapolated back to the time of the end of bombardment. Sub-

* This method neglects the 8.3-hr. half-life for formation of the Po^{210} mentioned below, but the resulting error introduced was found to be negligible in all cases.

[10] D. H. Templeton, J. J. Howland, and I. Perlman, Phys. Rev. 72, 758 (1947).

** It is not practical to use the difference in energy between the alphas of Po^{208} and Po^{210} to distinguish between the two because the difference is too small (5.298–5.14 Mev).

TABLE I. Experimental values of the cross section for the $Bi(\alpha,2n)At^{211}$ and the $Bi(\alpha,3n)At^{210}$ reactions at various energies of the bombarding alpha-particles.

	σAt^{211}			σAt^{210}	
α-energy Mev	Run I barns	Run II barns	Run III barns	Run I barns	Run II barns	Run III barns
18.8		0.000				
19.9	0.000					
20.0			0.000			
20.2		0.001				
21.2	0.01					
21.6		0.01	0.03			
22.4	0.10					
23.0		0.11				
23.1			0.16			
23.5	0.25					
24.2		0.29				
24.6	0.40		0.35			
25.4		0.45				
25.7	0.55					
26.1			0.57			
26.5		0.58				
26.7	0.67					
27.4			0.71			0.000
27.6		0.69			0.000	
27.7	0.75			0.000		
28.6	0.83		0.81	0.004		0.004
28.7		0.78			0.003	
29.6	0.90			0.013		
29.7		0.85			0.007	
29.9			0.90			0.015
30.5	0.89			0.06		
30.7		0.89			0.05	
31.0			0.91			0.10
31.4	0.86			0.17		
31.7		0.85			0.16	
32.2			0.81			0.28
32.3	0.75			0.35		
32.6		0.75			0.37	
33.1	0.62			0.53		
33.3			0.63			0.53
33.6		0.61			0.61	
34.0	0.48			0.73		
34.5			0.46			0.75
34.6		0.47			0.82	
34.8	0.39			0.93		
35.5		0.37			1.01	
35.6	0.30		0.33	1.03		0.94
36.4	0.24	0.29		1.14	1.16	
36.7			0.25			1.11
37.2	0.20	0.23		1.20	1.21	
38.0	0.17			1.24		
38.8	0.15			1.27		

tracting the extrapolated Po^{208} from the activity measured immediately after bombardment gave the Po^{210} due to the $Bi(d,n)$ reaction. From the extrapolated total Po^{210} activity and the Po^{210} activity due to the $Bi(d,n)$ reaction, the amount of RaE was found. The amount of RaE was also found by the growth of the total alpha-activity in the first week after bombardment. These two determinations of RaE agreed within one percent. The results of two runs of deuterons on bismuth reduced to absolute cross section *versus* energy of the bombarding deuterons are shown in Fig. 5 and Table II.

The Po^{208} activity seemed to be produced by deuterons of an energy too low to make a $(d,3n)$ reaction. A further close examination of the alpha-activity in the energy region between 10 and 15 Mev showed that we had also another Po isotope present, emitting alphas of 4.95 Mev. This substance is Po^{209} formed by the $(d,2n)$ reaction. If we assume that it decays only by α-emission and that the maximum cross section for its formation is about 10^{-24} cm^2, a half-life of about 200 years results.

ASTATINE^{210}

Bismuth bombarded with alpha-particles of 37-Mev energy yields the 7.5-hr. alpha-activity of At^{211}, and the 140-day alpha-activity of Po^{210}, as was mentioned above; in addition, there is an easily distinguishable gamma-ray activity. The Po^{210} alpha-activity was found to decrease with decreasing energy of the bombarding alphas, disappearing with alpha-energies below 29 Mev (see Fig. 4). The gamma-activity likewise disappeared with bombarding alpha-energies below 29 Mev. The gamma-activity was found to follow the At^{211} alpha-activity quantitatively through a chemical separation and through a vacuum distillation over to a cold platinum plate.[11] In the separated astatine fraction Po^{210} alpha-activity could be observed after the relatively short-lived At^{211} alpha-activity had decayed out. These results suggested that Po^{210} was formed as a decay product of a new isotope of astatine, probably by capture of an orbital electron of At^{210} which had been formed by an $(\alpha,3n)$ reaction on bismuth.

In order to study the formation of the Po^{210} more carefully, a G-M counter was constructed having an optimum x-ray counting efficiency in the region of the K x-rays of polonium. This counter was a Chicago type, having a cyclindrical aluminum wall 0.25 mm thick lined with tin foil 0.08 mm thick.

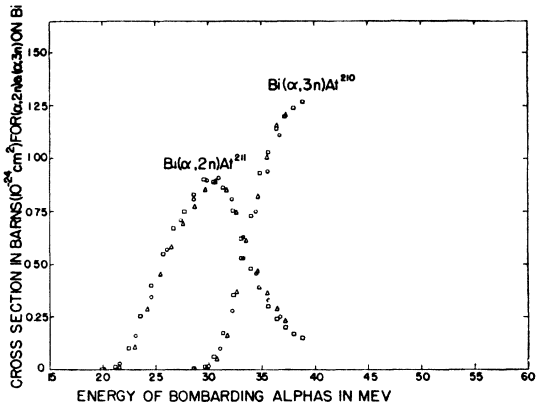

FIG. 4. Absolute cross section for the $Bi(\alpha,2n)$ reaction and the $Bi(\alpha,3n)$ reaction plotted as a function of the energy of the bombarding alphas.

[11] For the separation methods see Johnson, Leininger, and Segrè, "Chemical properties of astatine. I," J. Chem. Phys. **17**, 1 (1949).

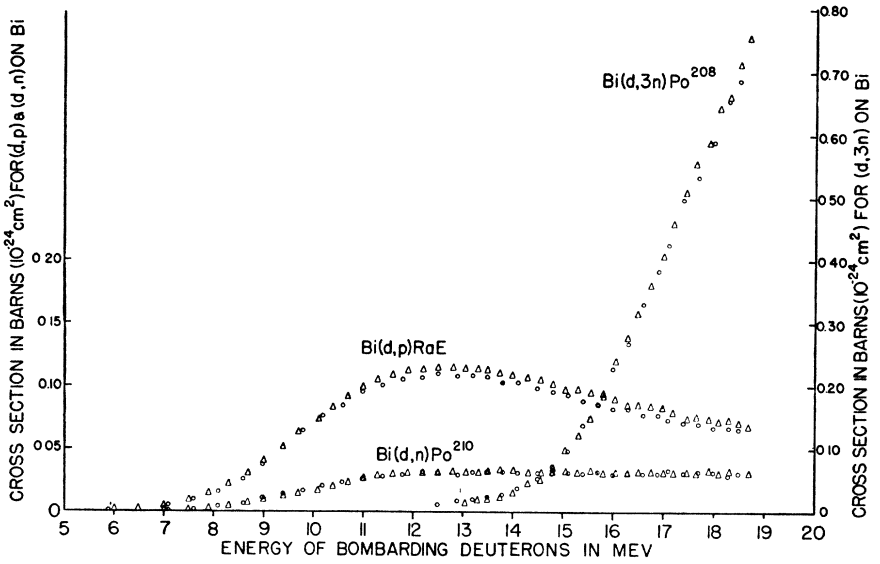

FIG. 5. Absolute cross sections for the Bi(d,p), Bi(d,n), and the Bi(d,$3n$) reactions plotted as a function of the energy of the bombarding deuterons.

The counter was filled with argon plus 10 percent of alcohol to a pressure of 10 cm of mercury.

Two samples of astatine were studied with this G-M counter and with the alpha-counter. Sample A was prepared by bombarding thin bismuth with alphas of 25-Mev energy and then extracting the astatine by a vacuum distillation over to a cold platinum plate; sample B was prepared in the same way except that the bombarding alphas had an energy of 37 Mev rather than 25 Mev. Absorption in lead indicated that a gamma-ray of 1.0-Mev energy was present in sample B but was not present in sample A, as is shown in Fig. 6. This gamma-ray was found to decay with a half-life of 8.3 hours. Absorption in aluminum showed that some 0.9-Mev electrons accompanied the gamma-rays; these were in all probability conversion electrons of the 1.0-Mev gamma-rays. Absorption in platinum and tungsten revealed that both samples emitted x-rays showing the absorption properties to be expected for the K lines of polonium. The ratio of the K x-ray counting rate to the alpha-counting rate was 10 to 14 times as large in sample B as in sample A. In sample A the half-life of the K x-rays was 7.5 hours; in sample B the half-life of the K x-rays was slightly more than 8 hours. Po^{210} was found in sample B but not in sample A. Clearly, sample B contained a new isotope of astatine, most if not all of which decayed into Po^{210} with the emission of K x-rays and gamma-rays.

The existence of At^{210} and its decay by orbital electron capture to Po^{210} being thus established, the question arises as to whether all the Po^{210} found in our alpha-bombardment was produced through the decay of At^{210} or whether some was formed directly by a Bi(α,$2np$) reaction. This question could be settled in several ways. The method we chose consisted, in principle, in dividing a thin bombarded bismuth foil into two equal parts and extracting all the astatine from one part immediately after bombardment. A week later only the Po^{210} activities were left and were readily determined by alpha-counting each sample. If all the Po^{210} formed is a daughter of At^{210}, the unextracted sample and the extracted astatine sample must each have the same activity. On the other hand, if some of the Po^{210} is formed directly at bombardment then the unextracted sample must have a greater activity than the extracted astatine sample.

In practice this procedure requires enough time so that an extrapolation must be made back to the time of the middle of the bombardment. In order to make this extrapolation the procedure was repeated allowing various time intervals between the bombardment and the astatine extraction. To eliminate the effect of unequal division of the bombarded bismuth foil and variation of the extraction yield, the amount of At^{211} alpha-activity in each sample was used for normalization. The ratio of the Po^{210} resulting from the decay of the extracted astatine to the total Po^{210} formed plotted as a function of extraction time is shown in Fig. 7. The decay is seen to agree quite well with the 8.3-hour half-life found for the gamma-rays. The zero time intercept (the time of the middle of the bombardment) shows that within the experimental error all the Po^{210} was formed by the decay of the At^{210}.

Clearly, the results shown in Fig. 7 are valid only if the astatine extractions are free from polonium contamination. For this reason the extraction process[11] employed here will be described briefly. When an alpha-bombarded sample of bismuth on aluminum is heated in the presence of silver in an evacuated glass vessel, the astatine vapor is selectively adsorbed by the silver. Careful tests have shown that after 10 minutes at 310°C more

TABLE II. Experimental values of the cross section for the Bi(d,p)RaE, the Bi(d,n)Po^{210}, and the Bi($d,3n$)Po^{208} reactions at various energies of the bombarding deuterons.

d-energy Mev	σRaE Run I barns	σRaE Run II barns	σPo^{210} Run I barns	σPo^{210} Run II barns	σPo^{208} Run I barns	σPo^{208} Run II barns
5.3		0.0002				
5.9		0.001				
6.0	0.001					
6.5	0.002	0.002	0.0003	0.0003		
7.0	0.004		0.0006			
7.1		0.005		0.001		
7.5	0.008		0.001			
7.6		0.009		0.002		
7.9	0.014		0.002			
8.1		0.016		0.004		
8.3	0.021		0.004			
8.6		0.026		0.007		
8.7	0.030		0.006			
9.0	0.040	0.037	0.009	0.010		
9.4	0.051	0.051	0.011	0.013		
9.7	0.062		0.014			
9.8		0.064		0.017		
10.1	0.073		0.016			
10.2		0.076		0.020		
10.4	0.082		0.019			
10.6		0.084		0.023		
10.7	0.091		0.023			
11.0	0.099	0.095	0.026	0.026		
11.3	0.104		0.028			
11.4		0.100		0.028		
11.6	0.108		0.029			
11.8		0.105		0.029		
11.9	0.111		0.030			
12.2	0.112	0.107	0.030	0.031		
12.5	0.114	0.109	0.030	0.031		0.01
12.8	0.114		0.031			
12.9		0.108		0.029		0.02
13.1	0.113		0.030		0.01	
13.2		0.108		0.031		0.02
13.3	0.113		0.030		0.02	
13.5	0.112	0.107	0.031	0.031	0.02	0.02
13.7	0.110		0.033		0.02	
13.8		0.102		0.031		0.03
14.0	0.109		0.032		0.03	
14.1		0.102		0.030		0.04
14.3	0.106		0.030		0.04	
14.5	0.104	0.098	0.031	0.030	0.05	0.05
14.8	0.101	0.095	0.031	0.031	0.07	0.07
15.1	0.096	0.093	0.032	0.031	0.10	0.10
15.3	0.097		0.030		0.12	
15.4		0.088		0.030		0.14
15.5$_5$	0.094		0.032		0.15	
15.7		0.086		0.031		0.17
15.8	0.091		0.030		0.19	
16.0		0.082		0.029		0.23
16.0$_5$	0.089		0.030		0.24	
16.3	0.084	0.081	0.030	0.030	0.27	0.27
16.5	0.084		0.031		0.31	
16.6		0.078		0.030		0.33
16.7$_5$	0.084		0.031		0.36	
16.9		0.077		0.030		0.38
17.0	0.082		0.031		0.41	
17.1		0.073		0.032		0.43
17.2	0.079		0.031		0.46	
17.4	0.074	0.071	0.031	0.031	0.51	0.50
17.7	0.075	0.070	0.030	0.032	0.55	0.53
17.9	0.074		0.032		0.59	
18.0		0.067		0.032		0.59
18.1	0.072		0.030		0.64	
18.3	0.073	0.067	0.032	0.029	0.66	0.66
18.5	0.070	0.066	0.032	0.031	0.71	0.69
18.7	0.068		0.030		0.75	

than 85 percent of the astatine alpha-activity was collected on the silver foil. Under the same conditions, using a bombarded bismuth sample from which all the astatine had decayed out, only 0.07 percent of the polonium alpha-activity present in the bismuth appeared on the silver foil. For this astatine separation method neither the temperature nor the heating time was very critical; however, the bismuth had to be melted (273°C or more), and the polonium contamination increased slowly with increasing temperature.

If there were any appreciable alpha-branching in the decay of At^{210}, as there is in At^{211}, one should see evidence of this alpha-activity and evidence of the decay product, which would be Bi^{206} with a 6.4-day half-life. Examination of extracted astatine in the 48-channel pulse analyser[12] showed no alpha-activity other than that of At^{211} and Po^{210}. If the branching ratio had been 1 part in 100 or larger the resulting alpha-activity could have been observed. Examination of the astatine extracted from a thick bismuth target bombarded with 200-microampere hours of alpha-particles having an energy of 37 Mev showed no evidence of 6.4-day activity. If 1 part in 10^4 of the At^{210} had decayed by alpha-emission, the 6.4-day Bi^{206} would have been observable.

CONCLUSIONS

The (d,p) and (d,n) reactions have recently been treated in a paper by Peaslee. In this paper he

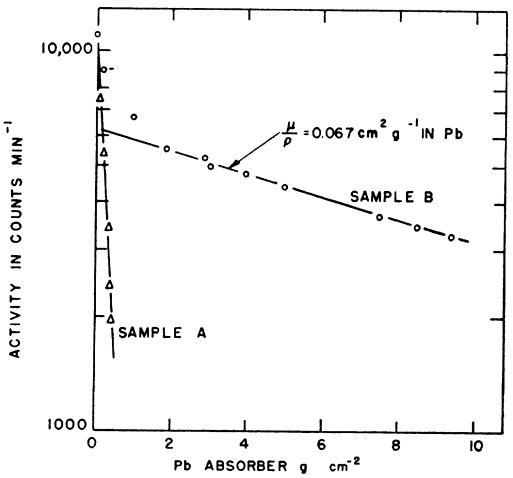

FIG. 6. The counting rate on a G-M counter of astatine samples plotted as a function of the thickness of lead absorber. Sample A consisted of the At extracted from a foil of Bi bombarded with alphas of 25-Mev energy; sample B consisted of the At extracted from a foil of Bi bombarded with alphas of 37 Mev. As a check of the geometry the mass absorption coefficient of a $Co^{60}\gamma$-standard was measured and found to be 0.055 cm^2g^{-1} in Pb.

[12] Ghiorso, Jaffey, Robinson, and Weissbourd, "An alpha-pulse analyser apparatus," *Plutonium Project Record* **14B**, 17.3 (1948), to be issued.

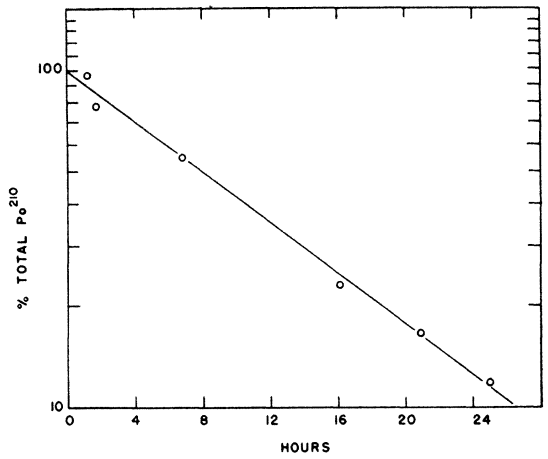

FIG. 7. The amount of Po^{210} formed by the decay of the extracted At^{210}, expressed as percent of the *total* Po^{210} formed, plotted as a function of the time from the middle of bombardment until the At extraction.

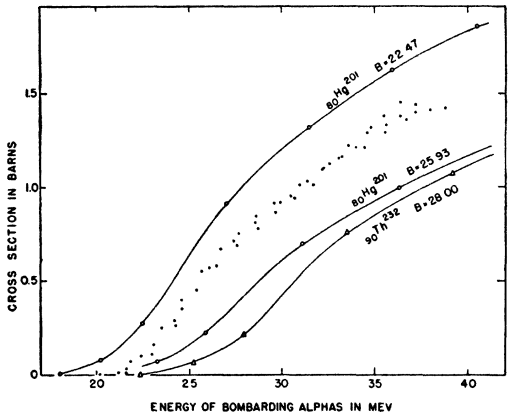

FIG. 8. The cross section of the compound nucleus (At^{213}) as a function of the energy of the bombarding nucleus. The solid lines represent the computed data of Weisskopf. The scattered points are experimental values of the sum of σ for Bi(α,2n) and σ for Bi(α,3n).

interprets our experimental material, and we refer to it for details.[13] The main qualitative conclusions are that the stripping processes of the deuteron as opposed to the formation of a compound nucleus in which the whole deuteron is absorbed are mainly responsible for the observed cross sections. In the (d,p) case the stripping process is the well-known Oppenheimer-Philips reaction; in the (d,n) case it is an analogous reaction.

The interpretation of the (α,2n) and the (α,3n) reactions can be made in a very simple semi-empirical way as follows.

Consider first the cross section σ_a for formation of the compound nucleus. This cross section has been calculated in some typical examples by V. F. Weisskopf.[14] In Fig. 8 the solid lines give Weisskopf's values for $_{80}Hg^{201}$ for two values of the barrier height, 25.93 Mev and 22.47 Mev corresponding to $r_0=1.3\times10^{-13}$ cm and 1.5×10^{-13} cm; the values are also given for $_{90}Th^{232}$ for a barrier height of 28.00 Mev corresponding to $r_0=1.3\times10^{-13}$ cm.

If we sum our (α,2n) and (α,3n) cross sections, we find passable agreement with Weisskopf's curve. See Fig. 8. This we interpret as meaning that all other competing reactions—(α,p), (α,pn), (α,γ), (α,α), etc.,—have small cross sections compared with (α,2n) and (α,3n) in the energy region considered. Exception to this is the (α,n) reaction which in the energy region around 20 Mev may have a cross section which, although small on an absolute scale, exceeds appreciably the (α,2n) cross section. Hence until experiments on this point are completed it will be impossible properly to fit the theoretical curve for the compound nucleus formation to our experimental data in the region near the threshold. An investigation of the (α,n) cross section is in progress.

It is interesting to consider the excitation energy of the compound nucleus above its ground state. The compound nucleus At^{213} in its fundamental state would certainly be alpha-radioactive. By comparison with neighboring known nuclei—At^{211}, AcC′, At^{212}, etc.,—one would make a fair guess of half-life of about 5×10^{-3} sec. and an alpha-energy of 7.5 Mev. Hence the excitation energy of the compound nucleus is approximately equal to the energy of the impinging alpha-particle minus 7.5 Mev. Thus to release 2 neutrons it takes at least $21.5-7.5=14$ Mev and to remove a third neutron an additional 8.5 Mev or at least $30-7.5=22.5$ Mev to remove 3 neutrons.

The cooperation of Dr. J. G. Hamilton, Mr. T. Putnam, Mr. B. Rossi, and other members of the 60-inch cyclotron group in making the bombardments for this work is gratefully acknowledged. Thanks are due Dr. R. F. Leininger for assistance in the preparation of the separated samples and also Mr. H. P. Robinson for help with the pulse analysis. The authors are indebted to Mr. R. W. Birge for the design and construction of some of the apparatus used and for some of the preliminary work on this problem.

This work was done under the auspices of the AEC.

[13] D. C. Peaslee, Phys. Rev. **74**, 1001 (1948).
[14] AEC Declassified Document MDDC 1175 (1947), *Lecture Series in Nuclear Physics*, LA24, Chapter 36, p. 105.