MEASUREMENTS OF YIELDS IN THE ^{93}Nb(^{6}Li,x)y REACTION

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Production cross section measurements were carried out for the reaction ^{93}Nb(^{6}Li,x)y for ^{6}Li beam energies of 55, 65, 77 and 91 MeV. A 5 mg/cm^2 thick ^{93}Nb target was used for the 55 and 65 MeV runs; for the 77 and 91 MeV runs a 17 mg/cm^2 target was used. A gamma ray spectrum taken at 77 MeV beam energy is shown in Figure 1. A cursory inspection of the figure reveals that the major transitions come from the Tc and Mo isotopes. In general, known gamma ray transitions were used to identify the final nuclei and to set lower limits on their production cross sections. The cross sections were calculated using the following relation:

$$\sigma(\text{mb}) = 454\ I_\gamma/f\ ,\ E_{Li} = 55,\ 65\ \text{MeV},$$

$$\sigma(\text{mb}) = 2731\ I_\gamma/f,\ E_{Li} = 77,\ 91\ \text{MeV},$$

where I_γ is the intensity of the gamma ray corrected for dead time and efficiency, and f is the probability that the gamma ray will occur if the excited nucleus was produced. The constants take into account total charge collected in the Faraday cup and target thickness, angle, isotopic enrichment, γ-ray detection efficiencies and solid angle.

The results for the (xn) channels leading to the Ru isotopes are compiled in Table 1. In the case of even-even isotopes the $2^+ \rightarrow 0^+$ (g.s. transition) accumulates most of the production strength; we therefore took f = 1 in the cross section calculation. For the odd-even Ru isotopes observations from (α,xn) reactions show that there are several strong transitions to the ground state (g.s.). We attempted to identify as many g.s. transitions as possible and summed their cross sections. Similar consideration

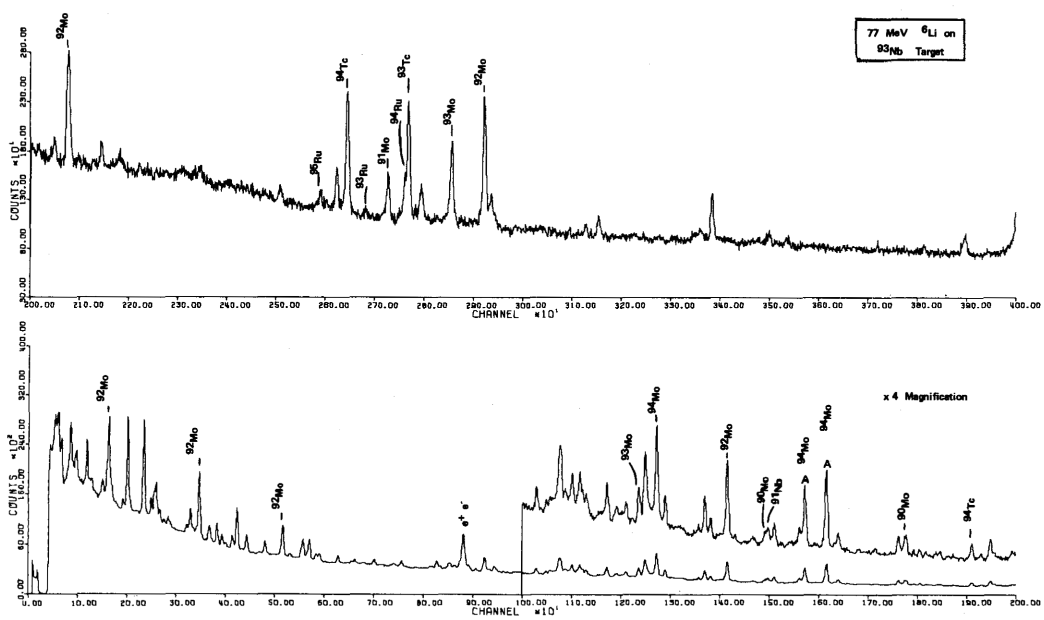

Figure 1. Sample in-beam γ-ray spectrum from ^{6}Li bombardment of ^{93}Nb at 77 MeV.

Table 1. Cross sections (in millibarns) for production of Ru isotopes by $^{93}Nb(^{6}Li,xn)$ reactions.

Final Products	Exit channel	E(^{6}Li), MeV 55	65	77	91
^{93}Ru	(6n)$^{a)}$			> 15	> 2
^{94}Ru	(5n)$^{b)}$	40	30	45	
^{95}Ru	(4n)$^{c)}$	70	80	110	30
^{96}Ru	(3n)$^{d)}$	10	10		
Total (xn) cross section		120	120	170	30 (lower limit)

a) Based on 1392 keV $13/2^+ \rightarrow 9/2^+$ g.s. transitions seen in (α,3n).
b) Based on 1429 keV $2^+ \rightarrow 0^+$ g.s. transition.
c) Based on 1346 keV and 941 keV transitions to g.s.
d) Based on 833 keV $2^+ \rightarrow 0^+$ transition.

Table 2. Cross sections (in millibarns) for production of Mo isotopes by $^{93}Nb(^{6}Li,2pxn)$ reactions.

Final Products	Exit channel	E(^{6}Li),MeV 55	65	77	91
^{90}Mo	(2p7n)$^{a)}$	35	35	65	80
^{91}Mo	(2p6n)$^{b)}$	20	80	120	80
^{92}Mo	(2p5n)$^{c)}$	90	70	220	230
^{93}Mo	(2p4n)$^{d)}$	> 70	> 60	> 140	> 55
^{94}Mo	(2p3n)$^{e)}$	170	210	370	140
Total (2pxn) cross section		380	450	910	580 (lower limit)

a) Based on the 949 keV $2^+ \rightarrow 0^+$ transition. No activity observed. A 947 keV transition is intense in 55 and 65 MeV spectra.
b) Based on 1414 keV $13/2^+ \rightarrow 9/2^+$ transition observed in (α,xn) and 502 keV $3/2^- \rightarrow 1/2^-$ transition, the latter has most of the negative parity strength.
c) Based on 1511 keV $2^+ \rightarrow 0^+$ transition. Decay component from ^{92}Tc negligible.
d) Based on 1477 keV transition $9/2^+ \rightarrow 5/2^+$ (g.s.). Negligible activity. Lower bound.
e) Calculated using 293 keV transition. From (αxn) work 293 keV (g.s. transition) ≃ 1/7.

Table 3. Cross sections (in millibarns) for production of Tc isotopes by $^{93}Nb(^{6}Li,pxn)$ reactions.

Final Products	Exit channel	E(^{6}Li),MeV 55	65	77	91
^{92}Tc	(p6n)$^{a)}$		> 5	>15	>20
^{93}Tc	(p5n)$^{b)}$	35	10	270	200
^{94}Tc	(p4n)$^{c)}$	180	170	320	120
^{95}Tc	(p3n)$^{d)}$	120	50	40	
Total (pxn) cross section		335	295	640	335 (lower limits)

a) Based on the 213 keV transition to the 7^+ ground state.
b) Based on the 1434 keV $13/2^+ \rightarrow 9/2^+$ (g.s.) transition and the 1016 keV $5/2^- \rightarrow 1/2^-$ transition. The $5/2^-$ level is the lowest negative parity state.
c) Based on the 102 keV transition to the 7^+ ground state and the 1373 keV transition to the g.s. observed in (α,xn) reactions.
d) Based on the 882 keV $13/2^+ \rightarrow 9/2^+$ (g.s.) transition observed in (α,xn) reactions.

Table 4. Cross sections (in millibarns) for production of Nb isotopes by $^{93}Nb(^{6}Li,3pxn)$ reactions.

Final Products	Exit channel	E(^{6}Li),MeV 55	65	77	91
^{90}Nb	(3p6n)$^{a)}$	> 15	> 15	> 50	> 20
^{91}Nb	(3p5n)$^{b)}$	10	20	110	120
^{93}Nb	(3p3n)$^{c)}$	> 20	> 15	> 70	> 80
Total		> 45	> 50	>230	>220

a) Based on 122 keV transitions to 7^+ g.s. Degenerate region in spectrum.
b) Based on 819 keV $17/2^+ \rightarrow 13/2^+$ transition and the 1082 keV $5/2^- \rightarrow 1/2^-$ transition.
c) Based on 385 keV $17/2 \rightarrow 13/2$ transition and 777 $5/2^- \rightarrow 1/2^-$ transition. $13/2^+ \rightarrow 9/2^+$ (g.s.) degenerate with 948 of ^{90}Mo.

NOTE: (Table 3.)
None of the Tc transitions had observable decay component from the Ru isotopes.

apply to the cross section estimates in Table 2 in which we compile the results for the (2pxn) channel leading to the Mo isotopes.

The results for the (pxn) and (3pxn) channels are compiled in Tables 3 and 4 respectively. Since many of the odd-odd Tc and Nb isotopes have not been studied with H.I. reactions the quoted estimates are lower limits only. Wherever possible, we used (α,xn) studies to determine the main ground state transitions.

Some of the measured cross sections were compared with the values predicted by the Geometry - Dependent Hybrid Model (GDHM), embodied in the computer code ALICE.[2] (See Figure 2.) Typically the two cross sections were within an order of magnitude of each other. In case of ^{94}Mo the GDHM calculation for ^{6}Li-induced reactions underestimates the measured cross section by several orders of magnitude. The excess cross section observed may be the result of other processes, for example (^{6}Li,αxn) involving absorption of the deuteron fragment of the ^{6}Li. Further study on this question is in progress.

In conclusion it appears that the reactions induced by ^{6}Li beams of intermediate energy are useful for spectroscopic studies. At 77 MeV, 8 isotopes were produced with cross sections greater than 100 mb. Furthermore, all of the high spin states observed in (α,xn) reactions have also been observed in the present work. The exciting question remains: Are there new types of states produced in these reactions? Work is underway to answer this question as well.

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1) M. Blann, Ann. Rev. Nucl. Sci. 25, 123 (1975).

2) M. Blann, University of Rochester, private communication, 1976.

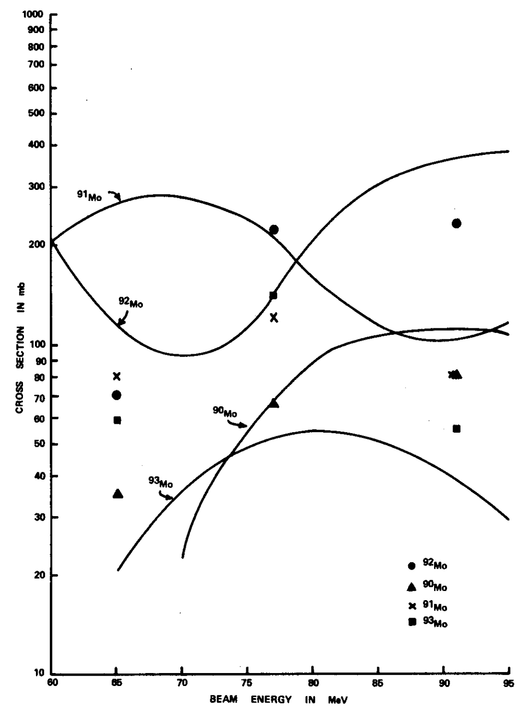

Figure 2. Summary of data for the production of Mo isotopes by ^{93}Nb(^{6}Li,2pxn) reactions. The solid curves are theoretical (GDHM) predictions. See discussion in text.