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STUDY OF THE (α,t) REACTION ON ZIRCONIUM-90, MOLYBDENUM-92, AND MOLYBDENUM-96 AT 41.5 MeV

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16. Abstract

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STUDY OF THE (α, t) REACTION ON ZIRCONIUM-90, MOLYBDENUM-92, AND MOLYBDENUM-96 AT 41.5 MeV

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SUMMARY

Angular distributions for the (α,t) reactions on Zr^{90}, Mo^{92}, and Mo^{96} leading to the ground states of Nb^{91}, Tc^{93}, and Tc^{97} have been measured from 15° to 60° for an alpha-particle energy of 41.5 MeV. The distorted wave Born approximation calculation for the stripping of a proton transferring 4 units of angular momentum provides an adequate description of the angular distributions. The spectroscopic strengths agree favorably with those deduced from a similar study using the (He^3,d) reaction. These results are consistent with a model which envisions the ground states of Nb^{91}, Tc^{93}, and Tc^{97} as a $1g_{9/2}$ proton coupled to a 0^+ core.

INTRODUCTION

The distorted wave Born approximation (DWBA) analysis of (d,n) and (He^3,d) stripping reactions is an invaluable tool for extracting nuclear structure information. The (α,t) reaction, which also involves the transfer of a proton to the target, should, in principal, be much like the (d,n) and (He^3,d) reactions. However, similar DWBA analyses of these reactions have been inconsistent, which suggests that the reaction mechanism is not well understood. The reaction Q-value for an (α,t) reaction is usually about 20 MeV less than that for the (d,n) or (He^3,d) reaction. This results in a significant difference between the linear momentum of the ingoing and outgoing particles. This momentum mismatch should suppress those reactions in which the proton is captured with $l \leq 2$. This supposition was borne out in a study of the Sc^{45} (α,t)Ti^{46} reaction (ref. 1). Using a conventional DWBA stripping calculation, good agreement between experiment and theory was obtained for reactions in which the proton was captured with $l = 3$. A further

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test would be to study (α,t) reactions involving the transfer of a proton with $l = 4$. Nuclei with protons in the $1g_{9/2}$ shell satisfy this requirement. Zirconium, molybdenum, niobium, and technetium nuclei are particularly suited since all have less than four protons outside of the closed $Z = 40$ shell. We report, herein, a study of the (α,t) reactions on targets of Zr^{90}, Mo^{92}, and Mo^{96}.

SYMBOLS

A	mass number
a	nuclear diffuseness
C	Clebsch-Gordan coefficient for isospin
$d\sigma/d\Omega$	differential cross section
J_f	spin of final state
$(2J_f + 1)C^2S_{lj}$	spectroscopic strength
J_i	spin of initial state
j	total angular momentum quantum number
l	orbital angular momentum quantum number
N	normalization constant
n_{lj}	average number of neutron holes in the l_j orbital
p_{lj}	average number of proton holes in the l_j orbital
r_0	reduced nuclear radius
S_{lj}	spectroscopic factor
V	real nuclear potential
V_c	Coulomb potential for uniformly charged sphere of radius $r_0A^{1/3}$
W	imaginary nuclear potential
γ	normalisation parameter for comparing experimental and theoretical cross sections
$\Delta\sigma_{EXPT}(\theta)$	experimental error
$\sigma_{DWBA}(\theta)$	differential cross section calculated from distorted wave Born approximation

$\sigma_{EXPT}(\theta)$ experimental differential cross section

χ^2 goodness-of-fit function

EXPERIMENTAL RESULTS

The experimental setup is described in an earlier report (ref. 1). The Zr^{90} target was a rolled foil having an areal density of 0.901±0.050 milligram per square centimeter. This was determined by measuring the energy lost by 8.78-MeV alpha particles passing through the foil. The Mo^{92} and Mo^{96} targets were evaporated films on a carbon backing. The areal density of these films was not determined by the alpha particle energy loss method because of their extreme fragility. Rather, the relative differential cross sections for the elastic scattering of 41-MeV alpha particles were measured and the data were normalized to a theoretical optical model calculation. The optical model calculation used a Woods-Saxon potential of the form

$$V_c - \frac{V}{1 + e^x} - \frac{W}{1 + e^{x'}} \tag{1}$$

where

$$x = \frac{r - r_0 A^{1/3}}{a}$$

$$x' = \frac{r - r_0' A^{1/3}}{a'}$$

The parameters were obtained by fitting the optical model calculation to measurements of the differential cross sections for the elastic scattering of 41-MeV alpha particles on Zr^{90}. The parameters used are shown in table I. The experimental results (table II) and optical model calculations are shown in figure 1.

The (α,t) reactions on Zr^{90}, Mo^{92}, and Mo^{96} lead to states of Nb^{91}, Tc^{93}, and Tc^{97}. The low-lying energy levels of these nuclei are shown in figure 2. A triton energy spectrum at a laboratory angle of 40° taken with the Mo^{92} target is shown in figure 3. Spectra taken with the Zr^{90} and Mo^{96} targets are very similar. The overall energy resolution is about 200 keV. This is sufficient to completely resolve the ground state of Tc^{93} but not that of Nb^{91} and Tc^{97}. However, the triton spectrum in figure 3 is completely dominated by the ground state group and therefore it is very likely that the strong transitions seen in Nb^{91} and Tc^{97} correspond almost entirely to production of the ground states.

Angular distributions of differential cross sections corresponding to the production of the ground states of Nb^{91}, Tc^{93}, and Tc^{97} are shown in figure 4. The numerical results are presented in table III. The overall uncertainty in the cross sections is estimated to be 15 percent.

DISCUSSION

The triton spectrum in figure 3 is to be compared with the (He^3,d) spectrum shown in figure 5. The (He^3,d) reaction strongly excites many states in Tc^{93}, whereas only the ground state of Tc^{93} is strongly excited in the (α,t) reaction. Analysis of the (He^3,d) results shows that only the ground state transition proceeds by $l = 4$ proton capture; the remaining transitions proceed by either $l = 1$ or $l = 2$. Thus, the supposition that (α,t) transitions proceeding by proton capture with $l \leq 2$ are strongly suppressed is borne out in this experiment.

The theoretical curves shown in figure 4 were calculated by the application of the DWBA stripping formalism of Tobocman (ref. 4). The theoretical expression for capture of a proton can be written as

$$\frac{d\sigma}{d\Omega} = N\left(\frac{2J_f + 1}{2J_i + 1}\right)C^2 S_{lj}\sigma_{DWBA} \tag{2}$$

The normalization constant, N, involves an overlap integral for the dissociation of an alpha particle into a triton and proton. In the study of the $Sc^{45}(\alpha,t)Ti^{46}$ reaction (ref. 1), N was determined empirically to be 28.0. This value was used in this work. The cross sections (σ_{DWBA}) were calculated with the FORTRAN code written by the authors of reference 5. The wave functions for the incident and exit channels were generated by solution of the Schroedinger equation with a Woods-Saxon potential (eq. (1)). The parameters for the incident system were those shown in table I. The parameters for the exit systems were estimated from the 20-MeV triton elastic scattering results of reference 6. These are shown in table IV. The bound state wave function for the captured proton was an eigenfunction of a Woods-Saxon Hamiltonian with eigenenergy equal to the binding energy of the proton in the residual nucleus. The potential did not contain a spin-orbit term. The radius and diffuseness parameters of the potential function were 1.25 and 0.65 fermi. The depth of the potential was chosen to reproduce the binding energy.

The theoretical calculations were adjusted in magnitude by determining a normalizing parameter γ which minimized the χ^2 function defined by

$$\chi^2 = \sum_{\theta} \left[\frac{\gamma\sigma_{DWBA}(\theta) - \sigma_{EXPT}(\theta)}{\Delta\sigma_{EXPT}(\theta)} \right]^2 \tag{3}$$

The theoretical fits are quite satisfactory in the angular region 12° to 40° and are reasonable at the larger angles. The quality of the fits is comparable to those obtained in the study of the $Sc^{45}(\alpha,t)Ti^{46}$ reaction. Since the fits are acceptable, it is meaningful to extract spectroscopic strengths. These, along with some (He^3,d) results (ref. 2), are shown in table V. The agreement between the (α,t) and (He^3,d) results is well within an estimated 20-percent error limit.

The total spectroscopic strength associated with a given single-particle state is the sum of the strengths for all states identified as fragments of the single-particle state. French and MacFarlane (ref. 7) have shown that for capture of a proton this sum is

$$\sum (2J_f + 1)C^2S_{lj} = \langle p_{lj} \rangle - \frac{\langle n_{lj} \rangle}{N - Z + 1} \tag{4}$$

where $\langle p_{lj} \rangle$ and $\langle n_{lj} \rangle$ are the average numbers of proton and neutron holes in the (lj) orbital of the ground state of the target. The neutron shells up through $1g_{9/2}$ are presumably filled in Zr^{90}, Mo^{92}, and Mo^{96}. Hence, if the proton is captured with $l = 4$ into a $1g_{9/2}$ orbital, $\langle n_j \rangle = 0$ for these nuclei. Then $\langle p_j \rangle = 10$, 8, and 8 for Zr^{90}, Mo^{92}, and Mo^{96}. These numbers are to be compared with 9.3, 6.7, and 6.0 obtained from experiment. Excepting Mo^{96}, the numbers agree within experimental error. Thus, the characterization of the $9/2^+$ ground state of Nb^{91}, Tc^{93}, and Tc^{97} as a $1g_{9/2}$ proton coupled to the 0^+ target ground state is reasonable.

CONCLUSION

The differential cross sections for the (α,t) reactions on Zr^{90}, Mo^{92}, and Mo^{96} leading to the ground states of Nb^{91}, Tc^{93}, and Tc^{97} are significantly larger than those leading to the excited states. The DWBA calculations for the stripping of a proton transferring 4 units of angular momentum yield reasonable fits to the angular distributions. Spectroscopic strengths deduced from the DWBA analysis compare favorably with those deduced from similar analyses on (He^3,d) reactions leading to the same states.

Comparison of the experimental spectroscopic strengths with theory indicates that the $9/2^+$ ground states of Nb^{91}, Tc^{93}, and TC^{97} are reasonably characterized as a $1g_{9/2}$ proton coupled to a 0^+ core.

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, April 27, 1971,

129-02.

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TABLE I. - OPTICAL MODEL PARAMETERS FOR ENTRANCE CHANNEL

Parameter	Zr^{90}	Mo^{92}	Mo^{96}
Real nuclear potential, V, MeV	195.95	195.95	195.95
Reduced radius for real potential, r_0, fm	1.355	1.355	1.355
Nuclear diffuseness for real potential, a, fm	0.5974	0.5974	0.5974
Imaginary nuclear potential, W, MeV	46.79	46.79	46.79
Reduced radius for imaginary potential, r_0', fm	1.355	1.355	1.355
Nuclear diffuseness for imaginary potential, a', fm	0.5974	0.5974	0.5974
Coulomb radius, r_{oc}, fm	1.25	1.25	1.25
Goodness of fit (χ^2 divided by number of data points)	1.09	2.67	1.71

TABLE II. - DIFFERENTIAL CROSS SECTIONS FOR ELASTIC SCATTERING OF 41.5-MeV ALPHA PARTICLES FROM Zr^{90}, Mo^{92}, AND Mo^{96}

Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, mb/sr	Statistical error, $\Delta\sigma$, mb/sr	Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, mb/sr	Statistical error, $\Delta\sigma$, mb/sr	Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, mb/sr	Statistical error, $\Delta\sigma$, mb/sr
Zr^{90}			Mo^{92}			Mo^{96}		
13.05	24919.	25.	18.25	5089.3	7.8	10.41	96584.	212.
15.66	10378.	11.	20.85	1830.7	5.2	12.49	39227.	133.
18.26	4554.7	6.3	23.45	1140.5	2.8	14.57	19803.	78.
20.87	1638.7	3.0	26.05	749.0	1.1	16.65	11075.	53.
23.47	1031.7	2.4	28.65	267.19	.86	18.73	4969.	25.
26.07	647.6	1.1	31.24	140.09	.51	20.81	2284.	13.
28.67	211.84	.58	33.84	151.98	.64	22.89	1476.1	9.1
31.27	97.42	.16	36.43	74.57	.32	24.97	990.6	6.0
33.87	121.30	.31	39.01	18.90	.20	27.04	481.3	3.4
36.46	62.16	.14	41.60	24.59	.20	29.12	216.1	1.5
39.05	14.45	.09	44.18	25.32	.19	31.19	179.1	1.4
41.63	17.63	.08	46.76	8.82	.10	33.26	154.5	1.0
44.22	21.92	.10	49.34	1.89	.06	35.33	78.23	.85
46.80	8.16	.05	51.91	6.16	.10	37.40	29.74	.49
49.38	1.18	.02				39.47	20.17	.42
51.95	4.56	.04				41.53	28.20	.38
54.52	5.66	.05				43.60	22.59	.46
57.08	1.81	.02				45.66	9.88	.29
59.65	.056	.004				47.72	2.93	.16
62.20	1.31	.02						

TABLE III. - DIFFERENTIAL CROSS SECTIONS FOR THE (α,t) REACTION ON Zr^{90}, Mo^{92}, AND Mo^{96}

Center-of-mass reaction angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, mb/sr	Statistical error, $\Delta\sigma$, mb/sr	Center-of-mass reaction angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, mb/sr	Statistical error, $\Delta\sigma$, mb/sr	Center-of-mass reaction angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, mb/sr	Statistical error, $\Delta\sigma$, mb/sr
Zr^{90}			Mo^{92}			Mo^{96}		
13.09	11.28	0.53	18.33	4.23	0.22	10.44	11.09	0.59
15.71	9.12	.32	20.94	3.01	.21	15.66	6.13	.19
18.33	6.20	.23	23.55	2.35	.13	20.87	3.04	.10
20.94	5.14	.17	26.16	2.05	.06	26.08	1.82	.07
23.55	3.94	.15	28.77	1.39	.06	31.27	.74	.03
26.16	2.98	.07	31.38	.88	.04	36.46	.64	.03
28.77	2.14	.06	33.98	.85	.05	41.64	.46	.03
31.38	1.37	.02	36.58	.69	.03	46.80	.22	.02
33.98	1.10	.03	39.18	.65	.04	51.96	.18	.01
36.58	.98	.02	41.77	.55	.03	57.09	.085	.009
39.18	1.01	.02	44.36	.39	.02			
41.77	.84	.02	46.95	.30	.02			
44.36	.63	.02	49.53	.30	.02			
46.95	.48	.01	52.11	.27	.02			
49.53	.44	.01						
52.11	.39	.01						
54.69	.33	.01						
57.26	.21	.006						
59.83	.148	.007						
62.39	.133	.006						

TABLE IV. - OPTICAL MODEL PARAMETERS

FOR EXIT CHANNEL

Real nuclear potential, V, MeV	153.2
Reduced radius for real potential, r_0, fm	1.24
Nuclear diffuseness for real potential, a, fm	0.678
Imaginary nuclear potential, W, MeV	20.6
Reduced radius for imaginary potential, r_0', fm	1.45
Nuclear diffuseness for imaginary potential, a', fm	0.841

TABLE V. - SPECTROSCOPIC

STRENGTHS

Residual nucleus	Spectroscopic strengths, (α,t)	Spectroscopic strengths, (He^3,d)
Nb^{91}	9.3±1.9	9.0±1.8
Tc^{93}	6.7±1.3	6.7±1.3
Tc^{97}	6.0±1.2	

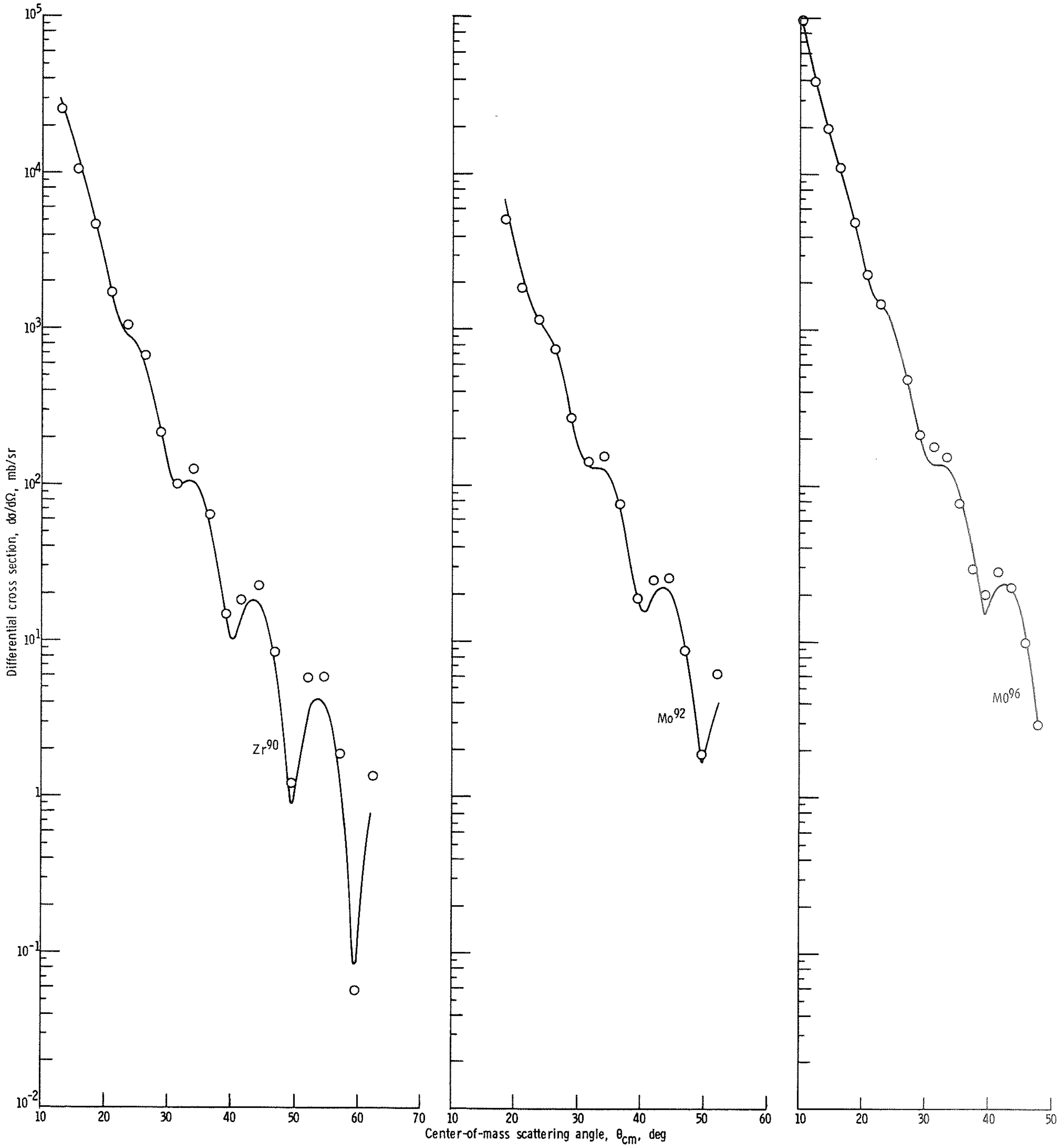

Figure 1. - Optical model fits to $Zr^{90}(\alpha,\alpha)Zr^{90}$, $Mo^{92}(\alpha,\alpha)Mo^{92}$, and $Mo^{96}(\alpha,\alpha)Mo^{96}$ angular distributions.

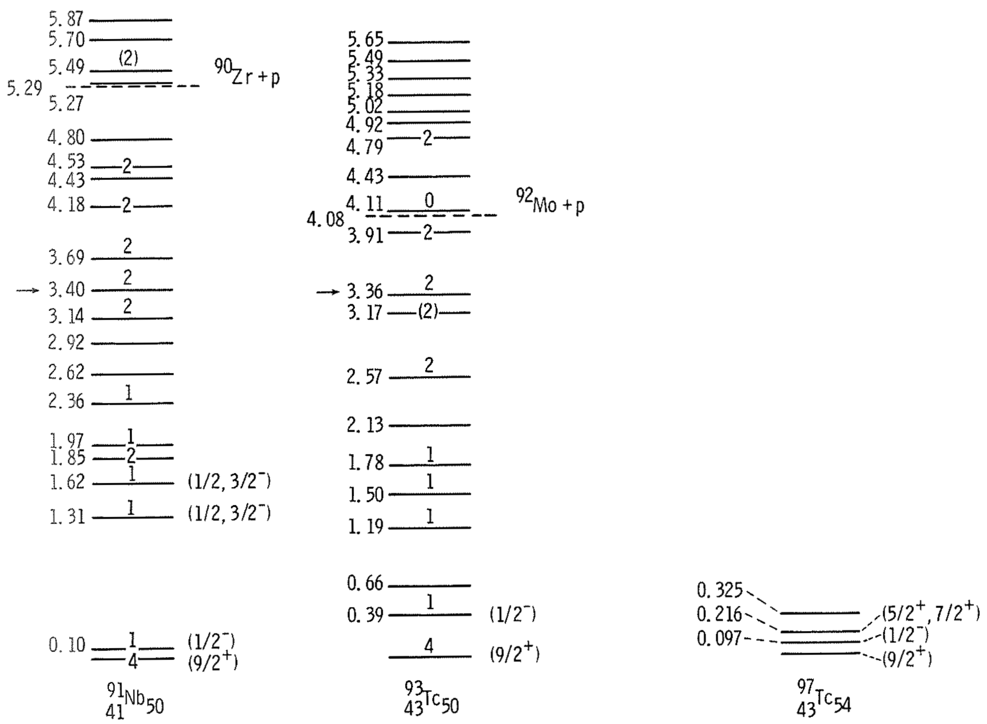

Figure 2. - The energy levels of Nb^{91}, Tc^{93}, and Tc^{97}. (The levels for Nb^{91} and Tc^{93} are those reported in ref. 2; the levels for Tc^{97} are taken from ref. 3.)

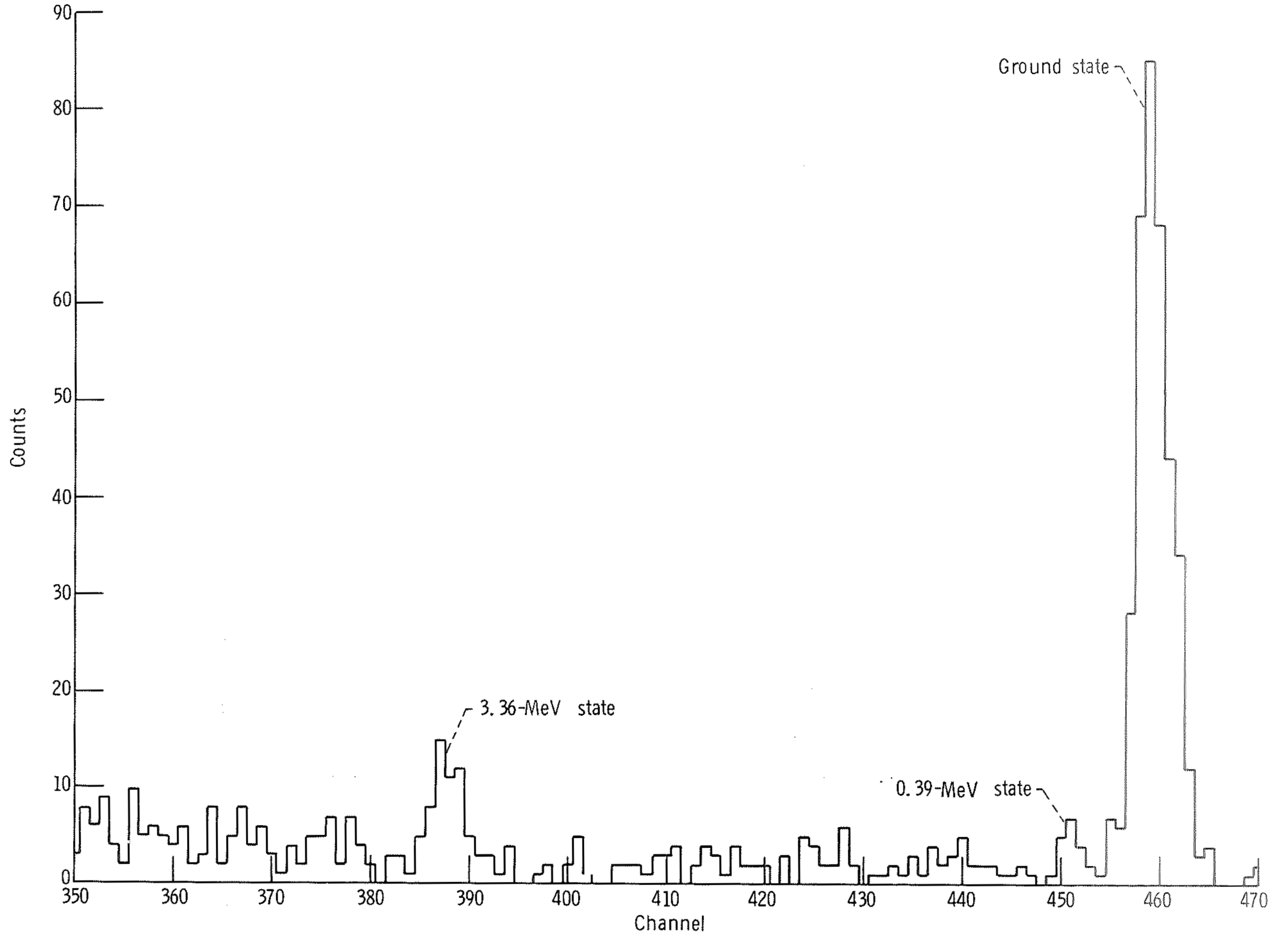

Figure 3. - Triton spectrum obtained at 40^0 for $Mo^{92}(\alpha, t)Nb^{93}$ reaction.

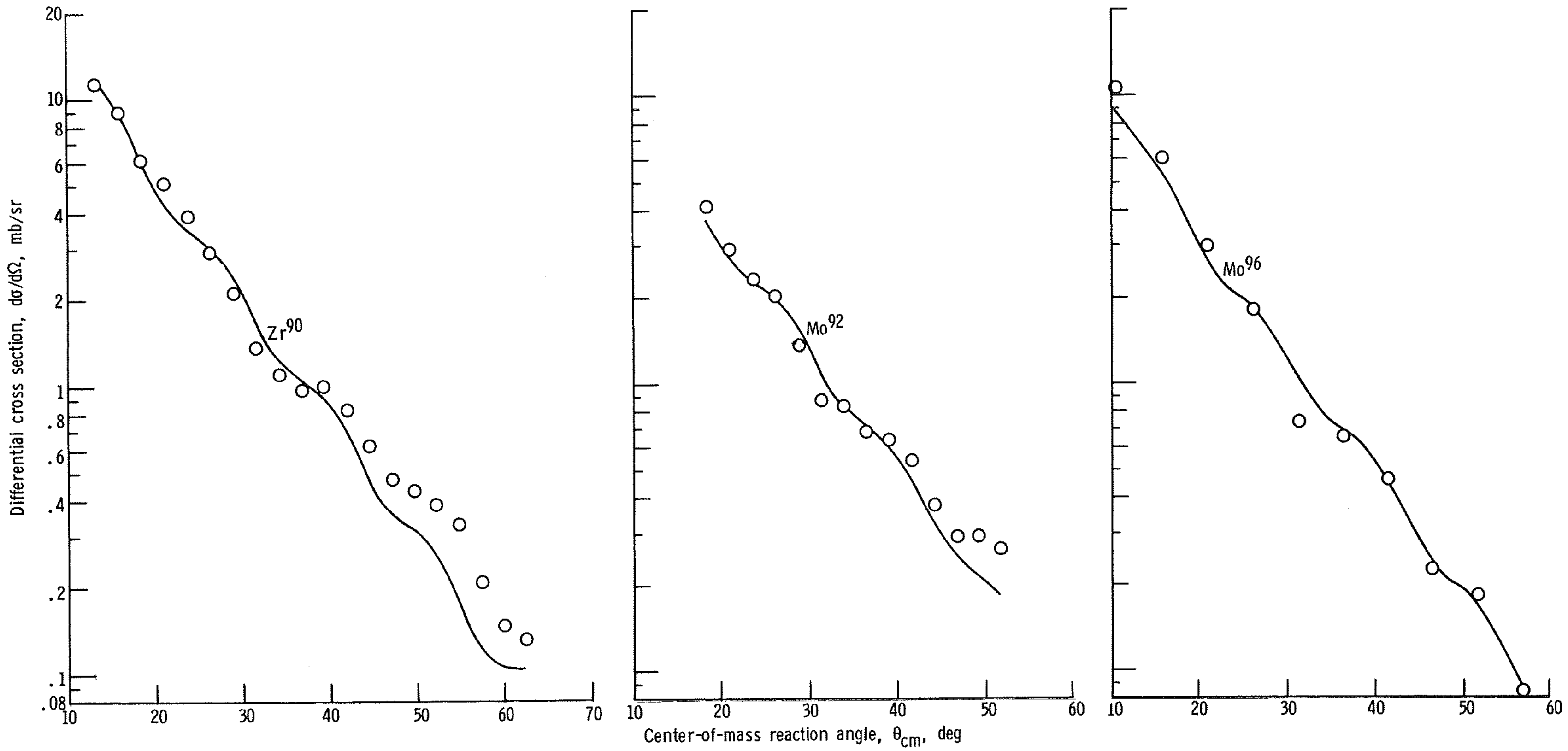

Figure 4. - Angular distributions of cross sections for $Zr^{90}(\alpha, t)Nb^{91}$, $Mo^{92}(\alpha, t)Tc^{93}$, and $Mo^{96}(\alpha, t)Tc^{97}$. (The statistical error is smaller than the size of the data point representing the measurement.)

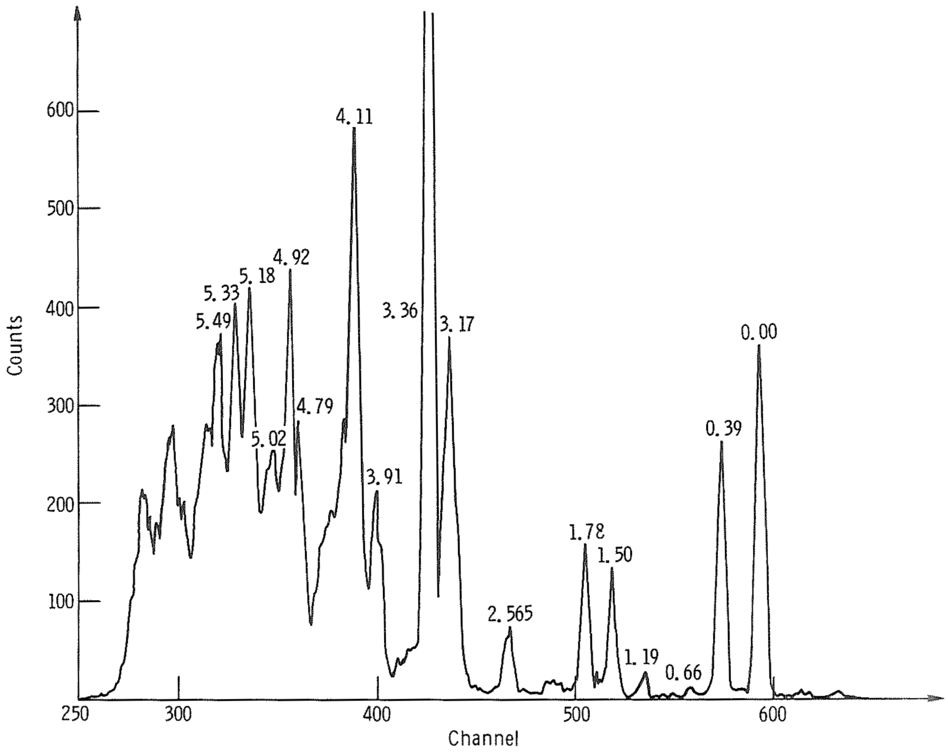

Figure 5. - Deuteron spectrum obtained at 30° for $Mo^{92}(He^3,d)Tc^{93}$ reaction at 18 MeV, as reported in reference 2.

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