Comparison of ^{3}He-, ^{4}He-, and ^{12}C-induced nuclear reactions in heavy-mass targets at medium excitation energies. I. Experimental cross sections*

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The excitation functions for the ^{197}Au(^{12}C,xn)$^{209-x}$At, ^{209}Bi(^{3}He,xn)$^{212-x}$At, ^{209}Bi(α,xn)-$^{213-x}$At, ^{187}Re(^{3}He,xn)$^{190-x}$Ir, ^{187}Re(α,xn)$^{191-x}$Ir, and ^{197}Au(^{3}He,xn)$^{200-x}$Tl reactions were obtained by the activation method employing the stacked-foil technique. The maximum laboratory kinetic energies were 70-MeV ^{3}He, 80-MeV ^{4}He, and 120-MeV ^{12}C ions. The radiations accompanying the decay of the induced radioisotopes were detected by a calibrated Ge(Li) detector and the cross sections were deduced by the activation method.

[NUCLEAR REACTIONS ^{197}Au(^{3}He,xn), ^{209}Bi(^{3}He,xn), ^{187}Re(^{3}He,xn), $x=2,6$, $E=20$ to 70 MeV, ^{209}Bi(α,xn), ^{187}Re(α,xn), $x=2,6$, $E=20$ to 80 MeV, ^{197}Au-(^{12}C,xn), $x=3,6$, $E=60$ to 120 MeV; measured $\sigma(E)$.]

I. INTRODUCTION

This study was conducted in order to determine the nuclear-reaction cross sections for the irradiation of selected heavy-mass nuclides with ^{3}He, ^{4}He, and ^{12}C ions at medium laboratory kinetic energies. Very few experimental papers on the measurement of the neutron-emission cross sections for ^{3}He-induced nuclear reactions have appeared in the literature. Scott, Cobble, and Daly[1] reported data on (^{3}He, xn) reactions on ^{181}Ta and ^{209}Bi targets using a maximum bombarding energy of 33 MeV. The principal motivation for the present study was to investigate properties of ^{3}He-induced reactions at somewhat higher excitation energies. Heavy-mass targets were chosen since many neutron-emission excitation functions could be measured by the activation technique. The α-particle irradiations were conducted on the same targets to obtain a comparison of reaction cross sections for the ^{3}He- and α-induced reactions. At the laboratory energies used in this study, very neutron-deficient isotopes were produced. In most cases, the decay schemes of these isotopes had not been studied. In general, some of the same isotopes were produced when the same target element is bombarded with ^{3}He and ^{4}He ions. By comparison of the helion-induced reactions, the errors in branching ratios for the radioisotopes were minimized. In one case, some of the same isotopes were also produced by ^{12}C-induced reactions on the appropriate target. Experiments of this type then provide a test of the independence hypothesis by a Ghoshal-type experiment.

The present systems studied were: ^{3}He- and ^{4}He-induced reactions on ^{187}Re targets to produce iridium isotopes; ^{3}He reactions on ^{197}Au to produce thallium isotopes; and the ^{3}He- and ^{4}He-induced reactions on ^{209}Bi targets and ^{12}C-induced reactions on ^{197}Au targets to produce astatine activities.

Presently, there have been no studies reported comparing the ^{4}He-, ^{3}He-, and ^{12}C-induced nuclear reactions in heavy-mass targets at medium excitation energies. In this study, the cross sections for the neutron-emission reactions from 80-MeV excitation energy down to the Coulomb barrier will be reported. The cross sections obtained will be compared in the following communication[2] to the predictions of the statistical model[3] and the equilibrium model with intermediate structure.[4]

II. EXPERIMENTAL PROCEDURE

A. Experimental

The excitation functions for the ^{209}Bi(^{3}He, xn)-$^{212-x}$At, ^{209}Bi(α, xn)$^{213-x}$At, ^{197}Au(^{12}C, xn)$^{209-x}$At, ^{187}Re(^{3}He, xn)$^{190-x}$Ir, ^{187}Re(α, xn)$^{191-x}$Ir, and ^{197}Au-(^{3}He, xn)$^{200-x}$Tl reactions were determined by irradiations using the Oak Ridge Isochronous Cyclotron. The stacked-foil technique was employed during the course of this investigation. The target stacks were constructed with the targets and interspersed aluminum degrader foils. By knowing the thickness of the aluminum degraders and the targets, the energy of the beam was calculated as the beam traverses both the aluminum and the targets. The cross section for production of a particular isotope was computed by the activation equation. The experiments were optimized to de-

tect only the radiations from isotopes produced by the (xn) reactions.

B. Target preparation

The targets were prepared by standard electrodeposition and vacuum evaporation techniques. Since the melting point of bismuth metal is low, vacuum evaporation of the bismuth metal was easily accomplished using an electron gun apparatus. The bismuth metal of 99.8% elemental purity was placed in a graphite boat and inserted into the electron gun assembly. The vacuum depositions were conducted until a layer of 100 to 1000 μg of the bismuth metal, monoisotopic in nature, had been deposited onto a 0.002-cm-thick aluminum backing foil of 99.9999% purity.

Rhenium targets were prepared from isotopically enriched rhenium metal purchased from the Isotopes Development Center of the Oak Ridge National Laboratory. The rhenium metal had been enriched to an isotopic abundance of 92.8% in ^{187}Re. The enriched rhenium metal was dissolved in a small amount of reagent-grade concentrated nitric acid. The solution was diluted to a concentration of 0.2 mg/ml with 0.1 M hydrochloric acid. A 10-ml aliquot was transferred to an electrodeposition apparatus and rhenium metal was electrodeposited onto a 0.002-cm aluminum backing foil which had been previously weighed. The electrodepositions were conducted using a dc potential of 15 V for approximately 10 min. Typically 2 mg of the ^{187}Re had been deposited over an area of 3.1 cm^2.

The gold targets were cut from 99.9% gold foil. The surface density was determined to be 2 mg/cm^2.

C. Irradiations

The target stack was placed in an electrically insulated target holder compatible with the 182-cm Oak Ridge National Laboratory isochronous cyclotron (ORIC). The samples were cooled with water at high pressure running over the back surface of the target holder.

After the target holder had been assembled, the

TABLE I. Irradiations used in the course of this study.

Projectile	Target	Average current (μA)	Incident energy (MeV)	Integrated charged (μC)	Irradiation description [a] (MeV)	Number of foils
α	^{187}Re	2.7	83.0	19 992	82.9–14.4	16
^{3}He	^{187}Re	6.8	71.4	6000	71.3–63.6	4
				6000	59.8–47.9	4
				6000	44.6–36.4	4
				12 000	34.2–28.5	3
^{3}He	^{209}Bi	2.5	69.8	3000	69.2–60.6	3
		4.0		4500	56.0–44.6	3
		4.0		4000	39.7–24.7	4
α	^{209}Bi	6.7	79.9	2400	79.4–69.6	3
				2400	65.6–54.6	3
				2400	49.7–38.1	3
				2400	33.9–24.0	3
^{12}C	^{197}Au	2.1	125.6	1000	125.6–116.7	3
		2.1		1280	113.8–107.5	3
		1.0		583	100.1–92.5	3
		1.0		659	89.3–85.0	2
^{12}C	^{197}Au	0.8	97.3	1200	96.3	1
		1.0		1200	91.5–83.7	3
		2.2		2400	84.3–75.9	3
		2.3		3600	75.4–66.0	3
		2.3		1200	93.7–85.2	3
^{3}He	^{197}Au	2.7	69.1	3600	69.0–58.0	3
				3600	53.1–43.1	3
				2000	36.4–27.1	3
				1000	22.6–16.4	2
^{3}He	^{197}Au	2.2	51.7	36 000	51.7–22.9	16

[a] Maximum and minimum bombarding energies reported.

target holder was inserted into the appropriate beam tube, and the bombardment was started. The beam current was monitored by measuring the charge collected on the target holder, which acts as a Faraday cup. The duration of the bombardment varied for different experiments and was chosen on the basis of the half-life of the isotopes and the yield of our detection system.

The energy of the cyclotron beam was measured using the analyzing magnet. The energy of the beam incident on each target and degrader foil was calculated from the stopping-power equations given by Williamson, Bouyot, and Picard.[5] The range-energy curves were obtained by numerically integrating the stopping-power equations.

The resulting range-energy curves were in good agreement with the ranges of ^{4}He and ^{12}C reported by Northcliffe and Schilling[6] and the ^{3}He ranges computed from the Northcliffe and Schilling[6] data. The agreement was typically better than 1% at energies above the Coulomb barrier.

Table I contains all the pertinent data concerning the irradiations. Due to the short half-lives of the isotopes produced, typically only four targets were run per stack which degraded the beam a total of 10 MeV. This table gives the incident particle, the target material, the average beam current, the incident energy of the beam, the integrated charge, the number of foils per irradiation, and the approximate energy range per stack.

After the bombardments, the samples were allowed to decay for approximately 10 min. At the end of this decay time, the stack was removed from the target holder and was dismantled. In the bismuth and the rhenium bombardments, the samples were separated from the aluminum backing foils. This separation was necessary due to the formation of light-mass isotopes in the target backings which would increase the background during the accumulation of the spectra of the samples. In a sample spectrum taken without separation, only the isotopes produced in the target backings were detected.

Dissolution of the ^{187}Re and the ^{209}Bi off the aluminum backing was accomplished with concentrated nitric acid. The acid solutions were collected in polyethylene vials. The aluminum backing was rinsed once with distilled water to ensure reasonable recovery. The polyethylene vials were placed in a suitable sample holder, and the γ-ray spectra detected using a lithium-drifted-germanium spectrometer.

The gold targets were merely taped onto cardboard mounts. The radioactive targets were covered with a 0.16-cm-thick aluminum foil which served as a β adsorber. The source holder could accommodate both vial samples and samples mounted on cardboard. Geometric reproducibility was assured by fixing the source holder to the detector.

The Ge(Li) detector used in this study had a resolution of 2.7 keV full width at half maximum (FWHM) at 1332 keV and a peak-to-Compton ratio of 14 to 1 at 1332 keV. The intrinsic efficiency versus energy response of the detector was determined using standard radioactive sources purchased from the National Bureau of Standards and using radiations from several relative-intensity standards. The relative γ-ray efficiencies were

TABLE II. Branching ratios for the iridium isotopes.

Isotope	Half-life (h)	E_γ (keV)	Branching ratio	Ref.
^{187}Ir	10.5	611	0.040	8–10
		913	0.046	
^{186}Ir^{g}	16.4	296	0.203	8,11
		434	0.111	
^{186}Ir^{m}	1.75	296	0.094	8
^{185}Ir	14.0	254	0.039	8,10
^{184}Ir	3.2	264	0.262	8
		841	0.032	
		961	0.050	

TABLE III. Branching ratios for the astatine isotopes.

Isotope	Half-life	E_γ (keV)	Branching ratio	Ref.
^{210}At	8.1 h	245	0.251	12
^{209}At	5.42 h	545	0.251	13
		782	0.234	
		792	0.151	
^{208}At	1.63 h	177	0.191	14
		660	0.223	
		685	0.242	
^{207}At	1.80 h	301	0.051	15
		588	0.078	
		814	0.176	
^{206}At	31.4 m	476	0.271	16–18
		700	0.331	
^{205}At	26. m	718	0.422	17–19
^{204}At	9.1 m	426	0.196	17,20,21
		516	0.282	
		609	0.062	
		682	0.306	
^{203}At	7.37 m	640	1.0	9,17,22
^{202}At	3.0 m	571	0.9	17,22
		675	1.0	

TABLE IV. Branching ratios of the gold and the thallium isotopes.

Isotopes	Half-life	E_γ (keV)	Branching ratio	Ref.
^{198}Tl	1.87 h	282	0.26	2,23
^{197}Tl	2.8 h	155	0.075	2
^{196}Tl	1.40 h	695	1.0	2,23
^{195}Tl	1.16 h	242	0.08	2
^{194}Tl	33 m	426	1.0	8
		734 [a]	1.0	
		746 [a]	1.0	
^{198}Au	64.8 h	412	0.96	2,8,23
^{194}Au	39.5 h	294	0.15	2,8
^{196}Au	6.18 h	356	0.87	2,24

[a] New radiations observed in the course of this study. These γ rays were used for the computation of the cross section.

determined and were normalized to the absolute efficiencies. The geometric efficiencies for all card and vial positions were determined using point sources and solution standards.

The γ-ray spectra were recorded with various multichannel analyzers. The data output devices from these analyzers included typewriter, magnetic tape, and paper punch tape.

III. RESULTS AND DISCUSSION

A. Isotopes produced

The γ-ray spectra were analyzed by the computer code RAGS.[7] Where possible the photon was assigned to a specific isotope on the basis of the energy of the γ ray. In order to determine the energy calibration, a series of spectra of standards were taken whose γ-ray energies were well established. Energy calibration spectra were taken both before and after the sample spectra to detect any gain shifts.

Once the energies of the γ rays from the targets had been determined, the isotopes associated with these γ rays could frequently be assigned. In some cases, the half-lives of the isotopes present in the spectra of the samples were determined in order to positively identify the radioisotopes produced during the irradiation.

The decay schemes of many of the isotopes produced in this study are not yet firmly established. Where possible, the branching ratio for the principal γ ray(s) was taken from the literature. In

TABLE V. Cross sections for the neutron-emission reactions from the reaction ^{197}Au + ^{12}C to produce the compound nucleus ^{209}At.

Energy (MeV) E_{lab}	E^*	Cross section (mb) (^{12}C, 3n) ^{206}At		(^{12}C, 4n) ^{205}At		(^{12}C, 5n) ^{204}At		(^{12}C, 6n) ^{203}At		(^{12}C, 7n) ^{202}At	
66.0(2.0) [a]	38.7	<1									
71.2(1.9)	43.6	94	(10)	16	(3)						
75.4(1.8)	47.6	77	(9)	220	(44)						
75.9(1.8)	48.0	65	(8)	137	(27)	15	(5)				
80.2(1.7)	51.9	21	(5)	101	(20)	55	(11)				
83.7(1.7)	55.4					100	(30)				
84.3(1.7)	56.0			75	(15)	150	(30)				
85.5(1.7)	57.0			42	(8)	164	(29)				
87.6(1.6)	59.1			23	(5)						
88.7(1.6)	60.1			15	(3)						
89.3(1.6)	60.7					220	(44)	16	(3)		
92.5(1.5)	63.7					100	(20)	213	(43)		
95.9(1.5)	66.8					55	(11)	360	(72)		
96.7(1.5)	67.6					37	(9)	376	(75)		
100.1(1.4)	70.8			5	(1)	17	(3)	380	(75)		
107.5(1.4)	77.8							213	(43)		
110.5(1.4)	80.6							156	(31)		
113.8(1.4)	83.7							115	(23)		
116.7(1.4)	86.5							82	(16)		
120.7(1.3)	90.3							33	(7)	20	(5)
125.6(1.2)	94.9							24	(5)	57	(12)

[a] The numbers in parentheses are error estimates for the cross sections and bombarding energies.

TABLE VI. Cross sections for the neutron-emission reactions from the reaction $^{197}Au + ^{3}He$ to produce the compound nucleus ^{200}Tl.

Energy (MeV)		Cross section (mb)									
		(^{3}He, 2n)		(^{3}He, 3n)		(^{3}He, 4n)		(^{3}He, 5n)		(^{3}He, 6n)	
E_{lab}	E^*	^{198}Tl		^{197}Tl		^{196}Tl		^{195}Tl		^{194}Tl	
16.4(3.6)	27.0	0.5	(0.1)	2.0	(0.4)						
22.6(3.2)	33.1	6	(1)	257	(51)	0.6	(0.1)				
27.1(3.1)	37.5			740	(148)	33	(7)				
32.2(3.0)	42.5			148	(30)	240	(48)				
36.4(2.9)	46.7			72	(20)	560	(112)	142	(28)		
43.1(2.5)	53.3					210	(42)	314	(63)		
48.0(2.3)	58.1					102	(20)	473	(95)	40	(8)
53.1(2.0)	63.1					60	(12)	187	(37)	190	(40)
58.0(1.8)	67.9					39	(8)			280	(50)
63.6(1.3)	73.5					29	(6)			312	(60)
69.6(1.0)	79.5							27	(6)	175	(40)

some cases, the branching ratio adopted was computed from the relative γ-ray intensities emitted in the decay of the isotope. Tables II–IV show the half-lives, branching ratios, and references (Refs. 8–24) for the isotopes produced in the course of this study.

B. Experimental cross sections

Before the cross section for the formation of a particular isotope could be computed, a number of corrections had to be applied. The attenuation of the γ rays had to be taken into account when a liquid sample was used. The attenuation correction had to be made for the solutions and for the polyethylene vial. The mass-attenuation coefficients for water as function of the energy of the γ rays were obtained from Grodstein.[25] The mass-attenuation coefficients for polyethylene were located in a report by Barthe.[26]

The fraction of the radioactive isotopes recovered from the targets when a separation of the target material from the backing foil was necessary was determined by neutron-activation analysis and polarographic techniques. The gold and the rhenium yields were determined by neutron-activation analysis months after the cyclotron irradiations. The gold and the rhenium samples were sealed in polyethylene vials and were irradiated with thermal neutrons using the University of Kentucky ^{252}Cf source. The irradiations were conducted for approximately 20 h. Copper flux monitors were introduced into the solutions in order to detect flux changes. Simultaneously, an accurately

TABLE VII. Cross sections for the neutron-emission reactions from the reaction $^{209}Bi + \alpha$ to produce the compound nucleus ^{213}At.

Energy (MeV)		Cross section (mb)									
		(α, 2n)		(α, 3n)		(α, 4n)		(α, 5n)		(α, 6n)	
E_{lab}	E^*	^{211}At		^{210}At		^{209}At		^{208}At		^{207}At	
24.0(3.2)	12.2	78	(16)								
29.8(3.1)	17.9	85	(17)								
33.9(2.1)	21.9	61	(25)	618	(124)						
38.1(3.0)	26.0			906	(181)						
44.2(2.8)	32.0			986	(197)	344	(69)				
49.7(2.6)	37.4			305	(41)	1036	(207)				
54.6(2.4)	42.2			150	(30)	1034	(207)	277	(135)		
60.1(2.1)	47.6			77	(15)	640	(70)	709	(142)		
65.5(1.9)	52.9					323	(70)	736	(147)	229	(86)
69.6(1.6)	56.9					150	(30)	508	(42)	569	(114)
74.0(1.3)	61.2					110	(28)	405	(100)	603	(100)
79.4(0.1)	66.5					72	(30)	296	(59)	484	(87)

TABLE VIII. Cross sections for the neutron-emission reactions from the reaction ^{187}Re + ^{3}He to produce the compound nucleus ^{190}Ir.

Energy (MeV)		Cross section (mb)							
		(^{3}He, 3n)		(^{3}He, 4n)		(^{3}He, 5n)		(^{3}He, 6n)	
E_{lab}	E^*	^{187}Ir		^{186}Ir		^{185}Ir		^{184}Ir	
28.5(3.1)	38.4	342	(65)	162	(30)				
32.1(3.0)	42.0	158	(32)			35	(10)		
34.2(3.0)	44.0	133	(27)	481	(100)	102	(20)		
36.4(2.9)	46.2	85	(17)	487	(97)	206	(42)		
38.6(2.8)	48.4			517	(103)	565	(113)		
41.1(2.7)	50.8					546	(109)		
44.6(2.6)	54.3	57	(11)	162	(52)	645	(129)	56	(11)
47.9(2.5)	57.5	47	(11)	88	(18)	621	(164)	206	(41)
51.4(2.3)	61.0			54	(10)	387	(77)	572	(114)
54.1(2.2)	63.6					222	(44)	550	(110)
57.0(2.1)	66.5					110	(22)		
59.8(1.2)	69.2			40	(10)	106	(21)	479	(96)
63.6(1.4)	73.0							436	(87)
66.4(1.2)	75.7					28	(6)	303	(61)
67.9(1.0)	77.2					27	(5)	240	(48)
71.3(0.0)	80.5							174	(55)

weighed standard was irradiated, and the weight of the sample was determined by comparing the activity of the sample to the activity of the standard.

The yield of the bismuth was confirmed by direct-current polarography. The samples were diluted to a known volume and were transferred to a flask in which distilled mercury had been placed. The samples were then analyzed using a dropping mercury electrode and polarograph with a flow rate of 3 drops of mercury per 10 sec. A polarogram was obtained, and the polarographic current was determined. The weight of bismuth present was determined by appropriate calibration with a series of standard bismuth solutions. A plot was constructed of the polarographic current of the standard versus the weight of the bismuth present in the standard. Using this curve, the weight of the bismuth present in the sample could be determined. Replicate analyses were performed where possible.

The decay time of the isotopes was computed from the difference in the time from the end of the irradiation to the time half way through the accumulation time of the spectra. The time half way through the accumulation time was computed using the formalism of Hoffman and Van Camerick.[27]

The laboratory energy of the irradiation of each sample was calculated using the computed range-energy curves. The bombarding energy of each

TABLE IX. Cross sections for the neutron-emission reactions from the reaction ^{209}Bi + ^{3}He to produce the compound nucleus ^{212}At.

Energy (MeV)		Cross section (mb)											
		(^{3}He, 2n)		(^{3}He, 3n)		(^{3}He, 4n)		(^{3}He, 5n)		(^{3}He, 6n)		(^{3}He, 7n)	
E_{lab}	E^*	^{210}At		^{209}At		^{208}At		^{207}At		^{206}At		^{205}At	
24.7(1.8)	29.6	30	(6)	236	(47)								
29.8(1.7)	34.6	41	(8)	1200	(300)	186	(37)						
34.4(1.6)	39.1	35	(1)	516	(103)	906	(300)	22	(8)				
39.7(1.5)	44.6			185	(37)	802	(160)	361	(72)				
44.6(1.4)	49.1			87	(17)			1164	(233)				
49.5(1.2)	53.9					477	(95)	966	(193)				
56.0(1.0)	60.3			70	(14)	326	(65)	664	(133)	681	(136)		
60.6(0.7)	64.8			77	(11)	292	(58)	431	(86)	1105	(221)	160	(12)
65.3(0.1)	69.4			72	(30)	240	(41)	350	(70)	942	(188)	176	(35)

TABLE X. Cross sections for the neutron-emission reactions from the reaction $^{187}Re+\alpha$ to produce the compound nucleus ^{191}Ir.

Energy (MeV)		Cross section (mb)									
		$(\alpha,3n)$		$(\alpha,4n)$		$(\alpha,5n)$		$(\alpha,6n)$		$(\alpha,7n)$	
E_{lab}	E^*	^{188}Ir		^{187}Ir		^{186}Ir		^{185}Ir		^{184}Ir	
25.9(2.0)	23.3	34	(27)								
29.8(1.9)	27.1	737	(147)								
32.5(1.9)	29.8	871	(174)								
36.0(1.8)	33.2	687	(137)	260	(50)						
41.4(1.7)	38.5	433	(87)	890	(180)						
45.9(1.7)	42.9	331	(46)	1150	(240)						
50.6(1.6)	47.5	250	(50)	1205	(240)	710	(140)				
54.1(1.5)	50.8	141	(28)	780	(200)	1830	(360)				
58.2(1.4)	54.9	126	(25)	490	(100)	1620	(330)				
62.0(1.3)	58.6			400	(100)	1750	(350)	380	(100)		
64.6(1.2)	61.2			330	(150)	1425	(300)	740	(150)		
67.8(1.0)	64.3					1070	(220)	1000	(220)		
71.8(0.9)	68.2					710	(150)	1170	(250)	85	(20)
74.2(0.7)	70.6					580	(130)	970	(200)	415	(80)
77.0(0.5)	73.3							1210	(270)	700	(150)
80.0(0.3)	76.3							930	(200)	1020	(200)
82.9(0.1)	79.1					152	(35)			980	(200)

target was converted to the center-of-mass energy. The Q value for the formation of the compound nucleus was calculated using the mass tables of Myers and Swiatecki.[28] The excitation energy of the compound system for each target was calculated. A tabulation of the incident laboratory energy, the excitation energy, and neutron-emission cross sections for each target is given in Tables V–X.

The energy maxima and shapes of the ^{12}C-induced reactions on ^{197}Au reported in this study are in reasonable agreement with the cross sections reported by Bimbot, Lefort, and Simon[29] although the magnitudes of the (xn) cross sections are 20–30% lower than those reported by Bimbot, Lefort, and Simon.[29] The deviations probably reflect errors in either the β-decay branching ratios used in this study or the α-decay branching ratios used by Bimbot, Lefort, and Simon.[29]

The errors involved in the present study come from a variety of sources. The integration of γ-ray peaks, detector efficiency measurements, attenuation factors, branching ratios of the γ rays of interest, charge integration, chemical yields, recoil losses, and uniformity of the targets were the principal source of error. The energy dispersion of the beam was estimated by assuming that the energy loss has a Gaussian distribution about the average value of the beam energy as it penetrated the target stack. The straggling was taken as the FWHM of the Gaussian distribution.[30] The absolute errors in the cross sections are difficult to determine because of possible errors in the decay schemes of the isotopes produced in the bombardments. Assuming no error in the branching ratios, the errors in the cross sections are approximately 20%.

IV. SUMMARY

The excitation functions for neutron-evaporation reactions from a variety of heavy-mass nuclei at medium excitation energies are measured. The cross sections for reactions produced by the bombarding projectiles ^3He, α, and ^{12}C will be compared to determine reaction effects. The results will be compared with existing reaction model calculations in the following communication.[2]

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[1]N. E. Scott, J. W. Cobble, and P. J. Daly, Nucl. Phys. A119, 131 (1968).
[2]K. J. Hofstetter and J. D. Stickler, following paper, Phys. Rev. C 9, 1072 (1974).
[3]V. F. Weisskopf and D. H. Ewing, Phys. Rev. 57, 473 (1940).
[4]C. K. Cline and M. Blann, Nucl. Phys. A172, 225 (1971).
[5]C. F. Williamson, J. P. Bouyot, and J. Picard, Centre d'Etudes Nucleaires de Saclay Report No. CEA-R 3042, 1966 (unpublished).
[6]L. C. Northcliffe and R. E. Schilling, Nucl. Data A7, No. 3–4 (1970).
[7]W. W. Bowman, Nucl. Instrum. Methods 96, 135 (1971).
[8]M. Finger *et al.*, European Organization for Nuclear Research Report No. CERN 70-29, 1970 (unpublished).
[9]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes*, (Wiley, New York, 1968).
[10]K. J. B. Ahlgren, Ph.D. dissertation, Purdue University, 1971 (unpublished).
[11]K. J. Hofstetter, T. T. Sugihara, and D. S. Brenner, Phys. Rev. C 8, 2442 (1973).
[12]M. B. Lewis, Nucl. Data B5, 631 (1971).
[13]M. J. Martin, Nucl. Data B5, 287 (1971).
[14]M. B. Lewis, Nucl. Data B5, 243 (1971).
[15]B. Jonson, M. Alpsten, A. Appelqvist, and G. Astner, Nucl. Phys. A177, 81 (1971).
[16]K. K. Seth, Nucl. Data B7, 161 (1972).
[17]T. Mopek, T. Vroaa, V. Vasmosv, H. Apostz, V. Noibert, and S. Hoinamki, JINR Report No. JINR-P6-4868, 1970 (unpublished).
[18]K. K. Seth, Nucl. Data B7, 161 (1972).
[19]P. K. Hopka, R. A. Naumann, and E. H. Spejewski, Nucl. Phys. A149, 63 (1970).
[20]M. R. Schmorak, Nucl. Data B6, 425 (1971).
[21]M. J. Martin, Nucl. Data B5, 601 (1971).
[22]R. L. Auble, Nucl. Data B5, 531 (1971).
[23]R. L. Auble, Nucl. Data B6, 319 (1971).
[24]M. R. Schmorak, Nucl. Data B7, 395 (1972).
[25]G. S. Grodstein, National Bureau of Standards Circular No. 583, 1957 (unpublished).
[26]J. P. Barthe, ORNL Report No. ORNL-tr-1504, 1965 (unpublished).
[27]B. W. Hoffman and S. B. Van Camerick, Anal. Chem. 39, 1198 (1967).
[28]W. D. Myers and W. J. Swiatecki, UCRL Report No. UCRL-11980, 1965 (unpublished).
[29]R. Bimbot, M. Lefort, and A. Simon, J. Phys. (Paris) 29, 563 (1968).
[30]N. Bohr, Phil. Mag. 30, 581 (1915).