^{6}Li, ^{7}Li induced reactions on ^{209}Bi[†]

H. Freiesleben,* H. C. Britt,‡ J. Birkelund,§ and J. R. Huizenga
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627

(Received 4 April 1974)

Results are reported on experimental measurements of total cross sections for (^{6,7}Li, xn), (^{6,7}Li, f), (^{7}Li, αxn), (^{7}Li, txn), and (^{7}Li, αp) reactions on a ^{209}Bi target at bombarding energies in the range 25–34 MeV. At ^{7}Li bombarding energies of 32 and 30 MeV, the cross sections for transfer reactions are 57 and 70%, respectively, of the total measured cross section. At energies below the Coulomb barrier, the cross section for transfer reactions becomes considerably larger than those for compound nucleus reactions.

[NUCLEAR REACTIONS ^{209}Bi(^{6,7}Li,xn), (^{6,7}Li,f), (^{7}Li,αxn), (^{7}Li,txn), (^{7}Li,αp), E=25–34 MeV; measured $\sigma(E)$.]

INTRODUCTION

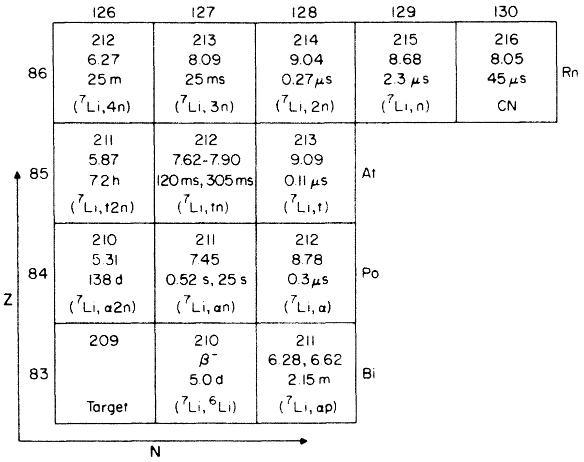
There have been a variety of previous experiments[1-8] performed to investigate the interactions of ^{6}Li and ^{7}Li projectiles with targets in the gold through bismuth region and, in one case,[8] with actinide targets. In most cases these measurements study direct reactions by observing the emission of α, d, or t particles. Hence it is difficult to differentiate between reactions involving the breakup in the Coulomb field of ^{6}Li(^{7}Li) into $\alpha+d(t)$ where both particles are emitted with high energy and those two-body reactions where only one particle is emitted and the residual piece of the projectile is captured. However, a recent experiment[7] where both α particles and tritons were observed from the ^{7}Li + ^{208}Pb reaction at 30 MeV showed a very much larger cross section for α than for triton production. These results suggest that most of the α particles come from reactions where an excited ^{211}Bi nucleus was formed. A reaction of this type could proceed by either a direct stripping reaction or by a two step reaction where the ^{7}Li first breaks up into $\alpha+t$ and then the triton is captured. Experimentally it is very difficult to tell the difference between these two processes and in this paper we will refer to a two-body reaction such as $^7\text{Li}+{}^{208}\text{Pb}\rightarrow\alpha+{}^{211}\text{Bi}$ as a "transfer" reaction even though we cannot rule out the possibility that there may be some contributions from two-step processes, i.e., breakup + capture. At energies near the Coulomb barrier for Sn isotopes, recent measurements[6] indicate that direct α particle emission cross sections are much larger for ^{6}Li than for ^{7}Li projectiles at the same bombarding energy. This result might indicate that the Coulomb breakup mechanism is more important for ^{6}Li than for ^{7}Li which would be consistent with the binding energy differences for the two projectiles.

In this paper we report experimental results on the cross sections for producing various isotopes of Rn, At, Po, and Bi following the bombardment of ^{209}Bi by ^{6}Li or ^{7}Li projectiles in the laboratory energy range 25–34 MeV. In addition, fission cross sections were measured and the branching ratios Γ_f/Γ_n were obtained from ratios of $\sigma_f/\sum_x\sigma_{xn}$ as a function of energy. A detailed analysis of the Γ_f/Γ_n results in terms of the fission barrier properties of the compound nucleus ^{216}Rn has been given in a previous publication.[9]

EXPERIMENTAL PROCEDURE

Because of their proximity to the $N=126$ and $Z=82$ closed shells most of the residual nuclei formed in ^{6,7}Li + ^{209}Bi reactions are short-lived α particle emitters. The α decay characteristics for nuclei which can be formed following various ^{7}Li reactions are shown in Fig. 1. For nuclei with $N\geq127$ (except for ^{210}Bi) it is seen that the α decay half-lives are generally short compared to a typical accelerator bombardment time of a few hours and the α decay energies are reasonably well spaced in the energy region of 6–9 MeV.

Cross sections for the formation of nuclei with $N\geq127$ and for ^{212}Rn were obtained by bombarding a ^{209}Bi target with pulsed ^{6,7}Li beams and observing the α particle decays between beam pulses. The beam was pulsed with a repetition time of 400 nsec. In order to eliminate prompt background only α particles were accepted in a semiconductor detector placed at 90° to the beam which occurred in a 100 nsec interval beginning 200 nsec after the beam pulses. Corrections in the yield were made for the decay of the shorter-lived activities during



Z \ N	126	127	128	129	130	
86	212 6.27 25 m (^{7}Li,4n)	213 8.09 25 ms (^{7}Li,3n)	214 9.04 0.27 μs (^{7}Li,2n)	215 8.68 2.3 μs (^{7}Li,n)	216 8.05 45 μs CN	Rn
85	211 5.87 7.2 h (^{7}Li,t2n)	212 7.62-7.90 120 ms, 305 ms (^{7}Li,tn)	213 9.09 0.11 μs (^{7}Li,t)	At		
84	210 5.31 138 d (^{7}Li,α2n)	211 7.45 0.52 s, 25 s (^{7}Li,αn)	212 8.78 0.3 μs (^{7}Li,α)	Po		
83	209 Target	210 β^- 5.0 d (^{7}Li,^{6}Li)	211 6.28, 6.62 2.15 m (^{7}Li,αp)	Bi		

FIG. 1. Diagram of nuclei populated by various reactions for the ^{7}Li + ^{209}Bi system. Entries in each box give mass number, decay energy of major α decay groups (MeV), α decay half-life, and reaction by which a particular residual product can be formed.

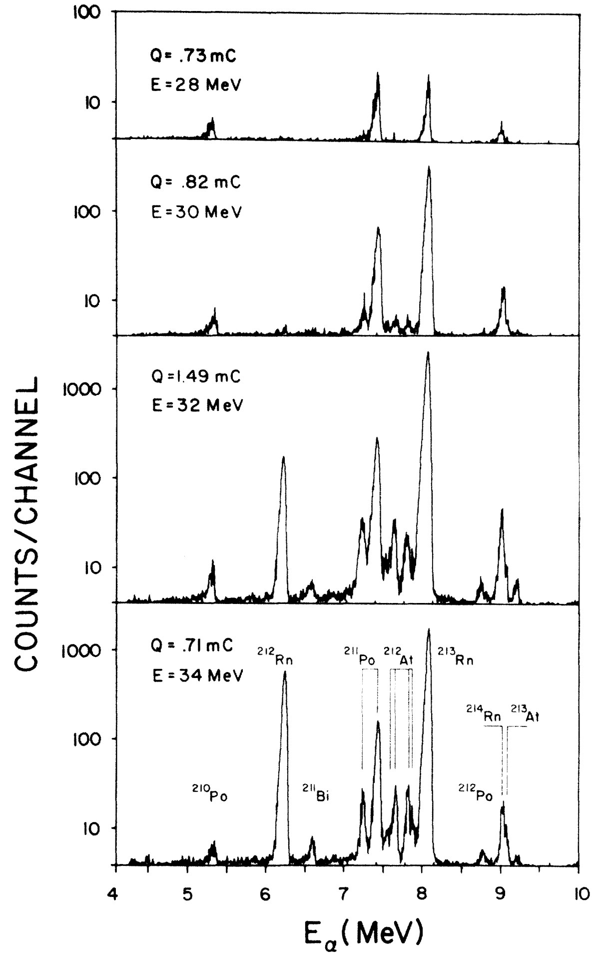


FIG. 2. α particle spectra observed at various bombarding energies for the ^{7}Li + ^{209}Bi system.

the 200 nsec period after the beam pulses and prior to counting. Absolute cross sections were obtained by measuring the rate of α particle emission relative to elastic scattering in the same semiconductor detector. The absolute elastic scattering cross sections at 90° were determined in a separate experiment where angular distributions of the elastic events were measured. The absolute cross section scale was calibrated by observing Rutherford scattering at forward angles. The absolute solid angle of the α detector was determined from a comparison of the count ratio from an α source for this detector and a reference detector with a small known solid angle.

At ^{7}Li energies of 30 and 32 MeV, the cross section for forming ^{210}Po was also measured by bombarding a target for several hours with a dc beam and then counting the 5.31 MeV decay α particles off line in known geometry. Again measurements were made relative to an absolute elastic scattering cross section at 90°.

Finally, measurements of the fission cross sec-

TABLE I. Measured cross sections in millibarns for various compound nucleus reactions.

Laboratory energy (MeV)	$\sigma(^7\text{Li}, 2n)$	$\sigma(^7\text{Li}, 3n)$	$\sigma(^7\text{Li}, 4n)$	$\sigma(^7\text{Li}, f)$	$\sigma(^6\text{Li}, 2n)$	$\sigma(^6\text{Li}, 3n)$	$\sigma(^6\text{Li}, f)$
34	4.6 ± 1.6	187 ± 19	77 ± 15	1.77 ± 0.03			2.25 ± 0.05
33	4.7 ± 1.6	189 ± 19	51 ± 15	1.05 ± 0.05			1.34 ± 0.04
32	4.1 ± 0.9	134 ± 13	11 ± 3	0.58 ± 0.03			0.75 ± 0.02
31	4.4 ± 0.6	89 ± 10	1.4 ± 0.7	0.24 ± 0.01			0.29 ± 0.01
30	3.3 ± 0.7	41 ± 4		0.086 ± 0.008	1.9 ± 0.4	43 ± 4	0.12 ± 0.006
29	2.0 ± 0.4	16 ± 2		0.020 ± 0.002			0.32 ± 0.002
28	1.1 ± 0.3	4.7 ± 0.5		0.0064 ± 0.0008	1.0 ± 0.2	5.8 ± 0.6	0.0094 ± 0.0010
27	0.5 ± 0.11	1.0 ± 0.1		0.0014 ± 0.0009			0.0015 ± 0.0003
26	0.3 ± 0.07	0.14 ± 0.04					
25	0.4 ± 0.013	0.026 ± 0.013					

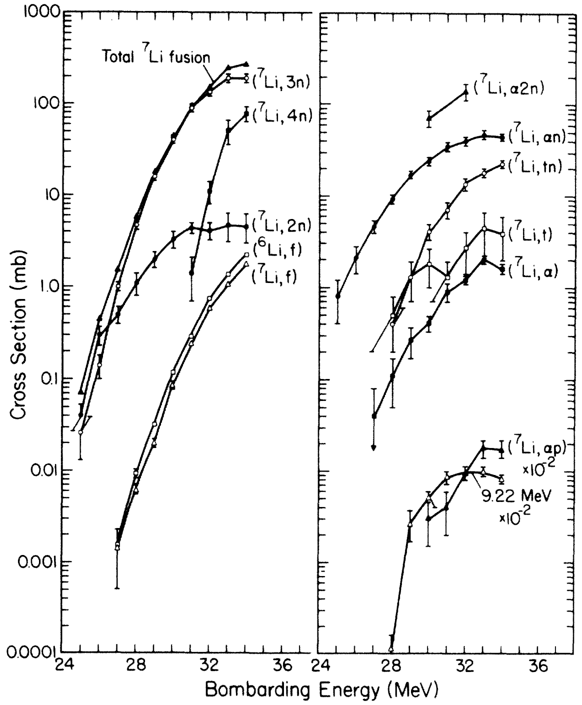


FIG. 3. Measured excitation functions for various reactions from ^{6,7}Li bombardment of ^{209}Bi. The excitation function labeled by 9.22 MeV is that of an unidentified isomer discussed in the text.

tion were made using dc beams of ^{6,7}Li projectiles by measuring coincident fission fragments at 90°. The coincidence requirement was found necessary to eliminate pileup of elastically scattered beam particles. Again, measurements were made relative to elastic scattering at 90° in the same detectors. Absolute cross sections were obtained assuming that the fragment emission is isotropic and later experiments showed that the error due to the neglect of anisotropy effects was small compared to other systematic and statistical errors.

Targets were produced by vacuum evaporation of deposits of ~200 μg/cm^2 on carbon backings of thickness 20 μg/cm^2 and 100 μg/cm^2. The targets with 20 μg/cm^2 gave the best energy resolution for the α particle observation so that weak peaks and close doublets could be resolved but not all of the recoil nuclei were stopped in the target plus backing so that a correction was necessary for nuclei which recoiled out of the target. This correction was determined from the observation of the large cross section group using targets with 100 μg/cm^2 backings.

RESULTS AND DISCUSSION

α particle spectra obtained in the ^{7}Li pulsed beam experiments at several energies are shown in Fig. 2. The results show α groups at known energies[10] for all of the nuclides shown in Fig. 1 except ^{215,216}Rn. These nuclei result from (^{7}Li, n) and (^{7}Li, γ) reactions and are expected to have very small cross sections at our bombarding energies due to the large excitation energies in the compound system. In addition to the peaks identified in Fig. 2, an α particle group with energy 9.22 ± 0.03 MeV was observed with a small cross section. This does not correspond to a reported energy decay for any of the nuclei shown in Fig. 1. This group probably results from the decay of a previously undiscovered isomer in one of these nuclides but from the present experiment it is not possible to tell which one. Also, we do not know the half-life of this transition and in converting to total cross sections we assumed that it was of the order or longer than our pulse repetition time (400 nsec). If the lifetime of this decay were less than 100 nsec then the cross section estimate would be significantly low.

The excitation functions for the various reactions

TABLE II. Measured cross sections in millibarns for various transfer reactions.

Laboratory energy (MeV)	$\sigma(^7\mathrm{Li},\alpha)$	$\sigma(^7\mathrm{Li},\alpha n)$	$\sigma(^7\mathrm{Li},\alpha 2n)$	$\sigma(^7\mathrm{Li},t)$	$\sigma(^7\mathrm{Li},tn)$	$\sigma(^7\mathrm{Li},\alpha p)$	$\sigma(^7\mathrm{Li},9.20\,\mathrm{MeV})$	$\sigma(^6\mathrm{Li},\alpha)$	$\sigma(^6\mathrm{Li},d)$	$\sigma(^6\mathrm{Li},dn)$
34	1.6 ± 0.2	44 ± 4		3.9 ± 2.0	23 ± 2	1.8 ± 0.4	0.82 ± 0.09			
33	2.0 ± 0.2	47 ± 5		4.4 ± 2.2	18 ± 2	1.8 ± 0.4	0.98 ± 0.10			
32	1.2 ± 0.1	40 ± 4	140 ± 20	2.7 ± 1.3	13 ± 2	1.0 ± 0.2	0.97 ± 0.10			
31	0.9 ± 0.2	35 ± 4		1.3 ± 0.6	7.1 ± 1.4	0.4 ± 0.2	0.86 ± 0.14			
30	0.4 ± 0.08	24 ± 3	71 ± 10	1.8 ± 0.8	4.1 ± 0.8	0.3 ± 0.15	0.49 ± 0.10	0.8 ± 0.2	1.6 ± 0.8	11 ± 2
29	0.27 ± 0.10	17 ± 2		1.3 ± 0.6	1.3 ± 0.6		0.27 ± 0.10			
28	0.11 ± 0.06	9.2 ± 0.9		0.5 ± 0.3	0.4 ± 0.2		0.011 ± 0.005	0.5 ± 0.2	0.25 ± 0.15	1.9 ± 0.4
27	0.04 ± 0.04	4.6 ± 0.7					0.007 ± 0.005			
26		2.1 ± 0.7								
25		0.8 ± 0.4								

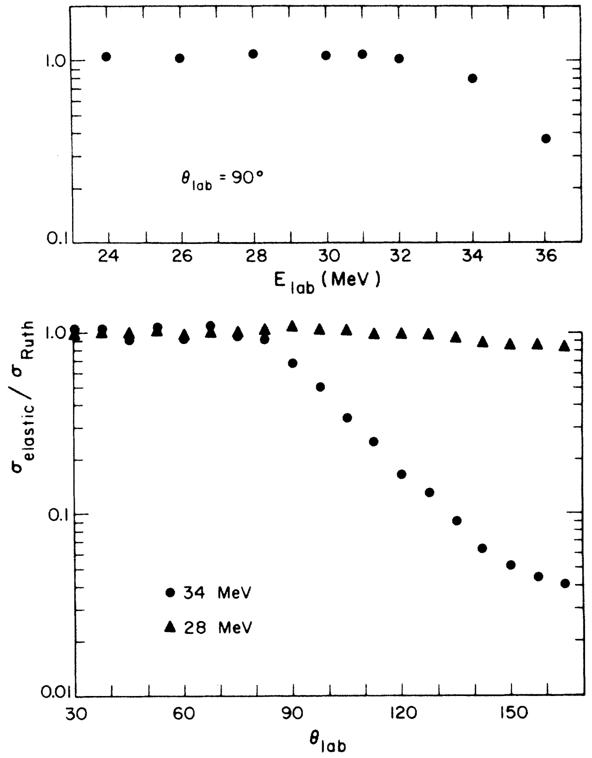


FIG. 4. Angular distributions and excitation functions for elastic scattering of ^{7}Li on ^{209}Bi.

are shown in Fig. 3 and the actual cross sections obtained are listed in Tables I and II. Elastic angular distributions and excitation functions at 90° are shown in Fig. 4 for ^{7}Li. In Figs. 1 and 3 the excitations of particular final nuclides have been labeled with particular reactions that could lead to these nuclides. In some cases these reactions are not unique and for example ^{210}Po could be populated either by the (^{7}Li, $\alpha 2n$) or (^{7}Li, ^{6}He) reactions.

The most remarkable features of these results are the large cross sections associated with transfer reactions relative to the fusion reactions and the much steeper slope for the fusion excitation function. For example, at 32 MeV the total cross section to Po and At isotopes is 200 mb compared to 150 mb for Rn isotopes. At 30 MeV the transfer cross section (Po + At) has decreased by a factor of 2 to 100 mb but the fusion cross section has decreased by a factor of 3.4 to 44 mb. Thus, at all energies equal to and below 32 MeV the transfer reactions make up the major part of the total reaction cross section.

The results appear consistent with a picture that the total reaction cross section has two major components. The first component is fusion with the subsequent evaporation of several neutrons to form the Rn isotopes. The second component consists of (^{7}Li, α) reactions to highly excited states followed by neutron evaporation to form Po isotopes and (^{7}Li, t) reactions to highly excited states followed by neutron evaporation to form At isotopes. Calculations[11] with a standard equilibrium evaporation code indicate that the contributions to the At and Po yields from evaporation of protons and α particles should be very small compared to measured yields.

Average excitation energies associated with the transfer reactions can be estimated from the optimum Q values[12] determined from reaction kinematics. For $E_{lab} = 34$ MeV, transfers at the optimum Q value lead to initial excitation energies of ~16 and ~10 MeV for the residual nuclei ^{212}Po and ^{213}At formed in the (^{7}Li, α) and (^{7}Li, t) reactions, respectively. This prediction suggests that the most likely residual products should be ^{210}Po from the (^{7}Li, $\alpha 2n$) reaction and ^{212}At from the (^{7}Li, tn) reaction. This prediction is consistent with the present data although it is still possible that we are missing a fraction of (^{7}Li, α) and (^{7}Li, t) cross sections by not observing the decays of the ^{209}Po and ^{211}At activities which are formed by (^{7}Li, $\alpha 3n$) and (^{7}Li, $t2n$) reactions, respectively.

The present results can also be compared to the direct α particle and triton measurements from the ^{7}Li + ^{208}Pb reaction at 30 MeV by Häusser *et al.*[7] At 30 MeV we measure total cross sections of 95 and 6 mb for populating Po and At isotopes, respectively. This represents a large fraction of the direct α particle and triton emission cross sections of ~150 and ~17 mb, respectively, which were determined from the angular distribution measurements of Häusser *et al.*,[7] and tends to confirm their postulate that the ^{7}Li reactions are dominated by transfer reactions.

The limited ^{6}Li results shown in Tables I and II are consistent with the ^{7}Li measurements. The present technique is not as useful for ^{6}Li because one would expect greater populations of nuclides with $N \leq 126$ which are not short-lived α particle emitters.

[†] Work supported in part by the U. S. Atomic Energy Commission and the National Science Foundation.

[*] Permanent address: Fachbereich Physik, Universität Marburg, W. Germany.

[‡] Permanent address: Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[§] Permanent address: Western Australia Institute of Technology, [illegible], W. Australia.

[1] C. E. Anderson, in *Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, 1960,* edited by A. Zucker, F. T. Howard, and E. C. Halbert (Wiley, New York, 1960), p. 67.

[2] R. Ollerhead, C. Chasman, and D. A. Bromley, Phys. Rev. 134, B374 (1964).

[3] K. Bethge and K. Meier-Ewert, Phys. Rev. Lett. 18, 1010 (1967).

[4] J. L. Quebert and H. Sztark, J. Phys. (Paris) 32, 255 (1971).

[5] D. L. Disdier, A. C. Ball, O. Häusser, and R. E. Warner, Phys. Rev. Lett. 27, 1391 (1971).

[6] K. O. Pfeiffer, E. Speth, and K. Bethge, Nucl. Phys. A206, 545 (1973).

[7] O. Häusser, A. B. McDonald, T. K. Alexander, A. J. Ferguson, and R. E. Warner, Phys. Lett. 38B, 75 (1972).

[8] Alain Fleury, thesis, Docteur És-Sciences, University of Bordeaux, 1969 (unpublished); private communication.

[9] H. Freiesleben, H. C. Britt, and J. R. Huizenga, in Proceedings of the Third International Atomic Energy Symposium on Physics and Chemistry of Fission, Rochester, 1973 (to be published), paper No. IAEA/SM-174/56.

[10] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967), 6th ed.

[11] We are indebted to M. Blann for providing the evaporation code.

[12] W. von Oertzen, in Nuclear Spectroscopy and Reactions, edited by J. Cerny (Academic, New York, to be published).