implies $\Lambda(\text{G.S.})=6.2\pm1.0$, and for the transition to the 4.43-Mev first excited state, $\Lambda(4.43)=0.9\pm0.7$. From Table I in Kurath's article, one has $\Lambda(\text{G.S.})=5.74$, $\Lambda(4.43)=0.66$, for $a/K=6.0$. The transition to the first excited state is calculated to be more than 95% $M1$ for $a/K>4$. The theoretical and experimental results agree when a/K lies between about 5.5 and 6.7, which Kurath states is a reasonable value for nuclei of mass number 12.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Alan Penfold for his many contributions to this work, and for many helpful discussions concerning it. Thanks is also rendered to the betatron section at the National Bureau of Standards for the calibration of the Kerst-Edwards ionization chamber, and to Dr. Evans Hayward and Dr. Everett Fuller for the calculation of the theoretical curves of Fig. 9.

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Excitation Functions of Bismuth and Lead*

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Cross sections for the reactions $Bi^{209}(He^4,2n)At^{211}$, $Bi^{209}(He^4,3n)At^{210}$, and $Bi^{209}(He^4,4n)At^{209}$ were measured with helium ions of energies from 20.6 to 43.3 Mev. Cross sections for the reactions $Bi^{209}(d,p)$RaE, $Bi^{209}(d,n)Po^{210}$, $Bi^{209}(d,2n)Po^{209}$, $Bi^{209}(d,3n)Po^{208}$, and $Pb^{208}(d,p)Pb^{209}$ were measured with deuterons of energies from 6.3 to 21.5 Mev. Some information is presented on the $Bi^{209}(He^4,t)Po^{210}$ reaction. A half-life of 7.23 ± 0.04 hr was measured for At^{211}. The $Bi^{209}(d,3n)Po^{208}$ threshold energy is 12.0 ± 0.3 Mev (center-of-mass system). The compound nucleus reaction cross sections are compared with the predictions of the Jackson model, and good agreement is obtained. The (d,n) and (d,p) stripping cross sections are discussed briefly.

INTRODUCTION

THE direct comparison of nuclear reactions of fissionable with nonfissionable materials allows one to draw certain conclusions about the mechanisms of these reactions. The elements lead and bismuth have extremely small fission cross sections[1] at the charged-particle bombarding energies used in this study, whereas isotopes of thorium, uranium, and other heavy elements have relatively large fission cross sections.

Bismuth is a convenient target for excitation function work with light projectiles since the resulting polonium and astatine isotopes are alpha emitters. In an earlier paper we reported results obtained from the bombardment of bismuth with 10.65-Mev protons.[2] Other investigators have bombarded bismuth with 19-Mev deuterons and 38-Mev helium ions.[3] However, it seemed worthwhile to extend the $(d,3n)$ and $(He^4,3n)$ measurements to slightly higher energies and to study the $(He^4,4n)$ reaction cross sections as a function of helium-ion energy. In addition, the $(d,2n)$ excitation function was established more accurately by examining the alpha activities of the target samples three years after the completion of bombardment. Since Po^{209}, the product of the $Bi^{209}(d,2n)$ reaction, has a long half-life compared with Po^{210}, a quantitative assay of Po^{209} by alpha-particle energy analysis is possible for some bombarding energies only after the gross polonium alpha activity has decayed by many factors.

The (d,p) excitation function obtained for bismuth represents only the reaction leading to the 5.0-day RaE isomer of Bi^{210}. The 2.6×10^6-yr isomer of Bi^{210} has too long a half-life for detection in the present experiments.

A study of the reaction $Pb^{208}(d,p)Pb^{209}$ was made in order to compare its excitation function with (1) the (d,p) excitation function of a fissionable material and (2) the excitation function obtained for the $Bi^{209}(d,p)$RaE reaction in search for indirect evidence that part of the bismuth reaction resulted in the long-lived isomer of Bi^{210}.

EXPERIMENTAL PROCEDURE

The bismuth plates were prepared by the technique previously described.[2] Bismuth metal was evaporated onto aluminum disks of 0.0005-inch thickness. The amount of bismuth on each target varied from 50 to 100 $\mu g/cm^2$. The weight of bismuth was determined, after the necessary counting data had been taken, by a colorimetric procedure.[2] The lead samples were lead foils of about 11 mg/cm^2 thickness.

The stacked-foil technique was used to obtain the desired energies of the bombarding particles. Blank aluminum foils of known weight were inserted between the

* Based on work performed under the auspices of the U. S. Atomic Energy Commission.
[1] A. W. Fairhall, Phys. Rev. **102**, 1335 (1956); E. F. Neuzil and A. W. Fairhall (private communication).
[2] Andre, Huizenga, Mech, Ramler, Rauh, and Rocklin, Phys. Rev. **101**, 645 (1956).
[3] E. L. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).

samples to give the desired amount of reduction in the energy of the beam. Using this procedure, cross sections at many different energies of the bombarding particles could be obtained in a single experiment.

The deuterons and helium ions used in these experiments were accelerated in the Argonne 60-in. cyclotron. The target arrangement was similar to the technique previously described.[2] The average current on the target for the helium-ion bombardment was 0.18 μa, and for each of the deuteron bombardments the current was about 0.23 μa. The charge input was obtained by an electronic integrator, with an accuracy of $\pm 1\%$. Total fluxes of 24.9, 52.0, 31.2, and 7.5 μa-min were recorded in the helium-ion bombardment, deuteron bombardments No. 1 and No. 2 of Bi^{209}, and the deuteron bombardment of Pb^{208}, respectively.

The energies of the bombarding helium ions and deuterons were determined by aluminum absorption techniques.[2] For each bombardment an energy determination was made before and after the run, with two or three intermediate checks during the irradiation. From these data, mean ranges of 192.2 ± 3.0, 376.8 ± 2.5, and 378.0 ± 3.0 mg/cm^2 of aluminum were obtained for the helium and the deuterium ions in the first and second bombardments of Bi^{209}, respectively. The above ranges were converted to the following energies, 43.3 ± 0.4 Mev (He^{++}), 21.4 ± 0.1 Mev (d^+, bombardment No. 1) and 21.5 ± 0.1 Mev (d^+, bombardment No. 2), using published range-energy curves.[4] The straggling $S = (R_{extr}-R_{mean})/R_{mean}$ was 1.3% for the helium ions and 1.4% for the deuterons.

Although no energy calibration was made in the deuteron bombardment of lead, it was assumed that the full energy of the deuterons was 21.5 Mev.

Excitation Functions of Bi^{209} Bombarded with Helium Ions

Immediately after the completion of the helium-ion bombardment of the bismuth, the target was disassembled, the foils were separated, and routine alpha counting of the individual samples was initiated. A decay curve of the gross alpha activity of each sample was obtained by making several alpha counts of each sample over a 17-day period. At the higher bombarding energies, astatine isotopes of masses 212, 211, 210, and 209 are produced by (He^4,n), (He^4,$2n$), (He^4,$3n$), and (He^4,$4n$) reactions, respectively. Since the half-life of At^{212} is too short (0.22 sec) for its activity to be observed in our experiments, and since the radiations of Bi^{208}, the daughter of At^{212}, have too long a half-life[5] to be observed in these experiments, we obtained no direct information on the Bi^{209}(He^4,n) excitation function. Excitation functions of other reactions[6] such as (He^4,p)Po^{212}, (He^4,pn)Po^{211}, etc., were also not observed, either due to the short half-lives of the products or due to low reaction yields.

The product of the Bi^{209}(He^4,$2n$) reaction is 7.2-hr At^{211}. This isotope decays by the emission of 5.86-Mev alpha-particles (41%) and by electron capture (59%) to 0.52-sec Po^{211} which decays chiefly by emitting 7.44-Mev alpha-particles.[7] The gross alpha activity from each sample is mainly from At^{211} and Po^{211}. The (He^4,$2n$) cross section is still about 100 mb at the highest bombarding energy and individual samples contained up to 10^6 dis/min of At^{211} and Po^{211}. The product of the Bi^{209}(He^4,$3n$) reaction is 8.3-hr At^{210} whose alpha to electron-capture branching ratio[7] is only 0.0017. The energies of the three known alpha-particle groups of At^{210} are 5.52 Mev (32%), 5.44 Mev (31%), and 5.36 Mev (37%).[7] The electron capture of At^{210} gives 138.4-day Po^{210} which decays by emitting 5.30-Mev alpha-particles. Because of this long half-life, Po^{210} is only a minor fraction of the total alpha activity during the first several hours after bombardment. The product of the Bi^{209}(He^4,$4n$) reaction is 5.5-hr At^{209} which decays mainly by electron capture (95%) to[2] 103-yr Po^{209}. At^{209} was detected in these experiments by its alpha-particles (5%) of 5.65-Mev energy.[7]

The (He^4,$2n$), (He^4,$3n$), and (He^4,$4n$) cross sections of Bi^{209} were determined by the following method. Shortly after the gross alpha counting, the alpha-active isotopes produced during the bombardment were identified by their characteristic alpha energies with an ionization chamber and a fifty-channel pulse-height analyzer. The first two samples in the stack (bombarding energies of 43.3 and 41.0 Mev) contained a sizable alpha-particle group at 5.65 Mev of At^{209}. From the intensity of this alpha group and the reported alpha branching ratio of 5% for At^{209}, the cross sections for the Bi^{209}(He^4,$4n$)At^{209} reaction were calculated at these two highest bombarding energies. The (He^4,$2n$) cross section at each bombarding energy was calculated from the gross alpha-activity multiplied by the ratio, (At^{211} α's+Po^{211} α's)/total α's. Except for the samples containing At^{209}, the major share ($>98\%$) of the alpha activity on each sample at the time of alpha pulse analysis was due to the 7.44-Mev alpha particles of Po^{211} and the 5.86-Mev alpha particles of At^{211}. In the samples that were bombarded at helium-ion energies below the threshold of the (He^4,$3n$) reaction, the decay of the gross alpha activity gave an average half-life of Po^{211} of 7.23 ± 0.04 hours. This value is in good agreement with previous half-life[7] determinations of At^{211} and was used in making the decay corrections.

The alpha particles of At^{210} were observed by alpha pulse-height analysis of several of the samples bombarded at the higher energies. A quantitative deter-

[4] Aron, Hoffman, and Williams, University of California Radiation Laboratory Report, UCRL–121, second revision, 1948 (unpublished); J. H. Smith, Phys. Rev. **71**, 32 (1947).
[5] Roy, Eastwood, and Hawkings, Can. J. Phys. **36**, 18 (1958).
[6] F. N. Spiess, Phys. Rev. **94**, 1292 (1954).
[7] Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585 (1958); W. H. Sullivan, *Trilinear Chart of Nuclides*, Atomic Energy Commission Report (U. S. Government Printing Office, Washington, D. C., 1957).

TABLE I. Experimental values of the cross sections in millibarns for the helium-ion induced reactions of Bi^{209} at various helium-ion energies.

Helium-ion energy (Mev) \ Reaction Product	(He^4,$2n$) At^{211}	(He^4,$3n$)[a] At^{210}	(He^4,$4n$) At^{209}
20.6	1.4	0.05	
21.8	42	0.09	
22.6	113	0.10	
23.6	205	0.07	
24.0	291	0.11	
24.7	406	0.13	
25.5	521	0.30	
26.1	576	0.47	
27.4	701	1.5	
28.6	811	2.9	
29.3	837	4.6	
29.8	870	11	
30.4	905	36	
31.0	908	81	
33.0	713	396	
34.2	499	715	
35.7	344	914	
37.3	226	1116	
38.6	165	1179	
40.1	134	1168	
41.0	110	1172	151
43.3	92	977	391

[a] These cross-section values include the following reactions: Bi^{209}[(He^4,t), (He^4,dn), (He^4,$p2n$)]Po^{210}, and Bi^{209}(He^4,He^3)Bi^{210}.

mination of the small percentage of the At^{210} alpha particles in the samples was not attempted, since it appeared more attractive to determine the At^{210} yield by another procedure. After the At^{209}, At^{210}, and At^{211} activities had decayed for two weeks, the samples were recounted for their Po^{210} content. As previously mentioned, At^{210} decays mainly by electron capture (99.8%) to Po^{210}. The quantitative assay of Po^{210} is very simple, and the corresponding (He^4,$3n$) reaction cross sections were calculated with the assumption that all of the Po^{210} was formed by the electron capture of At^{210}. Cross sections of reactions like Bi^{209}(He^4,$p2n$)Po^{210}, Bi^{209}(He^4,dn)Po^{210}, and Bi^{209}(He^4,t)Po^{210} are therefore assumed to be negligible compared with the Bi^{209}-(He^4,$3n$)At^{210} reaction cross section. This assumption is not entirely valid for bombarding energies below 28.4 Mev, the threshold[8] of the Bi^{209}(He^4,$3n$)At^{210} reaction, because we observed Po^{210} alpha activity down to the lowest bombarding energy of 20.6 Mev. The thresholds for the (He^4,$p2n$), (He^4,dn), (He^4,t), and (He^4,He^3) reactions are 23.7, 21.4, 15.0, and 16.2 Mev, (laboratory system), respectively.[8] The cross section for making Po^{210} varies from 0.05 mb with 20.6-Mev helium ions to 2.9 mb with 28.6-Mev helium ions, and in this energy range the Po^{210} is made directly. Since Po^{210} activity has been observed below the (He^4,$p2n$) and the (He^4,dn) thresholds, in this experiment, the most attractive mechanism for producing the Po^{210} is the (He^4,t) reaction.[9] The magnitude of the cross section for the reaction (or reactions) producing the Po^{210} in the helium-ion energy range of 25 to 30 Mev is comparable to the cross section for producing Np^{239} from U^{238} bombarded with helium ions,[10] and the cross sections of this same reaction with other target materials.[9] Bombarding U^{238} with 35-Mev helium ions, for example, we obtained a cross section of 15 mb[10] for the production of Np^{239}.

The cross sections of the (Bi^{209}+He^4) reactions are summarized in Table I. From the magnitude of the cross section values given in Table I, it is evident that most of the Po^{210} atoms are produced by the Bi^{209}(He^4,$3n$)At^{210} reaction at helium-ion energies greater than 30 Mev. The cross sections of the (He^4,$2n$), (He^4,$3n$), and (He^4,$4n$) reactions are plotted as a function of energy in Fig. 1. The contribution of reactions other than (He^4,$3n$) to the Po^{210} yield at the lower bombarding energies is readily seen in Fig. 1. In general, the (He^4,$2n$) and (He^4,$3n$) excitation functions agree quite well with those obtained by Kelly and Segrè.[3]

Excitation Functions of Bi^{209} Bombarded with Deuterons

Two deuteron bombardments of Bi^{209} were made. The first deuteron bombardment was made in April of 1954

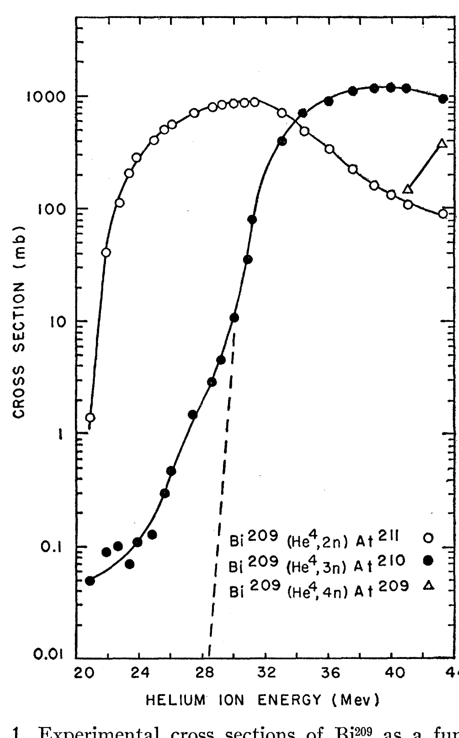

FIG. 1. Experimental cross sections of Bi^{209} as a function of helium-ion energy. The solid circles below 30.0 Mev represent the Bi^{209}(He^4,H^3)Po^{210} reaction. The dashed line gives the (He^4,$3n$) cross sections below helium-ion bombarding energies of 30.0 Mev.

[8] J. R. Huizenga, Physica **21**, 410 (1955).
[9] Wade, Gonzales-Vidal, Glass, and Seaborg, Phys. Rev. **107**, 1311 (1957).
[10] Wing, Ramler, and Huizenga (unpublished results, 1955); S. Ritsema, University of California Radiation Laboratory Report, UCRL-3266, 1956 (unpublished).

and will be referred to as bombardment No. 1, while bombardment No. 2 was made in January of 1957. The experimental details are discussed in an earlier section of this paper and in a previous publication.[2]

The activities produced by approximately 21-Mev deuterons on bismuth are $(d,n)Po^{210}$, a 138.4-day alpha emitter with 5.30-Mev alpha particles; (d,p)RaE, 5.00-day β^- emitter; $(d,2n)Po^{209}$, a 103-year alpha emitter[2] with an alpha-particle energy of 4.88 Mev; and $(d,3n)Po^{208}$, a 2.93-year alpha emitter with an alpha-particle energy of 5.11 Mev. The $(d,4n)Po^{207}$ reaction, although energetically possible at the higher deuteron energies, was not studied since the alpha branching ratio of Po^{207} is very small and its alpha-particle energy is nearly identical with that of Po^{208}.[7]

Shortly after the completion of the bombardment, the gross alpha activity of each sample was followed for several days. This activity represented the sum of (1) the alpha activity of the polonium isotopes produced in the bombardment, and (2) the activity of Po^{210} resulting from the decay of RaE. Since the half-lives of Po^{208} and Po^{209} are relatively long, their activities were essentially constant during this period of alpha counting. From the increase in the gross alpha counting rate, we were able to obtain the cross sections for the $Bi^{209}(d,p)$RaE reaction, without directly counting the β^- particles of RaE.

The relative amount of each polonium isotope present in each of the samples was determined from the alpha-particle energy spectrum obtained with the alpha pulse-height analyzer mentioned above. The Po^{209} half-life is very long compared with the half-lives of Po^{208} and Po^{210}, and, as a result, the determination of the amount of Po^{209} by alpha pulse-height analysis at most of the bombarding energies is subject to considerable error. In order to obtain a more accurate determination of Po^{209}, we allowed the polonium isotopes in the samples of bombardment No. 1 to decay for approximately three years before analysis. The alpha spectra of these samples contained only a small intensity of the 5.30 Mev (Po^{210}) peak, and the intensities of the two alpha groups of 4.88 Mev (Po^{209}) and 5.11 Mev (Po^{208}) were determined with greater accuracy.

We also analyzed by a slightly different technique the alpha spectra of three samples from bombardment No. 2 which had been bombarded by deuterons of energies 12.1 to 12.9 Mev. These measurements were made since bombardment No. 1 contained no sample near the $(d,3n)$ threshold. A collimator[11] placed over these samples enabled us to resolve the alpha groups at 5.11 and 5.30 Mev, and to obtain information on the $(d,3n)$ cross sections at bombarding energies slightly above the $(d,3n)$ threshold. The alpha spectrum of the sample bombarded with 12.6-Mev deuterons is shown in Fig. 2. At this deuteron energy Po^{208} is still produced. No detectable amount of Po^{208} was found in the sample bombarded with 12.1-Mev deuterons. The threshold for the $(d,3n)$ reaction derived from the data is

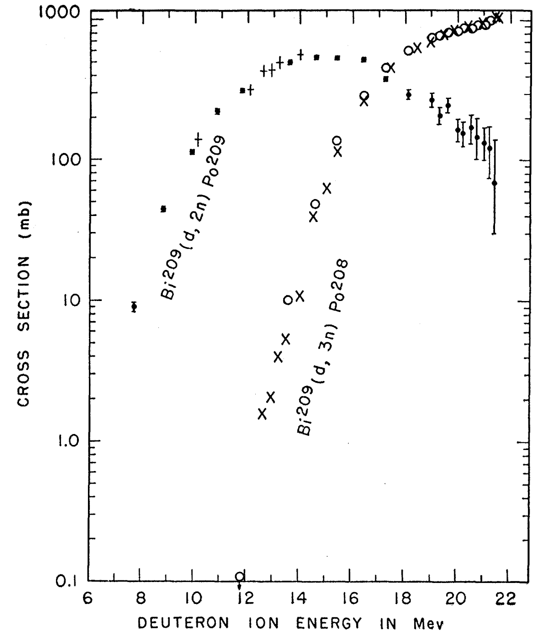

FIG. 3. Experimental cross sections of Bi^{209} as a function of deuteron energy for the $(d,2n)$ and $(d,3n)$ reactions. ○ and ● are data from bombardment No. 1; + and × are data from bombardment No. 2. *Note.*—The word "ion" beneath the figure should be deleted.

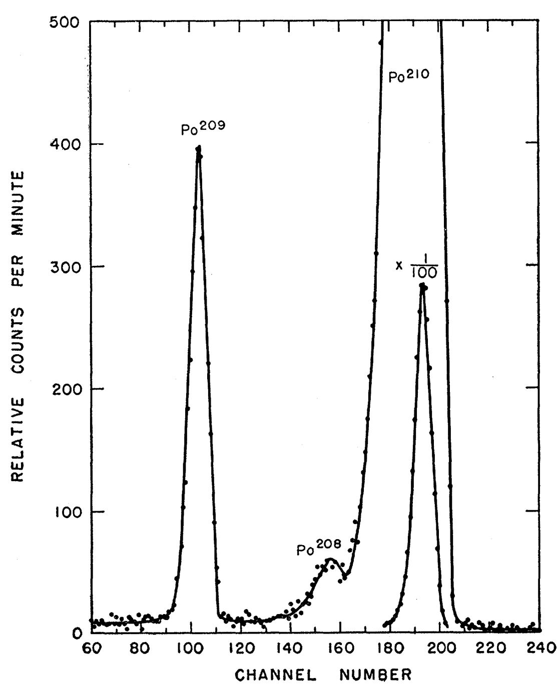

FIG. 2. Alpha energy analysis of a polonium sample produced by a 12.6-Mev deuteron bombardment of bismuth, at energy near the $(d,3n)$ threshold.

[11] D. W. Engelkemeir and L. B. Magnusson, Rev. Sci. Instr. **26**, 295 (1955).

TABLE II. Experimental values of the cross sections in millibarns for the deuteron-induced reactions of Bi^{209} at various deuteron energies.

Reaction / Product / Bombardment / Deuteron energy (Mev)	(d,p) RaE Bomb. No. 2	(d,n) Po^{210} Bomb. No. 2	$(d,2n)$ Po^{209} Bomb. No. 1	$(d,2n)$ Po^{209} Bomb. No. 2	$(d,3n)$ Po^{208} Bomb. No. 1	$(d,3n)$ Po^{208} Bomb. No. 2
6.3	2.2	0.26				
7.3	8.7	1.8				
7.7			9.1			
8.2	24	5.3				
8.8			45			
9.2	46	11				
9.9			116			
10.1	78	19		140		
10.9			224			
11.1	102	23				
11.8			315		≤ 0.11	
12.1	104	30		322		
12.6	106	32		430		1.7
12.9	112	29		434		2.1
13.2	110	29		499		4.1
13.5	106	29				5.5
13.6			500		10	
14.0	105	31		577		11
14.5	100	29				39
14.6			545		49	
15.0	100	31				64
15.4	98	31	540		138	116
16.4	87	29	529		291	266
17.2			379		463	
17.4	80	29				466
18.1			297		610	
18.4	62	34				647
18.9	60	31				710
19.0			271		756	
19.3			209		780	
19.4	56	34				797
19.6			250		823	
19.8	56	34				870
20.0			165		846	
20.2			156		880	
20.3	57	31				928
20.5			171		872	
20.7			148		925	
20.9	53	32				974
21.0			133		939	
21.2			124		1001	
21.4	54	27	70		986	1097
21.5	48	31				1050

(12.1±0.3) Mev in the laboratory system or (12.0±0.3) Mev in the center-of-mass system. This value is in good agreement with the previously determined threshold of the $Bi^{209}(p,2n)Po^{208}$ reaction.[2]

The cross sections of the ($Bi^{209}+d$) reactions are summarized in Table II and plotted as a function of deuteron energy in Figs. 3 and 4. Our experimental cross section values of the $(d,2n)$, (d,n), (d,p), and $(d,3n)$ reactions agree well with those of Kelly and Segrè.[3]

$Pb^{208}(d,p)Pb^{209}$ Excitation Function

Approximately two hours after the completion of a bombardment, the Pb^{209} activity was counted in a gas-flow proportional counter. Counting measurements continued for a period of time equal to several half-lives of Pb^{209}. Impurities in the lead gave rise to short-lived activities, e.g., 17-min Sb^{120}, but in the above counting interval it was easy to resolve the high intensity of Pb^{209} component from the decay curve. The intensity of other lead and bismuth activities were low compared with the Pb^{209} activity.

The effective geometry of the gas-flow proportional counter was experimentally measured by comparing the observed counting rates of lead samples with the counting rates of the same samples in a 4π counter. For the 4π counting, the lead foils were dissolved and a small measured aliquot was mounted on a very thin film.

The cross sections of the $Pb^{208}(d,p)Pb^{209}$ reaction are given in Table III and plotted as a function of deuteron energy in Fig. 5.

DISCUSSION

Nuclear reactions occurring at excitation energies below 50 Mev are commonly described by a mechanism of compound nucleus formation. This mechanism consists of two independent processes: (1) the interaction of the projectile and the target nucleus to form a compound nucleus in an excited state with a lifetime much longer than the nuclear interaction time, and (2) the subsequent de-excitation of the compound nucleus by successive emission of nucleons, preferentially neutrons, in a manner predicted by statistical theory. Our experimental results of the $Bi^{209}(d,xn)$ and $Bi^{209}(He^4,xn)$ reactions show the general features of this compound nucleus formation mechanism, i.e., the rapid rise of cross sections of a given mode of neutron emission with increasing bombarding energy above its threshold, and the subsequent rapid drop of cross sections at higher energies due to competition with emission of one more neutron.

The $Bi^{209}(d,n)Po^{210}$ excitation function, however, does not have the characteristic sharp peak. The cross sec-

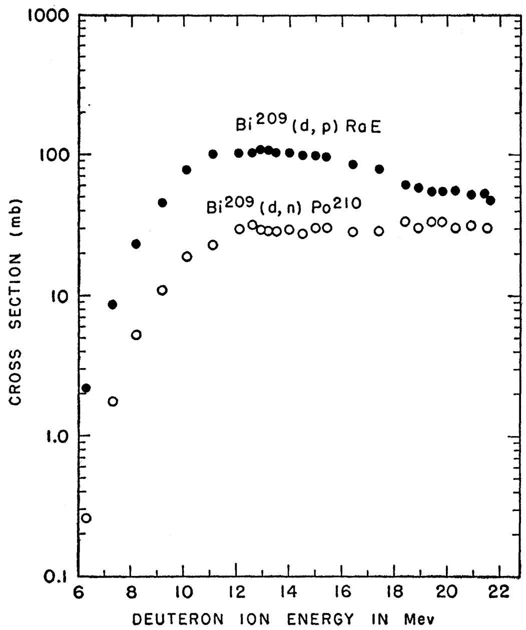

FIG. 4. Experimental cross sections of Bi^{209} as a function of deuteron energy for the (d,p) and (d,n) reactions (bombardment No. 2). *Note.*—The word "ion" beneath the figure should be deleted.

tions for this reaction are essentially constant with deuteron energy from 12 to 21.5 Mev (see Fig. 4). The large values of the (d,n) cross sections above 12 Mev can be explained by the mechanism known as the stripping process,[12] in which the loosely bound proton of the deuteron is absorbed by the target nucleus while the neutron carries away most of the available energy. The neutron binding energy of Po^{210} is 7.67 Mev and the proton binding energy is 5.06 Mev.[8] Protons with kinetic energies up to 2.61 Mev may be captured by Bi^{209} without leading to subsequent neutron evaporation. The magnitude of $Bi^{209}(d,n)Po^{210}$ reaction is expected to depend in some way on the number of levels in Po^{210} below 7.67 Mev. The $I^{127}(d,n)Xe^{128}$ excitation

[12] D. C. Peaslee, Phys. Rev. **74**, 1001 (1948).

TABLE III. Experimental values of the cross sections in millibarns for the $Pb^{208}(d,p)Pb^{209}$ reaction at various deuteron energies.

Deuteron energy (Mev) \ Reaction Product	(d,p) Pb^{209}
5.2[a]	0.7
5.6	1
6.5[a]	6
6.8	8
7.8[a]	24
8.1	32
8.9[a]	65
9.2	81
10.2[a]	140
10.2	130
11.2	170
11.6[a]	188
12.1	202
13.0	218
13.7[a]	200
14.0	214
14.7	200
15.4	196
16.2	183
16.6[a]	149
17.0	177
17.8	158
18.4	161
19.0	149
19.7	142
20.5[a]	133
20.6	137
20.8[a]	131
21.1	130

[a] Data from the 4π counting experiments.

function also exhibits a plateau with deuterons of energies greater than 9.5 Mev.[13] The cross section of 180 mb for the $I^{127}(d,n)$ reaction is, however, considerably larger than that of 30 mb for the $Bi^{209}(d,n)$ re-

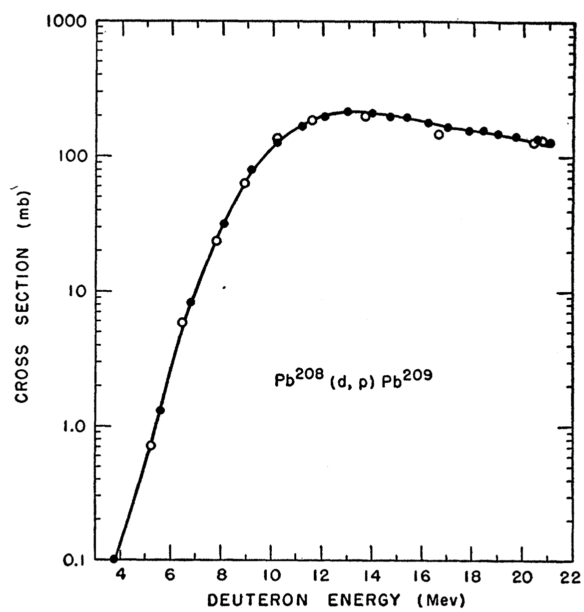

FIG. 5. Experimental cross sections of Pb^{208} as a function of deuteron energy for the (d,p) reaction. ○ indicate 4π counting data.

[13] S. J. Balestrini, Phys. Rev. **95**, 1502 (1954).

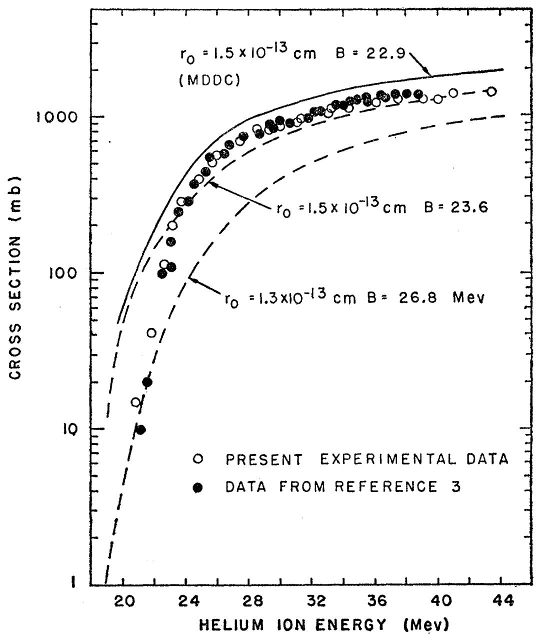

FIG. 6. Total reaction cross sections of Bi^{209} as a function of helium-ion energy. The dashed and the solid lines represent theoretical compound-nucleus formation cross sections calculated with the values given in references 16 and 17, respectively. Data from reference 3 are included for comparison.

action. The large neutron binding energy of 9.75 Mev[14] for Xe^{128} may qualitatively account for the large (d,n) cross section, although in a quantitative comparison of (d,n) cross sections, one must, among other things, consider the dependence of level density on the nuclear type of the intermediate nuclei. Several (d,n) cross sections of nuclides with $Z\geq 90$ have been measured. In general, the shapes of their excitation functions are similar to that observed for Bi^{209}. The magnitudes of these cross sections are less due to the fact that the fission activation energy for many of the very heavy elements is considerably smaller than the corresponding neutron binding energy.[15]

As one might expect, the (d,p) cross sections are higher than the (d,n) cross sections at the corresponding excitation energies. The effect of electrostatic repulsion on the deuteron renders the neutron in a more favorable position to reach the surface of the target nucleus than the proton. The (d,p) reaction cross sections measured in this work represent that part of the stripping process which leads to neutron capture in bound states. Both the $Pb^{208}(d,p)Pb^{209}$ and the $Bi^{209}(d,p)$RaE excitation functions have maximum cross sections with deuterons of energies 13 to 15 Mev and show a regular decrease in their cross sections at higher energies. This means that the probability of neutron capture to bound states decreases as the deuteron energy is increased above 14 Mev.

At comparable excitation energies, it is interesting to note that the $Pb^{208}(d,p)Pb^{209}$ cross sections are larger than the $Bi^{209}(d,p)$RaE cross sections by a factor of about two. This is probably due to the formation of a long-lived isomer of Bi^{210}, resulting from part of the $Bi^{209}(d,p)$ reaction, which was not observed in this study. From a comparison of these two (d,p) excitation functions, one obtains indirect evidence that the high-spin Bi^{210} isomer is formed with a probability about equal to that of RaE.

Numerical calculations have been made of cross sections for the formation of compound nucleus by charged particles at various barrier heights of many elements.[16–18] Good agreements between the calculated and the experimental cross sections have been found.[18] We have interpolated at $Z=83$ the values of Blatt[16] and Weisskopf[17] for the calculation of the total absorption cross sections of the $(Bi+He^4)$ reaction and Shapiro's[18] values for the $(Bi+d)$ reaction, and compared the results with our experimental data (Fig. 6 and Fig. 7). The (d,p) cross sections are not included in the experimental points since they do not represent the compound nucleus formation mechanism. The theoretical curves with $r_0=1.5\times10^{-13}$ cm fit the experimental data better than those with $r_0=1.3\times10^{-13}$ cm. The experimental $(Bi^{209}+He^4)$ cross sections at helium-ion energies less

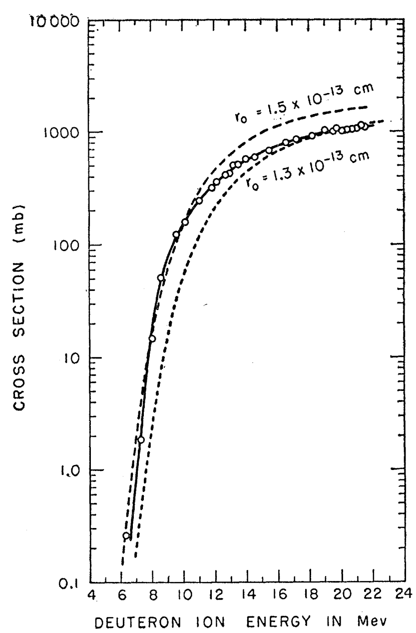

FIG. 7. Total reaction cross sections of Bi^{209} as a function of deuteron energy. The dashed lines represent theoretical compound nucleus formation cross sections calculated with the values given by reference 18. The (d,p) cross sections are not included in the experimental points. *Note*.—The word "ion" beneath the figure should be deleted.

[14] A. H. Wapstra, Physica **21**, 367 (1955).

[15] Wing, Ramler, Harkness, and Huizenga, following paper [Phys. Rev. **113**, 163 (1959)].

[16] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[17] AEC-MDDC 1175, Atomic Energy Commission Report (unpublished).

[18] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).

than 23 Mev lie below this theoretical curve. The omission of the (He^4,n) cross sections probably accounts for these low experimental values of the total cross sections at these energies. Similarly, at deuteron energies above 14 Mev, the experimental ($Bi^{209}+d$) cross sections lie below the theoretical curve of $r_0=1.5\times10^{-13}$ cm. This may be due in part to the neglecting of the (d,4n) reaction at the higher energies.

For the calculation of the individual (He^4,xn) and (d,xn) cross sections as a function of bombarding energy, we have applied the schematic model of nuclear reactions devised by Jackson.[19] This model divides the nuclear reactions into prompt (cascade) and evaporation processes. In our calculations, we assume no prompt multiple-collision processes and treat all the particle emission as nucleon evaporation. The cross section of a reaction at a particular energy is given by Jackson[19] as

$$\sigma(A,xn)=\sigma_c[I(\Delta_x,\,2x-3)-I(\Delta_{x+1},\,2x-1)],$$

where

$$\Delta_x=(E-\sum_{i=1}^{x}B_i)/T,$$

and A is the bombarding particle (helium or deuterium ions), E is the initial excitation energy, B the neutron binding energy of the intermediate nuclide during neutron evaporation, T the nuclear temperature, σ_c the total compound nucleus formation cross section, and the quantities inside the brackets are Pearson's incomplete gamma functions. The first term of these Pearson's functions gives the probability that at least x neutrons will be evaporated from the compound nucleus, and the second term gives the probability that at least ($x+1$) neutrons will be evaporated. The difference of these two terms gives the probability that the compound nucleus will emit only x neutrons. In this model, only the energy dependence upon the mode of decay of the compound nucleus is considered. The following assumptions are made and discussed by Jackson:[19] (1) The neutron energy spectrum is given by $\epsilon\exp(-\epsilon/T)$, where ϵ is the kinetic energy of the evaporated neutron, (2) $\epsilon_{max}\gg T$, where ϵ_{max} is the maximum neutron energy in the neutron spectrum, (3) neutron emission occurs whenever it is energetically possible, (4) proton and other charged-particle evaporations are neglected.

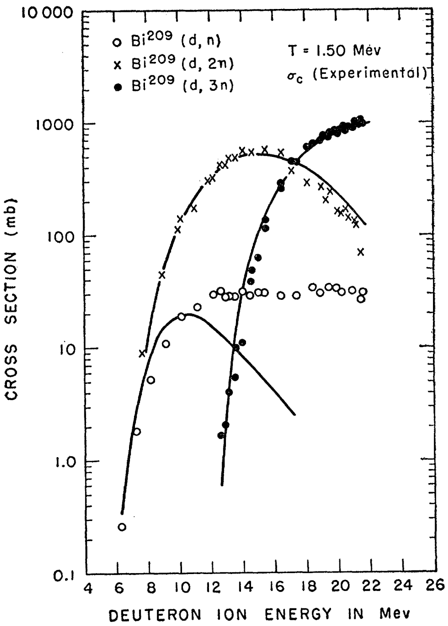

FIG. 9. Comparison of calculated and experimental excitation functions for (d,xn) reactions of Bi^{209}. The smooth curves represent the cross sections calculated by the Jackson model. *Note*.—The word "ion" beneath the figure should be deleted.

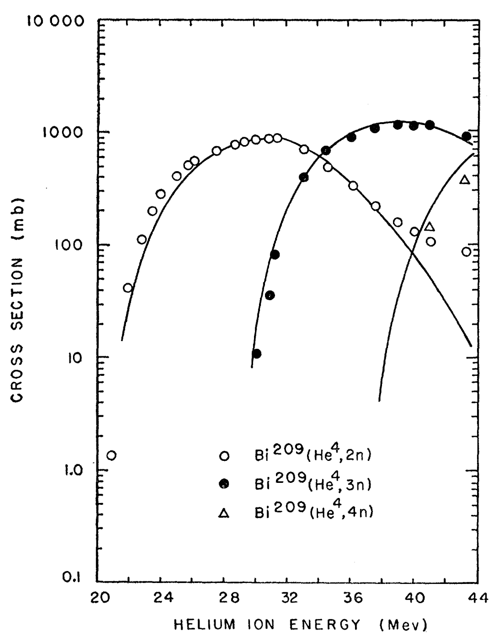

FIG. 8. Comparison of calculated and experimental excitation functions for (He^4,xn) reactions of Bi^{209}. The smooth curves represent the cross sections calculated by the Jackson model.

For the numerical calculations, the neutron binding energies were obtained from the tables of Wapstra[14] and Huizenga.[8] Values of σ_c were obtained from the experimental curves of the total compound-nucleus formation cross sections as a function of excitation energy. The experimental curve for the helium-ion bombardment was drawn parallel to the theoretical curve at low helium-ion energies since the (He^4,n) cross sections were not measured. A constant value of the nuclear temperature of 1.50 Mev was used in the calculations.

Comparisons of the calculated (He^4,xn) and (d,xn) cross sections with our experimental data are shown in Figs. 8 and 9. In general, the agreements are quite

[19] J. D. Jackson, Can. J. Phys. **34**, 767 (1956).

good, which suggests the applicability of Jackson's model at these bombarding energies. The excitation energies of the compound nuclei produced in the deuteron and helium ion bombardments range up to 28.7 and 33.0 Mev, respectively. Although it is desirable to attempt to fit the experimental data with an energy-dependent temperature, the Jackson equation can be evaluated only with the assumption of constant temperature. The excitation functions of the $(d,2n)$, $(d,3n)$, $(He^4,2n)$, and $(He^4,3n)$ reactions calculated with a nuclear temperature of 1.50 Mev agree quite well with the experimental data except for the "tail" on the $(He^4,2n)$ reaction. A nuclear temperature of 1.35 Mev gives results less agreeable with the experimental data. The agreement between the experimental $(He^4,4n)$ cross sections and theory is improved with a nuclear temperature larger than 1.50 Mev. This would not, however, improve the agreement between the calculated $(He^4,2n)$ cross sections and the experimental values. Nuclear temperatures calculated from the equation $T=(E/a)^{\frac{1}{2}}$, where a is a constant,[16] would vary by a factor of 3.0 for extreme values of the excitation energies reached in our experiments. The nuclear temperature of 4 Mev for Po^{209} obtained previously[2] from a study of the competition between (p,n) and $(p,2n)$ reactions on Bi^{209} is probably too large due to the fact that the excitation energy in this experiment only slightly exceeded the $(p,2n)$ threshold energy, and therefore the energy excess above the Po^{209} neutron binding energy was not large compared with T.

The direct interaction mechanism in the $Bi^{209}(d,n)$ reaction is clearly indicated in Fig. 9 at deuteron energies greater than 12 Mev. The "tail" in the $Bi^{209}(He^4,2n)$ excitation function at helium-ion energies greater than 35 Mev has also been observed in the same reaction of many other heavy elements and becomes especially significant for fissile targets. These large $(He^4,2n)$ cross sections (compared with the evaporation model predictions) at the large helium-ion energies are probably due to a direct interaction in which one high-energy neutron is ejected, leaving the residual nucleus with an amount of excitation energy sufficient to evaporate only one neutron. Since the magnitude of the maximum $(He^4,2n)$ cross section is greatly reduced for fissile targets (due to the competition of fission with neutron emission),[15] it is apparent that the direct interaction will, on a relative basis, give a larger contribution to the cross section for a fissile target.

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