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Experimental Study of the (d, t) Reaction on Even-Mass Mo Isotopes*

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The (d, t) reaction on $Mo^{92,94,96,98}$ was studied with the 23-MeV deuteron beam from the Argonne cyclotron. The experimental angular distributions of triton groups were compared with the distorted-wave Born approximation (DWBA) theory, and the l values and the spectroscopic factors were determined. The level structure of the Mo^{91} nucleus is very similar to that of Zr^{89}. Evidence for core excitation in Mo^{92} was found. The results for the other isotopes show that neutron orbits higher than the $2d_{5/2}$ shell are admixed in the ground-state configuration of these nuclei. These results are compared with previous data and with shell-model calculations.

I. INTRODUCTION

THE neutron structure of Mo isotopes has been the object of many experimental and theoretical papers. Hjorth and Cohen[1] studied the (d, p) and (d, t) reactions on even-even Mo isotopes, and interpreted their experimental results in terms of the pairing theory with the neutron-proton interaction. Unfortunately, in the work of Hjorth and Cohen only the ground state could be observed in the $Mo^{94}(d, t)Mo^{93}$ reaction, and the $Mo^{92}(d, t)Mo^{91}$ reaction was not studied. Recently, these experiments have been repeated[2] with better resolution.

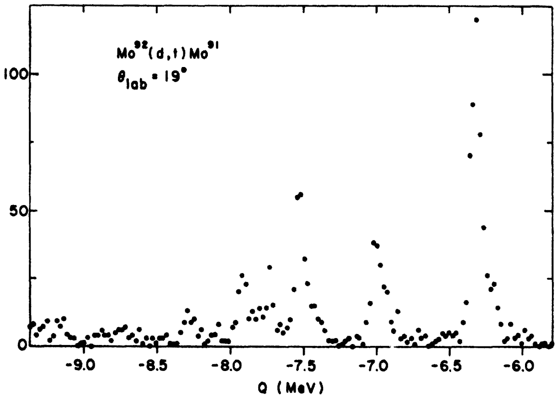

FIG. 1. Spectrum of tritons from the $Mo^{92}(d, t)Mo^{91}$ reaction.

The excited states of Mo^{97} were studied by Ajzenberg-Selove and Maxman.[3] In their work, proton groups from the $Mo^{96}(d, p)Mo^{97}$ reaction were analyzed by a magnetic spectrograph, and level energies in Mo^{97} were obtained. Moore *et al.*[4] studied the analog resonances in Tc isotopes and the results were compared with the (d, p) results of Hjorth and Cohen.[1] Excited states of Mo^{93} resulting from the $Mo^{92}(d, p)Mo^{93}$ reaction were investigated by use of a magnetic spectrograph[5] and by the neutron decay of isobaric-analog resonances[6] in the $Nb^{93}(p, n)Mo^{93}$ reaction. In the latter work, spins and parities of levels in Mo^{93} were assigned by comparing the intensities of neutron groups from different resonances with the calculated transmissions. Besides these reaction experiments, several studies[7–12] of β decays have yielded information on Mo isotopes.

However, there is very little experimental information about the level structure of Mo^{91}. Recently, the $Zr^{90}(p, d)Zr^{89}$ reaction was studied by Ball and Fulmer.[13] Levels at 0, 588, 1094, and 1450 keV in Zr^{89} were strongly excited and assigned to be the $1g_{9/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ hole states, respectively. Similar results were obtained from the studies[14,15] of the $Zr^{90}(He^3, \alpha)Zr^{89}$ reaction. The level structure of the Mo^{91} nucleus is expected to be similar to that of Zr^{89}, since both nuclei have the same neutron number, 49.

Several shell-model calculations have been done[16–18] for the nuclei in this mass region. However, only the $2p_{1/2}$ and $1g_{9/2}$ proton orbits and the $2d_{5/2}$ neutron orbits were taken into account in these calculations.

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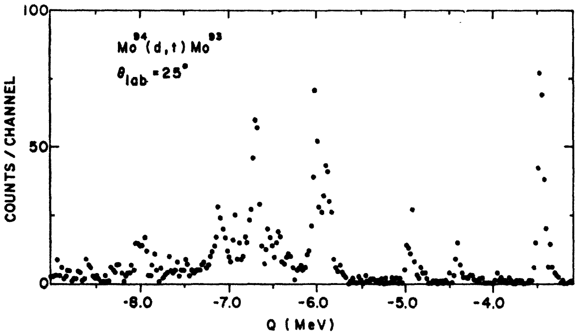

FIG. 2. Spectrum of tritons from the $Mo^{94}(d, t)Mo^{93}$ reaction.

It had already been pointed out[19] that such calculations might be inadequate because very-low-lying states with large $2p_{3/2}$ and $1f_{5/2}$ proton-hole strengths were observed[19,20] in the (d, He^3) reaction on even-even Zr and Mo isotopes. Neutron particle and hole strengths from higher orbits than $2d_{5/2}$ were also observed[1,21] in the (d, p) and (d, t) reactions on Zr and Mo isotopes. In spite of these experimental observations, however, the shell-model calculations with these oversimplified assumptions do, in general, reproduce the properties of nuclei in this region fairly well.

In contrast to the rather abundant experimental data on the (d, p) reaction, data on the (d, t) reaction are relatively scarce. Hence, it appeared worthwhile to reinvestigate the neutron pickup reaction on Mo isotopes, since much information on the levels of these nuclei has been accumulated since the experiment of Hjorth and Cohen. In this paper the results of the (d, t) reactions on $Mo^{92,94,96,98}$ are reported.

II. EXPERIMENTAL PROCEDURES AND ANALYSIS

In this study, performed with the 60-in. scattering chamber,[22] the reaction was induced by the 23-MeV deuteron beam from the Argonne cyclotron. The tritons were detected by a (dE/dx)-E telescope which consisted of surface-barrier silicon detectors. Self-supporting metallic Mo foils, usually 500–1000 $\mu g/cm^2$ thick and enriched to 93–99%, were used. Typical spectra obtained are shown in Figs. 1–4. The over-all resolution width was about 80–100 keV, mainly due to the target thickness. The peak-shape fitting program was used to analyze spectra when it was necessary. Uncertainties in the energies obtained are about 30 keV. The absolute cross sections were estimated by comparing the angular distributions of the elastically scattered deuterons with the calculated angular distributions from the optical-model-potential parameters given in Table I. These parameters were obtained from the analysis[23] of the elastic scattering of deuterons on Fe^{54} between 12 and 18 MeV. Uncertainties in the absolute cross sections for the (d, t) reaction are about 25%.

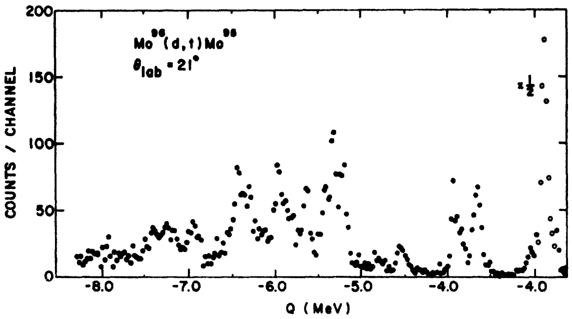

FIG. 3. Spectrum of tritons from the $Mo^{96}(d, t)Mo^{95}$ reaction.

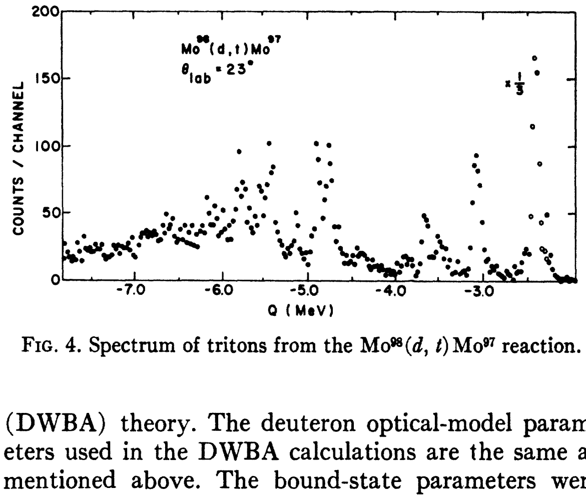

FIG. 4. Spectrum of tritons from the $Mo^{98}(d, t)Mo^{97}$ reaction.

The angular distributions of triton groups were measured between 13° and 33° (lab) in 2° steps, and compared with the distorted-wave Born approximation (DWBA) theory. The deuteron optical-model parameters used in the DWBA calculations are the same as mentioned above. The bound-state parameters were $r_0=1.2$ F, $r_c=1.4$ F, $a=0.65$ F, and $\lambda_{so}=25$. A normalization factor[24] of 3.3 was used for the (d, t) reaction. No cutoff was used. In the analysis of the (d, He^3) reaction on Mo isotopes, the zero-range nonlocal calculation [with the local-energy approximation[25] and the nonlocalities $\beta(d)=0.54$ and $\beta(He^3)=0.2$] consistently gave spectroscopic factors which were close to the sum-rule limit. When the triton parameters were kept the same as the He^3 parameters used for the (d, He^3) reaction and the spectroscopic factors were calculated in the same way and with the same nonlocalities, the results for the ground state and the first excited state of Mo^{91} were about 90% of the sum-rule limit. However,

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TABLE I. Optical-model parameters used in the DWBA calculations.

Particle	V (MeV)	W (MeV)	r_0 (F)	a (F)	r_c (F)	r' (F)	a' (F)	W' (MeV)	V_{so} (MeV)
d	105	···	1.06	0.86	1.3	1.42	0.65	54	6.0
$t(1)$	173	18	1.14	0.723	1.4	1.55	0.8	···	···
$t(2)$	152	19.6	1.24	0.684	1.25	1.48	0.771	···	···

it was suggested by Hafele *et al.*[25] that the magnitude of the imaginary term of the optical potential is smaller for the triton than for the He^3 particle. Bassel[26] introduced an isospin-dependent surface-absorption term in the optical potential for a mass-3 particle. If one uses 1.55 instead of 1.65 F for the radius of the imaginary potential of a triton [$t(1)$ in Table I], the spectroscopic factors for the above-mentioned two states of Mo^{91} are about 70% of the sum-rule limit for the zero-range nonlocal calculation, 55% for the finite-range nonlocal calculation, 75% for the finite-range local calculation (range parameter 1.54 F in both finite-range cases), and 90% for the zero-range local calculation. The "150-MeV" triton parameters obtained by Hafele *et al.* [$t(2)$ in Table I] gave calculated cross sections 14% larger than before under all assumptions, and therefore the spectroscopic factors were 14% smaller. In all cases, calculated angular distributions and the relative cross sections for the different values of l and Q do not change appreciably in the angular range over which the experimental data were taken. Therefore, we assumed that this ambiguity in the spectroscopic factors comes from the over-all normalization and took the values obtained in a zero-range local calculation with the parameters $t(1)$ of Table I.

III. RESULTS AND COMPARISONS WITH OTHER DATA

A. Mo^{92} (*d*, *t*)Mo^{91} Reaction

The angular distributions for the $Mo^{92}(d, t)Mo^{91}$ reaction are shown in Fig. 5 together with the calculated curves. Table II summarizes these results and compares them with those from the $Zr^{90}(p, d)Zr^{89}$ reaction[13] and the $Zr^{90}(He^3, \alpha)Zr^{89}$ reaction.[14,15]

The ground state and the metastable state at 0.63 MeV were excited by an $l=4$ and an $l=1$ neutron pickup, respectively. They are presumed to be the $g_{9/2}$ and the $p_{1/2}$ neutron-hole states. The proton configuration of the ground state of Mo^{92} may be described[19] by the wave function

$$70\%[(p_{1/2})_0{}^2(g_{9/2})_0{}^2]+30\%[(g_{9/2})^4].$$

In other words, there are 2.6 protons in the $g_{9/2}$ orbit and 1.4 protons in the $p_{1/2}$ orbit. Then the sum of the spectroscopic factors for the $T_<$ states in Mo^{91} is 9.7 for the $g_{9/2}$ hole states and 1.8 for the $p_{1/2}$ hole states. The remarkable similarity between the level structure of Mo^{91} observed here and that of Zr^{89} suggests that the $g_{9/2}$ and $p_{1/2}$ strengths are almost exhausted by the ground state and the first excited state. The fact that no other state with $l=4$ strength was observed in the present experiment supports this conjecture. As discussed in Sec. II, the spectroscopic factors (Table II) obtained in a zero-range local calculation with the triton optical-model parameters $t(1)$ of Table I are about 90% of the sum-rule limit.

Another $l=1$ transfer leads to a level at 1.20 MeV, which is probably a $p_{3/2}$ hole state. The sum-rule limit of the $p_{3/2}$ strength in Mo^{91} is 3.6 if the $p_{3/2}$ proton orbit is filled. The spectroscopic factor for the 1.20-MeV state observed experimentally is 2.1; this is to be compared with the value 2.4 for the spectroscopic factor of the 1.094-MeV state in Zr^{89}. Both states carry roughly 60% of the total $p_{3/2}$ strength.

A transition to a state at 1.58 MeV was assigned to be an $l=3$, most likely a $1f_{5/2}$ neutron pickup. Its energy is again very close to the energy (1.450 MeV) of the $\frac{5}{2}^-$ state in Zr^{89}. If this is a $\frac{5}{2}^-$ state, it contains approximately half of the total $f_{5/2}$ strength.

A weak transition with an $l=2$ angular distribution was observed at 1.41 MeV; it probably corresponds to a $2d_{5/2}$ neutron pickup. This indicates that there is a weak core excitation in the Mo^{92} nucleus. Such a core excitation was also found in the $Zr^{90}(p, d)Zr^{89}$ reaction by Ball and Fulmer.[13] They interpreted the transition to the 1.626-MeV state in Zr^{89} as a pickup of one of a pair of $2d_{5/2}$ neutrons present in the ground state of Zr^{90} in the form of a two-particle two-hole excitation.

B. Mo^{94} (*d*, *t*)Mo^{93} Reaction

In the work of Hjorth and Cohen,[1] only the ground state was observed in the $Mo^{94}(d, t)Mo^{93}$ reaction. Six strong peaks were seen in the present work, one of which is probably a doublet. The angular distributions are shown in Fig. 6, and in Table III the results are summarized and compared with the previous (d, t) data of Hjorth and Cohen.[1] In Fig. 7, our observed levels in Mo^{93} are compared with the results from other reactions.

The ground state of Mo^{93} is known to be $\frac{5}{2}^+$, and the

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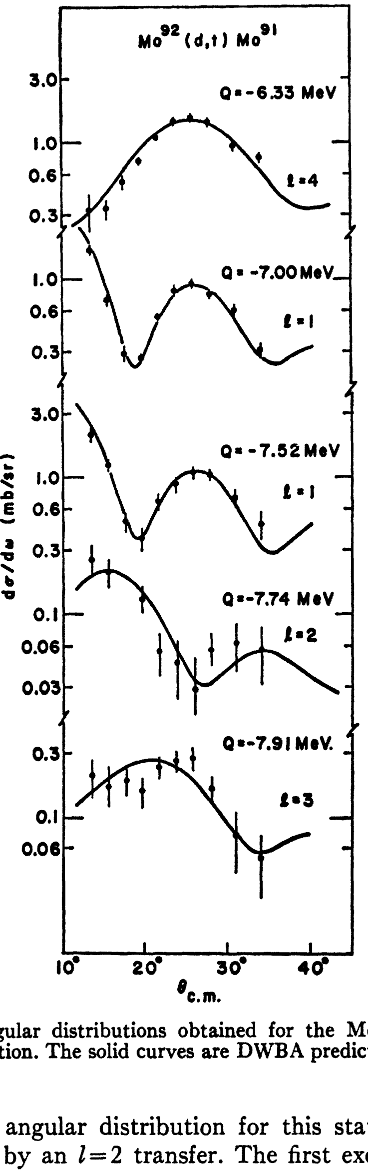

FIG. 5. Angular distributions obtained for the $Mo^{92}(d, t)Mo^{91}$ reaction. The solid curves are DWBA predictions.

measured angular distribution for this state is fitted very well by an $l=2$ transfer. The first excited state, which was assigned[1,6] to be $\frac{1}{2}^+$, was weakly excited in the present experiment. This indicated that there is an admixture of the $s_{1/2}{}^2$ component in the ground state of Mo^{94}. There was some indication that the $\frac{7}{2}^+$ state at 1.362 MeV is also excited in the (d, t) reaction, but the peaks were very weak and a satisfactory angular distribution could not be obtained.

A peak near 1.5 MeV probably includes contributions from the $\frac{5}{2}^+$ state observed[8] at 1.477 MeV in the β decay of Tc^{93} and the 1.486-MeV state which is strongly excited[1] by an $l=2$ transfer in the (d, p) experiment and therefore assigned to be $\frac{5}{2}^+$. Moore *et al.*[4] observed an $l=2$ resonance at $E_p=5.89$ MeV ($E_x=1.51$ MeV in Mo^{93}) in the study of the analog resonances of Tc^{93}. Finckh and Jahnke[6] interpreted the results of the $Nb^{93}(p, n)Mo^{93}$ reaction by assuming a $\frac{5}{2}^+ + \frac{3}{2}^+ + \frac{7}{2}^+$ mixture for the neutron groups around 1.5 MeV. Our angular distribution of this group is fitted fairly well by a mixture of $l=2$ and $l=4$ neutron pickup. The dashed curves in Fig. 6 show the DWBA curves for separate components; the solid curve is the sum of these two. The present results show that there is an admixture of $d_{3/2}{}^2$ as well as $s_{1/2}{}^2$ components in the ground state of Mo^{94}.

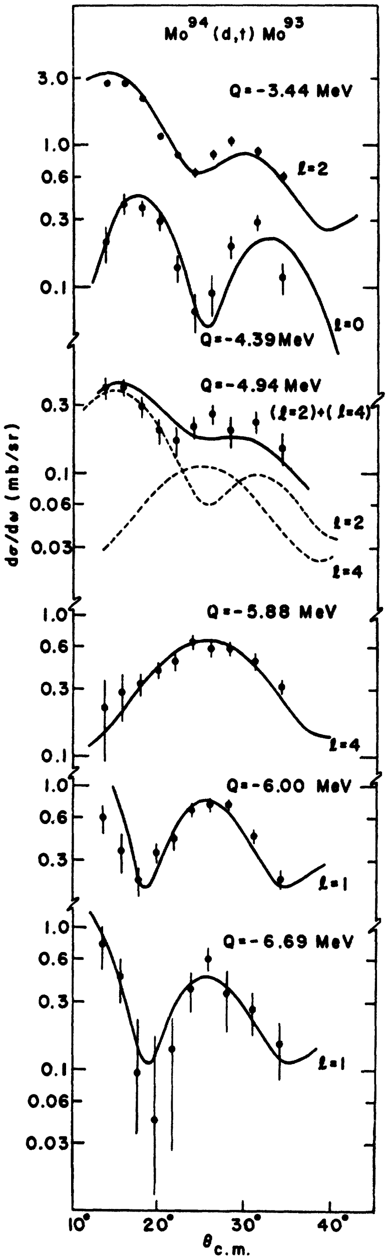

FIG. 6. Angular distributions obtained for the $Mo^{94}(d, t)Mo^{93}$ reaction. The solid curve for the transition with $Q=-4.94$ MeV is the sum of the two dashed curves.

TABLE II. Summary of the results for the $Mo^{92}(d,t)Mo^{91}$ reaction and comparison with the Zr^{89} data.

$Mo^{92}(d,t)Mo^{91}$ reaction Present results						Vervier[a]			$Zr^{90}(p,d)Zr^{89}$ and $Zr^{90}(He^3,\alpha)Zr^{89}$ Ohnuma and Yntema[b]			Preedom *et al.*[c]		
Q (MeV)	E_{exc} (MeV)	l	j^π	C^2S	Sum rule	E_{exc} (MeV)	j^π	C^2S	E_{exc} (MeV)	j^π	C^2S	E_{exc} (MeV)	j^π	C^2S
−6.33	0	4	$\frac{9}{2}^+$	8.7	9.7	0	$\frac{9}{2}^+$	9.6	0	$\frac{9}{2}^+$	10.0	0	$\frac{9}{2}^+$	3.41
−7.00	0.63	1	$\frac{1}{2}^-$	1.7	1.8	0.588	$\frac{1}{2}^-$	1.7	0.59	$(\frac{1}{2}^-)$	1.7	0.58	$(\frac{1}{2}^-)$	2.07
−7.53	1.20	1	$(\frac{3}{2}^-)$	2.1	3.6	1.094	$\frac{3}{2}^-$	2.4	1.07	$(\frac{3}{2}^-)$	2.6	1.08	$(\frac{3}{2}^-)$	2.41
−7.74	1.41	2	$(\frac{5}{2}^+)$	0.2	0	1.626	$\frac{5}{2}^+$	0.05						
−7.91	1.58	3	$(\frac{5}{2}^-)$	2.4	5.5	1.450	$\frac{5}{2}^-$	3.0	1.44	$(\frac{5}{2}^-)$	2.7	1.45	$(\frac{5}{2}^-)$	2.59
						1.513	$\frac{9}{2}^+$	0.33	(1.52)					
						1.740	$(\frac{3}{2}, \frac{1}{2})$	0.22 0.24	1.72	$(\frac{5}{2}^-)$	(0.4)	1.82	$(\frac{5}{2}^-)$	1.08
						1.866	$(\frac{3}{2}, \frac{1}{2})$	0.40 0.42	1.84	$(\frac{3}{2}^-)$	0.9			
						2.098	$\frac{5}{2}^-$	0.66	2.06	$(\frac{5}{2}^-)$	0.9			
									8.10	$\frac{1}{2}^-$	0.7			
									(9.60)	$(\frac{3}{2}^-)$	(1.3)			

[a] Reference 13.
[b] Reference 14.
[c] Reference 15.

There is a well-known metastable state at 2.43 MeV in Mo^{93}. This state is probably $(21/2)^+$. The existence of such a high-spin state was first explained by Auerbach and Talmi.[17] The shell-model calculations also predict the existence of a $\frac{9}{2}^+$ state in the vicinity of the $(21/2)^+$ state. Finckh and Jahnke found $\frac{9}{2}^+$ states at 2.401 and 2.532 MeV and possibly at 2.242 and 2.664 MeV. We observed a level at 2.44 MeV to be excited by an $l=4$ transfer. This state must be $\frac{9}{2}^+$, since it is very unlikely that such a strong $g_{7/2}$ component is admixed in the ground state of Mo^{94}. However, this state does not necessarily correspond to any theoretical prediction; a Sr^{88} core was assumed in the theoretical calculations and $g_{9/2}$ neutron-hole configurations were not taken into account, but the experiment shows that this state has a large component of such a hole configuration.

TABLE III. Summary of the results for the $Mo^{94}(d,t)Mo^{93}$ reaction and comparison with the previous data of Hjorth and Cohen.[a]

Present results					Hjorth and Cohen		
Q (MeV)	E_{exc} (MeV)	l	j^π	C^2S	E_{exc} (MeV)	j^π	C^2S
−3.44	0	2	$\frac{5}{2}^+$	1.1	0	$\frac{5}{2}^+$	2.29
−4.39	0.95	0	$\frac{1}{2}^+$	0.1			
−4.94	1.50	4	$\frac{9}{2}^+$	(0.5)			
		2	$\frac{3}{2}^+$	(0.2)			
−5.88	2.44	4	$\frac{9}{2}^+$	3.5			
−6.00	2.56	1	$(\frac{1}{2}^-)$	0.9			
−6.69	3.25	1	$(\frac{1}{2}^-)$	1.0			

[a] Reference 1.

Two other states were strongly excited in the present experiment. One is at 2.56 and the other at 3.25 MeV; both are fitted by $l=1$ transfer. They are probably $p_{1/2}$ hole states which were not predicted by the calculations nor observed in the (d,p) experiments. Alexander and Scharf-Goldhaber[8] found a $(\frac{1}{2}^-, \frac{3}{2}^-)$ state at 2.645 MeV in their study of the β decay of the isomer of Tc^{93}, and Finckh and Jahnke assigned $\frac{3}{2}^-$ to a state at 2.639 MeV, which is likely to be the one found in the β decay.

C. Mo^{96} $(d,t)Mo^{95}$ Reaction

The angular distributions for the $Mo^{96}(d,t)$ reaction are shown in Fig. 8. A summary of the results and a comparison with the (d,t) data of Hjorth and Cohen[1] are given in Table IV. The comparisons with the various experiments are given in Fig. 9.

The ground state was strongly excited and its angular distribution shows the typical $l=2$ character. This is consistent with the $\frac{5}{2}^+$ assignments[7] for this state. The first excited state was not seen in the (d,p) and (d,t) experiments of Hjorth and Cohen.[1] It is known[7] to be $\frac{3}{2}^+$ and its energies were well reproduced[16,18] by the shell-model calculations. According to the wave function given by Bhatt and Ball,[16] the predominant component of this state is $(d_{5/2}{}^3)_{3/2}$. In the present experiment the first excited state was weakly excited. The angular

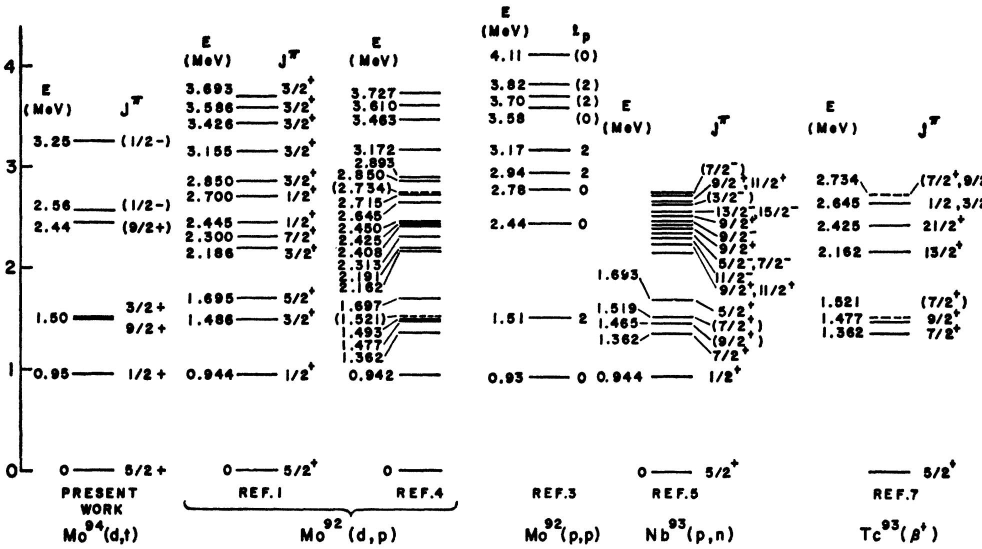

FIG. 7. Comparison of levels in Mo^{93} with previous results.

distribution for this state can be fitted by an $l=2$ DWBA curve, although the statistics are not very good. This fact may indicate that the excitation of this state is not a secondary process and the $d_{3/2}$ component is present both in the ground state of Mo^{96} and in the first excited state of Mo^{95}.

The angular distribution for a peak at 0.79 MeV can be fitted either by an $l=0$ or by an $l=2$ pickup. It is known[7,11] that there are many states in this region. Hjorth and Cohen[1] observed unresolved $l=0$ and $l=2$ transitions at 0.806 MeV in the $\mathrm{Mo}^{94}(d,p)\mathrm{Mo}^{95}$ reaction, and states at 0.79 and 0.87 MeV in the $\mathrm{Mo}^{96}(d,t)\mathrm{Mo}^{95}$ reaction. They interpreted the $l=2$ transition in the (d,p) reaction as due to $d_{3/2}$ neutron stripping. It is not clear whether one or both of those states are excited in the present experiment. In any case, the present results again indicate the presence of either an $s_{1/2}$ or a $d_{3/2}$ component or both in the ground state of Mo^{96}.

Two $l=2$ transitions to the states at 0.94 and 1.63 MeV and an $l=0$ transition to the state at 1.06 MeV probably correspond to those Hjorth and Cohen[1] observed at 0.970, 1.63, and 1.055 MeV, respectively, in the $\mathrm{Mo}^{94}(d,p)\mathrm{Mo}^{95}$ reaction and at 0.99, 1.63 and 1.09 MeV in the $\mathrm{Mo}^{96}(d,t)\mathrm{Mo}^{95}$ reaction. Weak transitions to states at 1.20 and 1.44 MeV in the $\mathrm{Mo}^{96}(d,t)\mathrm{Mo}^{95}$ reaction were reported in the latter paper, but these transitions are not seen in our work.

Besides these peaks, many triton groups to higher states were observed. Six strong transitions could be analyzed. Four of these are fitted by $l=1$ transfers and are tentatively assigned to be $2p_{1/2}$ neutron pickups. The other two groups show $l=4$ angular distributions and are presumably $1g_{9/2}$ neutron pickups. Three probable $l=1$ transitions were observed in the (d,p) work of Hjorth and Cohen.[1] The excitation energies of these states were 2.39, 2.62, and 3.150 MeV. The first and the last of these may be the 2.35- and 3.11-MeV states observed in the present experiment.

TABLE IV. Summary of the results for the $\mathrm{Mo}^{96}(d,t)\mathrm{Mo}^{95}$ reaction and comparison with the previous data of Hjorth and Cohen.[a]

Present results					Hjorth and Cohen		
Q (MeV)	E_{exc} (MeV)	l	j^π	C^2S	E_{exc} (MeV)	j^π	C^2S
−2.90	0	2	$\frac{5}{2}^+$	1.7	0	$\frac{5}{2}^+$	3.90
−3.09	0.19	2	$\frac{3}{2}^+$	0.1			
−3.69	0.79	2	$(\frac{3}{2}^+)$	0.5	0.79	$\frac{3}{2}^+$	0.230
		0	$\frac{1}{2}^+$	0.2	0.87	$\frac{1}{2}^+$	0.097
−3.84	0.94	2	$(\frac{5}{2}^+)$	0.2	0.99	$\frac{5}{2}^+$	0.193
−3.96	1.06	0	$\frac{1}{2}^+$	0.2	1.09	$\frac{1}{2}^+$	0.174
					1.20	$\frac{1}{2}^+$	0.097
					1.44	$\frac{5}{2}^+$	0.088
−4.57	1.67	2	$(\frac{5}{2}^+)$	0.1	1.63	$\frac{5}{2}^+$	0.157
−5.25	2.35	1	$(\frac{1}{2}^-)$	0.5			
−5.36	2.46	4	$(\frac{9}{2}^+)$	2.1			
−5.47	2.57	4	$(\frac{9}{2}^+)$	1.3			
−5.68	2.78	1	$(\frac{1}{2}^-)$	0.3			
−6.01	3.11	1	$(\frac{1}{2}^-)$	0.2			
−6.38	3.48	1	$(\frac{1}{2}^-)$	0.2			

[a] Reference 1.

D. Mo^{98} (*d*, *t*)Mo^{97} Reaction

The angular distributions for this reaction are shown in Fig. 10. The results are summarized and compared with those of Hjorth and Cohen[1] in Table V. The information about the level structure of the Mo^{97} nucleus from various sources is collected in Fig. 11.

The ground state of Mo^{97} is well known to be $\frac{5}{2}^+$, and the measured angular distribution for this state is well fitted by an $l=2$ transfer. Hjorth and Cohen[1] concluded that there are three states at 0.699 MeV and they are excited by $l=0$, 2, and 4 neutron transfers in the $\mathrm{Mo}^{96}(d,p)\mathrm{Mo}^{97}$ reaction. Ajzenberg-Selove and Maxman[3] analyzed proton groups from the same reaction and resolved two levels at 0.683 and 0.727 MeV.

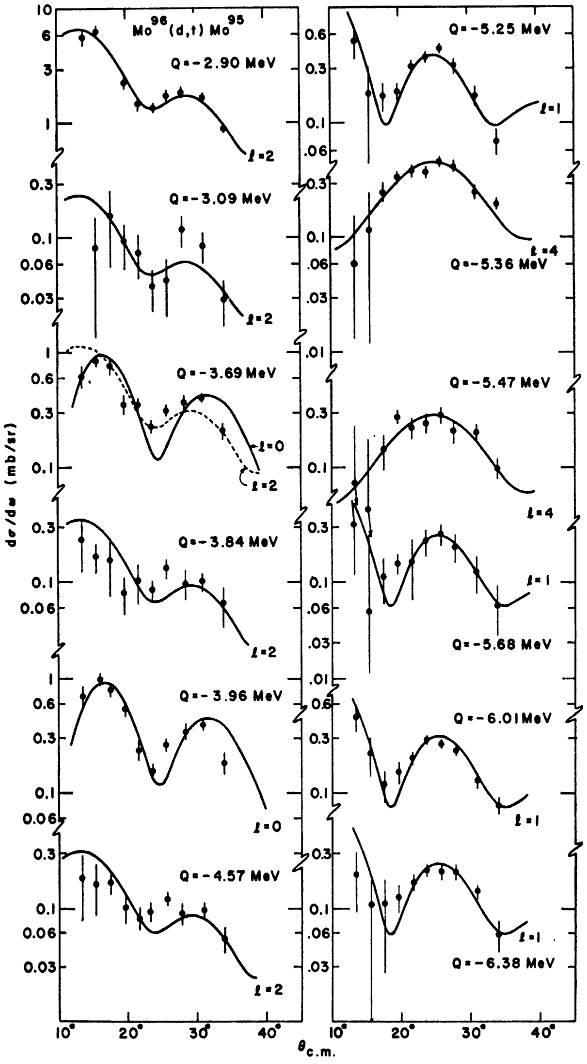

FIG. 8. Angular distributions obtained for the $\mathrm{Mo}^{96}(d,t)\mathrm{Mo}^{95}$ reaction. The solid and dashed curves show the DWBA predictions.

TABLE V. Summary of the results for the $\mathrm{Mo}^{98}(d,t)\mathrm{Mo}^{97}$ reaction and comparison with the previous data of Hjorth and Cohen.[a]

Present work					Hjorth and Cohen		
Q (MeV)	E_{exc} (MeV)	l	j^π	C^2S	E_{exc} (MeV)	j^π	C^2S
−2.39	0	2	$\frac{5}{2}^+$	2.1	0	$\frac{5}{2}^+$	5.82
−3.07	0.68	(0)	$(\frac{1}{2}^+)$	(0.3)	0.695	$(\frac{1}{2}^+)$	0.79
		(2)	$(\frac{3}{2}^+)$	(0.2)			
					0.900	$\frac{1}{2}^+$	0.082
−3.51	1.12	2	$(\frac{5}{2}^+)$	0.2	1.136	$\frac{5}{2}^+$	
−3.67	1.28	2	$(\frac{3}{2}^+)$	0.4	1.288	$\frac{3}{2}^+$	0.61
					1.56	$\frac{7}{2}^-$	
					1.71	$\frac{5}{2}^+$	0.25
					1.78	$\frac{7}{2}^+$	2.04
					2.06	$\frac{1}{2}^+$	0.059
					2.17	$\frac{3}{2}^+$	0.248
−4.79	2.40	1	$(\frac{1}{2}^-)$	0.4			
−4.92	2.53	4	$(\frac{9}{2}^+)$	1.5			
−5.22	2.83	1	$(\frac{1}{2}^-)$	0.2			

[a] Reference 1.

They observed that the 0.683-MeV level was strongly peaked in the forward direction. This observation agrees with the analog-resonance experiment by Moore *et al.*,[4] who found an $l_p=0$ resonance in Tc^{97} at an energy corresponding to an excitation $E_x=0.67$ MeV in Mo^{97}. Another resonance of an $l_p=2$ character, found in Tc^{97} in this vicinity, corresponds to an excitation energy of 0.76 MeV in Mo^{97}. Recently, Graeffe and Siivola[12] studied the β decay of Nb^{97} in detail. They assigned $(\frac{7}{2},\frac{9}{2})^+$ to a state at 658 keV, and also suggested the existence of a state at 720 keV. The shell-model calculation by Vervier[18] predicted three states in this region with spins $\frac{3}{2}^+$, $\frac{1}{2}^+$, and $\frac{3}{2}^+$. In the present (*d*, *t*) experiment, a sum of $l=0$ and $l=2$ distorted-wave curves gives the best fit for the angular distribution for the peak at 0.68 MeV as shown in Fig. 10. Therefore, this peak most likely corresponds to a doublet of $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states. However, the possibility that there is a slight admixture of an $l=4$ transition in the angular distribution obtained here cannot be excluded.

The state near 900 keV, which Hjorth and Cohen[1] saw both in the (*d*, *p*) and in the (*d*, *t*) experiment, was not strongly excited in our work. Transitions to the states at 1.12 and 1.28 MeV can be fitted by $l=2$ neutron pickups. They possibly correspond to states that Hjorth and Cohen[1] observed at 1.136 and 1.28 MeV. They assigned $\frac{5}{2}^+$ and $\frac{3}{2}^+$, respectively, to these states. If that is correct, there is a strong $d_{3/2}$ component in the ground state of Mo^{98}.

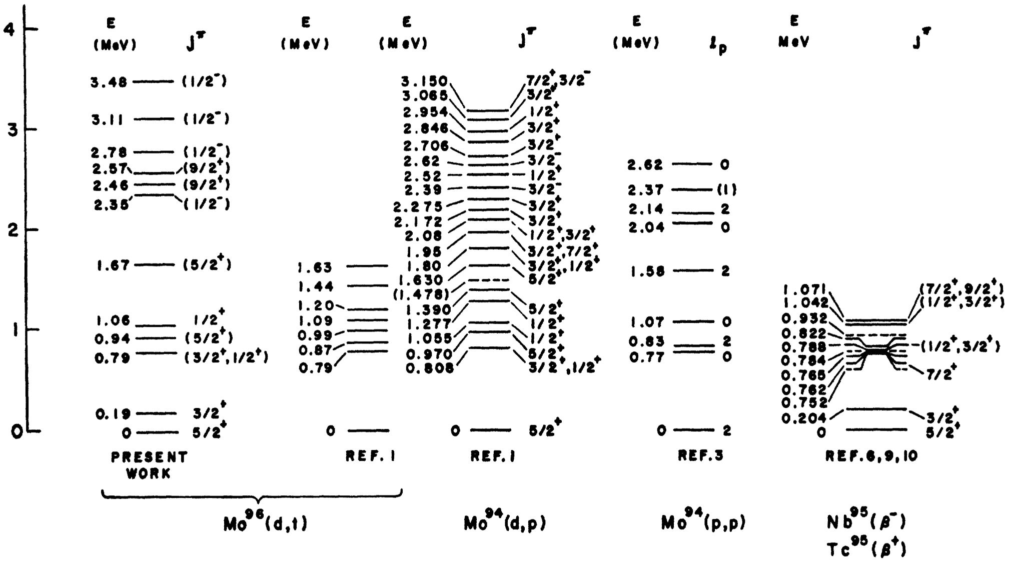

FIG. 9. Comparison of levels in Mo^{95} with previous results.

Although several states are reported between 1.3 and 2.4 MeV in Mo^{97}, none of them was excited strongly enough in the present experiment to allow detailed analysis. At least three states were seen in our spectra between 2.4 and 2.9 MeV. Two of them, the states at 2.40 and 2.83 MeV, can be fitted by $l=1$ DWBA curves and are tentatively assigned to $p_{1/2}$ hole states. Another one at 2.53 MeV is an $l=4$ transition and most likely goes to a $g_{9/2}$ hole state. Hjorth and Cohen[1] found possible $l=1$ transitions to states at 2.35 and 2.46 MeV in their (d, p) measurements. Levels at 2.52 and 2.561 MeV were reported in Ref. 3. The former, which was excited only weakly, might be the $g_{9/2}{}^+$ state observed here.

There is evidence that more states at higher energies were excited in the present (d, t) experiment, but the spectra were so complicated in that region that we could not analyze them.

IV. DISCUSSION AND CONCLUSIONS

The spectroscopic factors for Mo^{93}, Mo^{95}, and Mo^{97} obtained here are only about half those quoted in Ref. 1. The absolute cross sections may have errors of about 25% in this experiment, as mentioned earlier. The different assumptions in the DWBA calculations lead to different calculated cross sections, and consequently the spectroscopic factors vary by almost 50%. However, similar procedures[19] were followed and consistently gave spectroscopic factors close to the sum-rule limit in the case of the (d, He^3) reactions on Mo isotopes. The spectroscopic factors that we obtained for the $Mo^{92}(d, t)Mo^{91}$ reaction are close to the sum-rule limits, as discussed above. The sum of the (d, t) spectroscopic factors given in Ref. 1 exceeds the sum-rule limit in all cases. Moreover, it is very likely that the neutron strength is spread out among many levels and some of these are too weak to have been observed. Therefore, we believe that the spectroscopic factors obtained in the present work are closer to the correct values than are

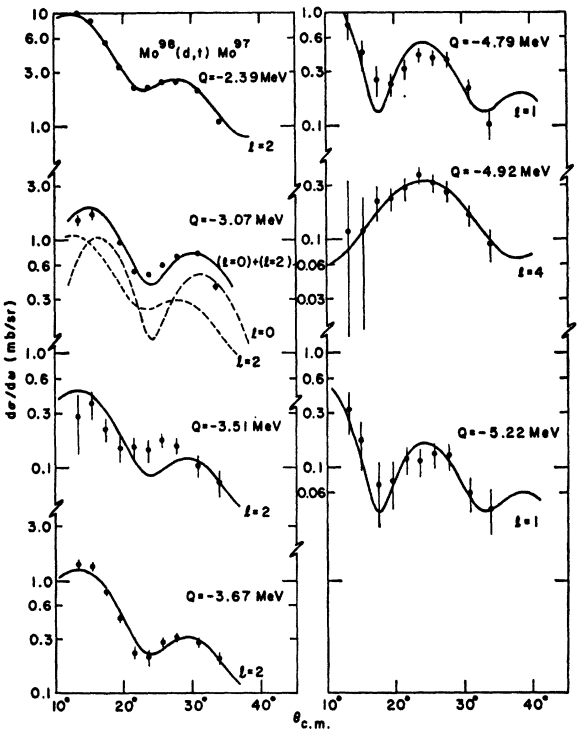

FIG. 10. Angular distributions obtained for the $Mo^{98}(d, t)Mo^{97}$ reaction. The solid curve for the transition with $Q=-3.07$ MeV represents the sum of the two dashed curves.

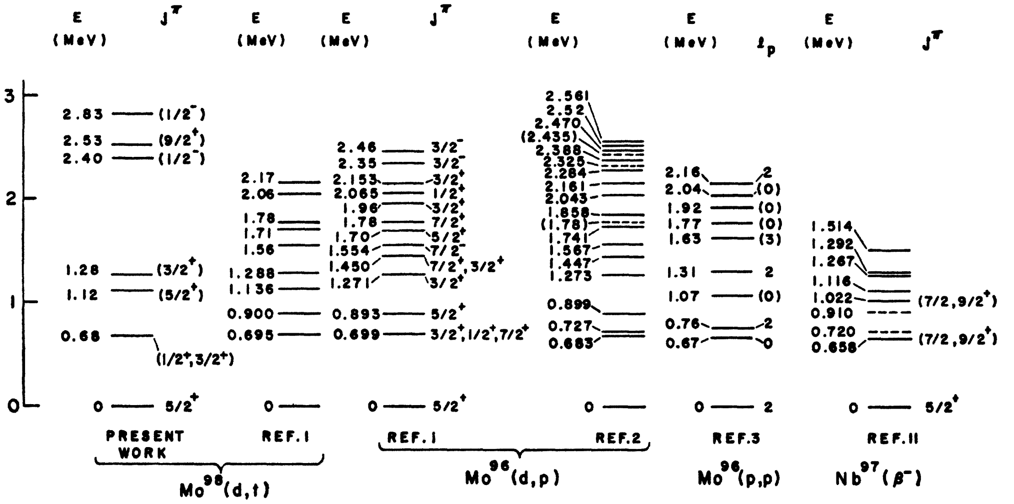

FIG. 11. Comparison of levels in Mo^{97} with previous results.

those obtained by Hjorth and Cohen. If that is the case, then in the present experiment roughly 70% of the total strength of the neutrons outside the $N=50$ core was observed for Mo^{94} and Mo^{96}, and roughly 50% for Mo^{98}. Several states observed in the previous measurement[1] were not seen here. If we are correct in our assumption that we have missed a significant number of levels, it would not be meaningful to obtain the centroid of the hole strengths or the occupation numbers of the target nuclei from the results of this experiment.

It is safe to say, however, that the neutron configurations of the ground states of Mo^{94}, Mo^{96}, and Mo^{98} are not pure $(2d_{5/2})^n$ configurations but contain considerable $2d_{3/2}$ and $3s_{1/2}$ components. This means that one has to take the higher neutron orbits as well as higher proton orbits[19] into account in discussions of the properties of these nuclei. Significant admixtures of higher neutron orbits have also been observed[13] in the ground state of Zr^{92}. So far, all shell-model calculations for nuclei in this region have included only the $p_{1/2}$ and $g_{9/2}$ orbits for protons and the $d_{5/2}$ orbit for the extra neutrons. Such calculations[16–18] could explain many properties, especially energy-level schemes, of these nuclei. The predicted spectroscopic factors for the neutron pickup reactions are available in some cases. Vervier[18] calculated $2d_{5/2}$ spectroscopic factors for the reactions studied in this paper except for the $Mo^{92}(d,t)Mo^{91}$ reaction. In each case the calculated results show that most of the strength is concentrated in the ground-state transition. The spectroscopic factors calculated from the wave functions of Mo^{94} and Mo^{93} given by Bhatt and Ball[16] are almost 2 for the ground state and 0.05 for the state predicted at 1.84 MeV. These predictions are in qualitative agreement with the present observation that the ground state carries the largest part of the $d_{5/2}$ strength in Mo^{93}, Mo^{95}, and Mo^{97}. Naturally, these calculations could not give any $d_{3/2}$ or $s_{1/2}$ strength in the (d,t) reaction. No $1g_{7/2}$ transition was observed in the present experiment. Most $l=4$ transitions were strong and therefore assigned to be $1g_{9/2}$ neutron pickups. In one case (the 1.50-MeV level in Mo^{93}), the spin of the state is known to be $\frac{9}{2}^+$. A few $1g_{7/2}$ transitions were found in the $Zr^{92}(p,d)Zr^{91}$ reaction[13] and $Zr(He^3,\alpha)$ reactions.[15] Cross sections for the $l=4$ pickups were much less than for pickups with the other l values, and weak $g_{7/2}$ transitions probably could not be detected in the present experiment.

The assumption of shell closure at $N=50$ seems very good, although a weak $l=2$ transition was found in the $Mo^{92}(d,t)Mo^{91}$ reaction. This transition may be a pickup of one of the $2d_{5/2}$ neutrons in the $N=50$ nucleus Mo^{92}.

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