PHYSICAL REVIEW C VOLUME 12, NUMBER 6 DECEMBER 1975

Neutron hole states of ^{99}Mo†

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(Received 7 August 1975)

The (p, d) and (d, t) reactions on ^{100}Mo have been used at bombarding energies of ~ 40 MeV to populate neutron hole states of ^{99}Mo. Excitation energies and angular distributions were measured for levels up to 4.25 MeV in excitation. A distorted wave Born approximation analysis was used to make l assignments and to obtain spectroscopic factors. Three distinct groups of weakly excited levels, one corresponding to $l = 4$ and two corresponding to $l = 1$, were observed lying above 2.15 MeV excitation. A hole-core-coupling model is used to predict the properties of ^{99}Mo and fair agreement with the experiment is obtained.

[NUCLEAR REACTIONS, NUCLEAR STRUCTURE ^{100}Mo(p, d), ^{100}Mo(d, t), $E \simeq 40$ MeV; measured $\sigma(\theta)$, ^{99}Mo levels, deduced l, S; calculated J, π, S, particle-core-coupling model.]

I. INTRODUCTION

Recent studies of proton and neutron configurations of odd-A nuclei in the mass region of 90–100 have revealed several interesting features for nuclear model calculations. Good agreement for level positions, spectroscopic factors, and electromagnetic transition probabilities for the low-lying positive-parity states of ^{97}Mo and negative-parity states of ^{95,97,99}Nb was obtained[1–3] using a quasiparticle core coupling model. Also, study of the ^{98}Mo$(p, d)^{97}$Mo reaction[1] revealed three distinct groups of weakly excited neutron hole states, one corresponding to an $l = 4$ transfer and two corresponding to an $l = 1$ transfer lying above 2.7 MeV excitation. Although these strengths were spread among many levels, the groups were resolved very nicely.

The information on the level structure of ^{99}Mo below 3 MeV has been compiled by Medsker.[4] Spectroscopic information on neutron hole states has been obtained up to about 1 MeV in excitation using the ^{100}Mo$(d, t)^{99}$Mo reaction,[5,6] and l assignments have been made for a few more levels up to 2.11 MeV by Ishimatsu *et al.*[7] with the (p, d) reaction. In the present work, nuclear structure information is obtained for levels up to 4.25 MeV excitation using the ^{100}Mo$(p, d)^{99}$Mo reaction. As a further check on this work, (d, t) data were also taken at a few angles. The results are compared with previous experimental work and with the theoretical predictions of a quasiparticle core-coupling model.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The details of the experimental set up and data analysis have been described elsewhere.[8] A self-supporting Mo foil, enriched to 95.9% in ^{100}Mo, was bombarded with 38.6 MeV protons and 40.6 MeV deuterons accelerated by the Texas A&M University cyclotron. The foil thickness (0.599 mg/cm^2) was determined by weighing and checked using the energy loss of α particles from an ^{241}Am source. Two silicon detector telescopes spaced 5° apart were used simultaneously for the (p, d) reaction to reduce data acquisition time and selected data points were checked by measurement with both systems. The detector telescopes consisted of 700 μm(ΔE), 3 mm (E), and 2 mm (veto) detectors for the forward stack and 700 μm (ΔE), 3 mm (E), and 1 mm (veto) detectors for the other stack. The telescope for the (d, t) studies consisted of 500 μm (ΔE), 3 mm (E), and 1.5 mm (veto) detectors. The veto detectors were used to eliminate pulses due to elastically scattered particles. The overall resolution obtained was about 50 and 60 keV for the outgoing deuterons and tritons, respectively. Deuteron and triton spectra, shown up to an excitation energy of about 5 MeV in Fig. 1, actually extend up to about 16 MeV in order to extract information on the isobaric analog states, which are the subject of a future communication. Due to the high density of levels above 2 MeV, a multipeak fitting program, described previously,[1] was used in analyzing the spectra.

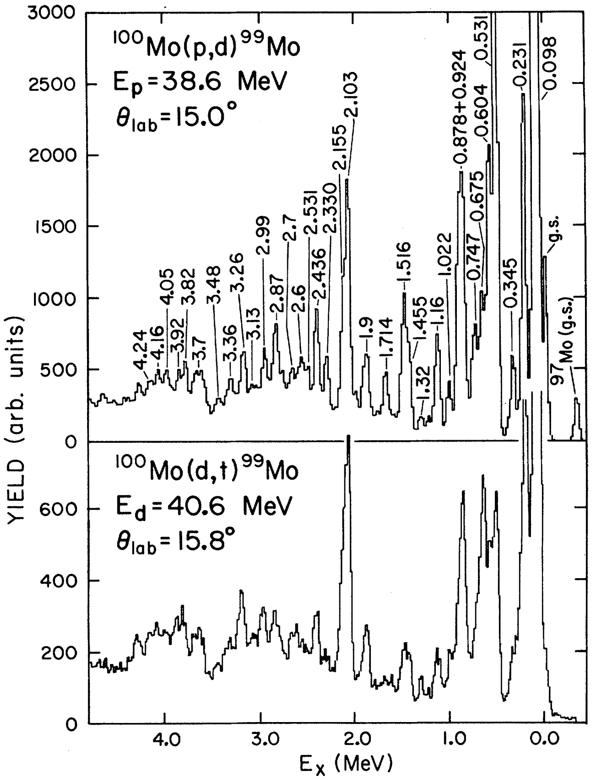

FIG. 1. The spectra of the ^{100}Mo(p, d)^{99}Mo and ^{100}Mo-(d, t)^{99}Mo reactions. The excitation energies of observed states are indicated in MeV. Some of the weak states at this angle are not indicated.

Distorted-wave-Born-approximation (DWBA) calculations were performed with the computer code DWUCK[9] using the parameters listed in Table I. The calculated and experimental cross sections are related by

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}}=\frac{NC^2S}{2J+1}\left(\frac{d\sigma}{d\Omega}\right)_{\text{DW}}\,, \tag{1}$$

where J is the transferred angular momentum, N is the normalization constant determined from the internal structure of the projectiles, and C^2S is the spectroscopic factor. We have used a value of $N=2.54$ for the (p, d) reaction and 3.33 for the (d, t) reaction. Angular distributions for 53 groups kinetically identified with the (p, d) reaction for laboratory angles from 7.5° to 42.5° are shown in Figs. 2–5 along with DWBA predictions. The known $\frac{1}{2}^+$ ground state could not be fitted well with an $l=0$ prediction. A similar difficulty was encountered for the known $\frac{1}{2}^+$ states of ^{97}Mo populated by the ^{98}Mo(p, d)^{97}Mo reaction.[1] The state at 0.878 MeV could be best fitted by a mixture of $l=2$ and 4 transfers. The rest of the levels are fitted reasonably well by single l transfers except for the states at 3.260, 3.707, and 3.918 MeV where the scatter in the data is fairly large. In the higher excitation region ($E_x \gtrsim 3$ MeV) undoubtedly only the dominant strengths have been identified: for example, the small angle points for the $l=4$ levels (Fig. 5) at 3.483, 3.666, and 3.817 MeV are much higher than expected indicating the presence of unresolved weak levels of lower l (probably $l=1$). Angular distributions for some of the states populated by the (d, t) reaction are shown in Fig. 6. Although the data are somewhat sparse, the $\frac{1}{2}^+$ ground state is fitted very nicely by the DWBA prediction.

The information on energy levels, l value assignments, and spectroscopic factors obtained in the present study is summarized and compared with previous studies in Table II. The spectroscopic factors from the (p, d) and (d, t) reactions are in reasonable agreement. In general, our spectroscopic factors are lower than those obtained in (d, t) studies at the University of Pittsburgh,[5, 6] although the relative values are in satisfactory agreement. There was a similar disagreement in normalization between our ^{98}Mo-(p, d)^{97}Mo reaction spectroscopic factors[1] and those of Ref. 5, although our results were in excellent agreement with those obtained by Ohnuma and Yntema.[13] Also, the sum of the ^{100}Mo(d, t)^{99}Mo spectroscopic factors given in Refs. 5 and 6 exceed the sum rule limits, whereas ours do not. It is

TABLE I. Optical-model and finite-range nonlocal (FRNL) parameters used in DWBA calculations (in MeV fm).

Particle	V	r_0	a	W	$4W_D$	r_I	a_I	r_c	V_{so}	r_{so}	a_{so}	β[a]	R[b]
p[c]	49.11	1.17	0.75	5.84		1.32		1.3	24.8	1.01	0.75	0.85	
d[d]	100.8	1.099	0.835		53.64	1.344	0.747	1.3	6.53	1.099	0.835	0.54	0.695
t[e]	151.1	1.240	0.685	24.06		1.432	0.870					0.25	0.845
n		1.15	0.65				$\lambda_{so}=25$					0.85	

[a] Nonlocal parameter used in DWUCK.

[b] Finite-range parameters for the (p,d) and (d,t) reaction, respectively, used in DWUCK.

[c] Reference 10.

[d] Reference 11.

[e] Reference 12.

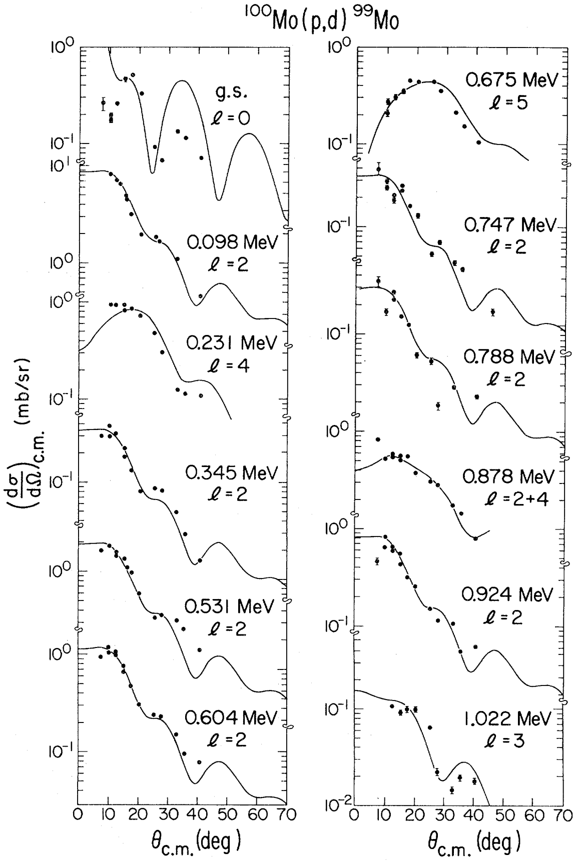

FIG. 2. Angular distributions for the ^{100}Mo(p, d)^{99}Mo reaction. The errors shown are statistical only. The curves are DWBA calculations for the l transfers indicated. The excitation energies are indicated.

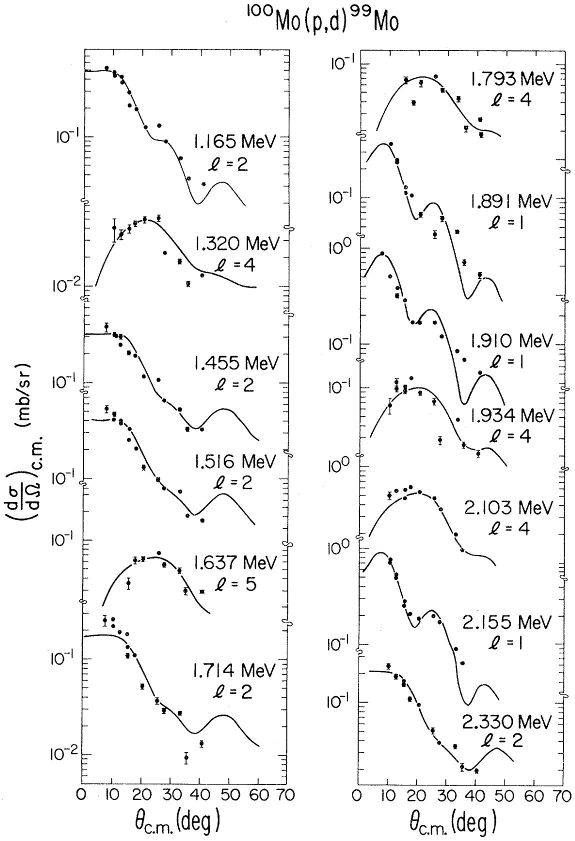

FIG. 3. Angular distributions for the ^{100}Mo(p, d)^{99}Mo reaction. See Fig. 2 caption.

very likely that some of the neutron strength is distributed among many weak levels that are not observed in these experiments.

The levels above 2.15 MeV fall into three groups, the first ranging from 2.15 to 3.0 MeV, corresponding primarily to $l=1$ transfer; the second ranging from 3.1 to 3.8 MeV, where most of the strength is from $l=4$ transfer; and the third from 3.8 to 4.3 MeV with an $l=1$ transfer. The strengths are distributed among many levels with individual states populated weakly. Although assignments for a few of the weak levels may not be definite, the over-all splitting of the levels into three distinct groups is apparent. Similar gross structure was observed for ^{97}Mo.[1]

As no spin assignments are made in the present study, definite allocation of $l=2$ and 4 strengths between the $2d_{3/2}$, $2d_{5/2}$, and $1g_{7/2}$, $1g_{9/2}$ orbitals, respectively, could not be made. However, Diehl *et al.*[6] used the ratio of $S(d,t)/S(d,p)$ to suggest the J^π values of a few low-lying levels which are shown in Table II. The $2d_{5/2}$ strength is spread in many levels, the first excited state at 0.098 MeV containing most of it. There appears to be a significant mixing of $3s_{1/2}$, $2d_{3/2}$, $2d_{5/2}$, and $1g_{7/2}$ orbitals in the ground state of ^{100}Mo with a small admixture of the $1h_{11/2}$ orbital also. The strongest $l=4$ levels at 0.231 and 2.103 MeV probably contain most of the observed $1g_{7/2}$ and $1g_{9/2}$ strengths, respectively, although insufficient $l=4$ strength is seen to exhaust the $lg_{9/2}$ strength alone. Many levels corresponding to $l=1$ transfer are observed, but the total strength for $2p$ levels is also not exhausted. The remainder of the $2p$ and $1g$ strength is expected to lie in unresolved levels at higher excitation.

III. STRUCTURE CALCULATIONS WITH THE PARTICLE-CORE COUPLING MODEL

The present study shows that the level structure of ^{99}Mo is very complicated. The level density is high and there is a large admixture of several orbitals in the ground state of ^{100}Mo. We have used[1-3] a particle-core coupling model[14] to predict properties of proton hole states of odd-A Nb isotopes and neutron hole states of ^{97}Mo, with

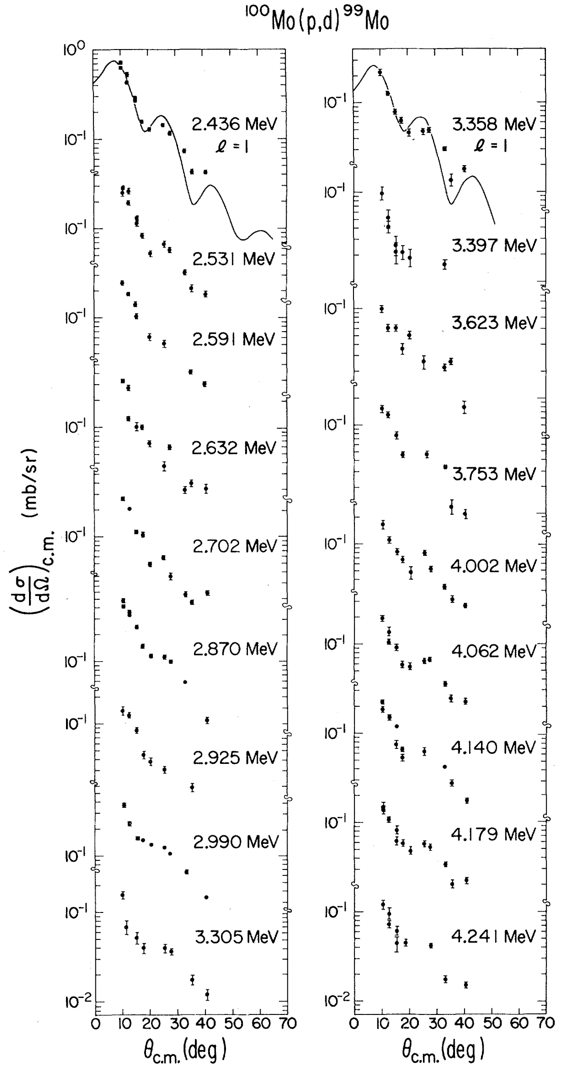

FIG. 4. Angular distributions for the ^{100}Mo(p, d)^{99}Mo reaction for states fitted by an $l = 1$ DWBA calculation. Sample DWBA curves are shown for two energies.

reasonable success. In this model, the simple particle states are coupled with the ground state and low-lying excited states of the core. We used this model to predict the positive-parity $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$, $\frac{9}{2}^+$, $\frac{11}{2}^+$, and $\frac{13}{2}^+$ levels of ^{99}Mo by coupling of the neutrons in $3s_{1/2}$, $2d_{3/2}$, $2d_{5/2}$, $1g_{7/2}$, and $1g_{9/2}$ orbitals with 0^+ ground state and the first 2^+ excited state of ^{100}Mo. Since the spectroscopic information indicates that these orbits are not completely filled, a quasiparticle formalism is used here. Quasiparticle energies and occupation numbers used in the present calculations are shown in Table III. The values of Hamiltonian parameters χ_1, χ_2, and ξ, defined in Ref. 14, were fixed and taken to be 0.45 MeV fm^{-2}, -0.33 MeV fm^{-2}, and -0.02 MeV, respectively. The strength of QQ term was taken to be the self-consistent value using the experimental transition probability $B(E2;\ 0^+ \rightarrow 2^+)$ from Ref. 15. The parameter χ_2 was obtained from an experimental value of the quadrupole moment of the 2^+ state of ^{100}Mo. Using the reorientation effects in Coulomb excitation, Nolan[16] obtained $Q_{2^+} = -0.39 \pm 0.08$ eb or -0.13 ± 0.08 eb for constructive 2_2^+ or destructive 2_2^+ interference, respectively. We used the former value in our calculations. The value of the parameter ϵ, the strength of the jj term, was taken to be the same as in our previous calculations.[1-3]

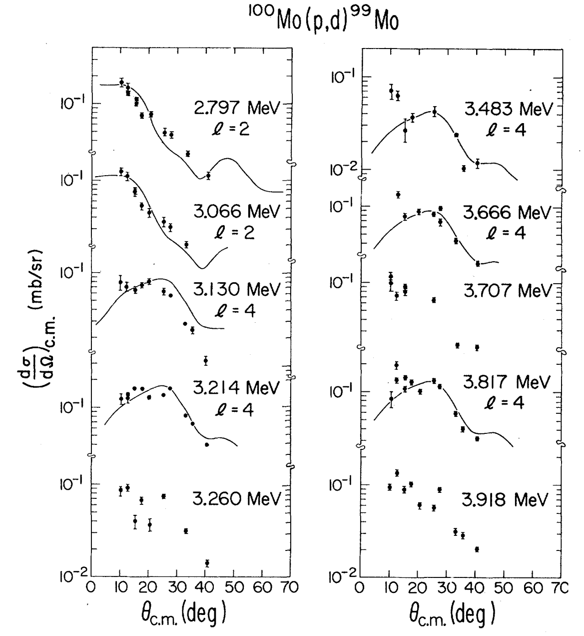

FIG. 5. Angular distributions for the ^{100}Mo(p, d)^{99}Mo reaction. See Fig. 2 caption.

Theoretical and experimental results for ^{99}Mo are shown in Fig. 7. Three $\frac{1}{2}^+$ levels are predicted, one of which corresponds to the ground state while the other two would be weakly excited in neutron pickup reactions. Three excited $\frac{1}{2}^+$ states are known in this energy region from other studies, two of which are reproduced by the calculations. The known $\frac{1}{2}^+$ level at 0.53 MeV is not reproduced here. The predicted number of levels, energies, and spectroscopic factors for low-lying $l = 2$ levels are in fair agreement with the data. The strongest $l = 4$ levels at 0.23 and 2.10 MeV are reproduced well. The experiment reveals that the $l = 4$ strength is fragmented into several more levels at higher excitation than predicted by the calculations. The over-all agreement of the $l = 4$ predictions with the data up to

TABLE II. Summary of experimental results for ^{99}Mo.

^{99}Mo*			C^2S_n				Nuclear data [a]	
E_x			Present work				E_x	
(MeV ± keV)	l_n	J^π [b]	(p,d)	(d,t)	(d,t) [c]	(d,t) [d]	(keV ± keV)	J^π
0.0	0	$\frac{1}{2}^{+}$	(0.30)	0.14	0.33	0.33	0.0	$\frac{1}{2}^{+}$
0.098 ± 2	2	$\frac{5}{2}^{+}$	1.84	1.80	2.89	2.98	98 ± 1	$(\frac{3}{2},\frac{5}{2})^{+}$
0.231 ± 4	4	$\frac{7}{2}^{+}$	1.39	1.75	2.26	0.90	236 ± 10	$(\frac{7}{2},\frac{9}{2})^{+}$
0.345 ± 5	2	$\frac{3}{2}^{+}$	0.06	0.16	0.13	0.30	352 ± 1	$(\frac{3}{2},\frac{5}{2})^{+}$
0.531 ± 6	0	$\frac{1}{2}^{+}$	small [e]		0.44		526 ± 10	$\frac{1}{2}^{+}$
	2	$\frac{3}{2}^{+}$	0.33	0.55	0.79	1.21	549 ± 1	$(\frac{3}{2},\frac{5}{2})^{+}$
0.604 ± 10	2	$\frac{5}{2}^{+}$	0.24	0.32	0.46		615 ± 1	$(\frac{3}{2},\frac{5}{2})^{+}$
0.675 ± 5	5	$\frac{11}{2}^{-}$	0.50	(1.2)	0.86	(2.43)	687 ± 5	$(\frac{9}{2},\frac{11}{2})^{-}$
0.747 ± 14	2	$\frac{5}{2}^{+}$	0.07	0.10				
					0.48		754 ± 10	$(\frac{5}{2},\frac{7}{2})^{-}$
0.788 ± 20	(2)	$\frac{3}{2}^{+}$	0.06	0.08	0.15	0.17	793 ± 1	$(\frac{3}{2},\frac{5}{2})^{+}$
0.878 ± 7	(2)	$\frac{3}{2}^{+}$	0.07	0.06	0.12		890 ± 10	$(\frac{3}{2},\frac{5}{2})^{+}$
	(4)	$\frac{9}{2}^{+}$	0.59	0.30				
					0.15		905 ± 1	$\frac{1}{2}^{+}$
							(913 ± 5)	
0.924 ± 12	2	$\frac{5}{2}^{+}$	0.15	0.22	0.29	0.85	945 ± 1	$(\frac{3}{2},\frac{5}{2})^{+}$
							952 ± 5	$(\frac{5}{2},\frac{7}{2})^{-}$
1.022 ± 20	(3)	$\frac{5}{2}^{-}$	0.26				1033 ± 5	$(\frac{1}{2},\frac{3}{2})^{-}$
1.165 ± 15	2	$\frac{5}{2}^{+}$	0.10	0.08			1150 ± 20	$(\frac{1}{2},\frac{3}{2})^{-}$
							(1190 ± 1)	
							(1209 ± 1)	
							1261 ± 5	$\frac{1}{2}^{+}$
1.320 ± 15	4	$\frac{7}{2}^{+}$	0.10					
							1391 ± 1	$(\frac{3}{2},\frac{5}{2})^{+}$
1.455 ± 10	2	$\frac{3}{2}^{+}$	0.10	0.10			(1453 ± 1)	
							(1475 ± 1)	
							1493 ± 5	$(\frac{3}{2},\frac{5}{2})^{+}$
1.516 ± 10	2	$\frac{3}{2}^{+}$	0.13	0.15			1548 ± 5	
1.637 ± 12	5	$\frac{11}{2}^{-}$	0.07					
							1672 ± 5	
1.714 ± 20	2	$\frac{3}{2}^{+}$	0.05	0.05			1722 ± 5	$(\frac{1}{2},\frac{3}{2})^{-}$
							1755 ± 5	$(\frac{3}{2},\frac{5}{2})^{+}$
1.793 ± 10	4	$\frac{7}{2}^{+}$	0.17	0.10				
							1812 ± 5	
							1845 ± 5	
1.891 ± 15	1	$\frac{1}{2}^{-}$	0.12	0.11				
1.910 ± 20	1	$\frac{1}{2}^{-}$	0.27				1920 ± 20	$(\frac{1}{2},\frac{3}{2})^{-}$
1.934 ± 12	4	$\frac{9}{2}^{+}$	0.19				1930 ± 5	$\frac{1}{2}^{+}$
							1948 ± 5	$\frac{1}{2}^{+}$
							1965 ± 5	$\frac{1}{2}^{+}$
2.103 ± 20	4	$\frac{9}{2}^{+}$	1.02	1.00			2110 ± 20	
2.155 ± 12	1	$\frac{1}{2}^{-}$	0.28	0.26			≃2200	
2.330 ± 10	2	$\frac{3}{2}^{+}$	0.063				≃2360	
2.436 ± 10	1	$\frac{1}{2}^{-}$	0.24	0.20			≃2430	
							≃2490	
2.531 ± 12	1	$\frac{1}{2}^{-}$	0.10				≃2540	

TABLE II *(Continued)*

^{99}Mo* E_x (MeV±keV)	l_n	J^{π} [b]	C^2S_n Present work (p, d)	C^2S_n Present work (d, t)	C^2S_n (d, t) [c]	C^2S_n (d, t) [d]	Nuclear data [a] E_x (keV±keV)	Nuclear data [a] J^{π}
2.591±12	1	$\frac{1}{2}^-$	0.09					
2.632±12	1	$\frac{1}{2}^-$	0.13				2641± 2	
2.702±12	1	$\frac{1}{2}^-$	0.10					
							2734± 2	
2.797±15	2	$\frac{5}{2}^+$	0.04				2791± 2	
2.870±15	1	$\frac{1}{2}^-$	0.17					
2.925±15	1	$\frac{1}{2}^-$	0.06				(2952± 2)	
2.990±15	(1)	$\frac{1}{2}^-$	0.14					
3.066±15	2	$\frac{3}{2}^+$	0.04					
3.130±15	(4)	$\frac{9}{2}^+$	0.15					
3.214±20	4	$\frac{9}{2}^+$	0.05					
3.260±20								
3.305±20	(1)	$\frac{1}{2}^-$	0.06					
3.358±20	1	$\frac{1}{2}^-$	0.08					
3.397±20	(1)	$\frac{1}{2}^-$	0.03					
3.483±20	4	$\frac{9}{2}^+$	0.08					
3.623±25	(1)	$\frac{1}{2}^-$	0.03					
3.666±20	4	$\frac{9}{2}^+$	0.21					
3.707±25								
3.753±20	1	$\frac{1}{2}^-$	0.07					
3.817±20	4	$\frac{9}{2}^+$	0.33					
3.918±25								
4.002±25	1	$\frac{3}{2}^-$	0.07					
4.062±25	1	$\frac{3}{2}^-$	0.08					
4.140±25	1	$\frac{3}{2}^-$	0.09					
4.179±25	1	$\frac{3}{2}^-$	0.06					
4.241±25	1	$\frac{3}{2}^-$	0.05					

[a] Reference 4.

[b] J^{π} values are those which have been used for the DWBA calculations; no assignment has been made. Assignments below 1 MeV have been taken from Ref. 6, except for 0.747 and 0.878 MeV states.

[c] Reference 6; spectroscopic factors listed are those which were obtained by DWUCK calculation including FRNL corrections.

[d] Reference 5.

[e] A mixture of $l=0$ and 2 was tried for this level. The data could be fitted by an $l=2$ transfer; the $l=0$ contribution would be small, if any.

2 MeV is fair.

The $l=1$ strength is also fragmented into many levels. One would need to couple several core states to the neutron states to reproduce such a large level density for $l=1$ and 4 states. This is illustrated in the present calculations as this simple model predicts a strong $\frac{9}{2}^+$ level at 4.8 MeV which contains about half of the sum rule strength. Coupling with more core states would fragment this strength into several states. However, such calculations would require more parameters.

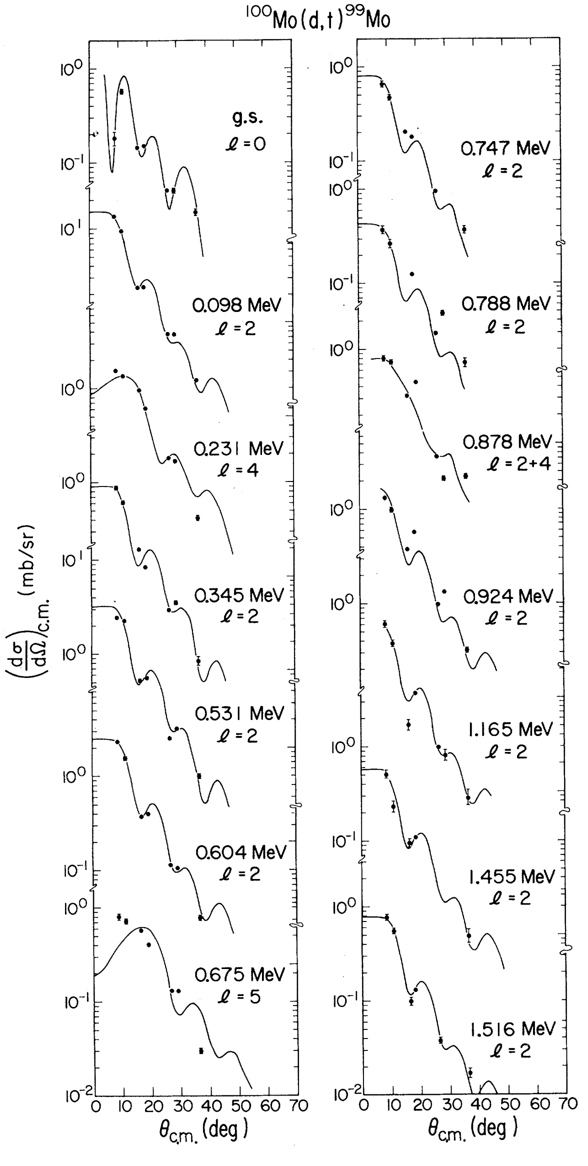

FIG. 6. Angular distributions for the ^{100}Mo$(d, t)^{99}$Mo reaction. See Fig. 2 caption.

TABLE III. Parameters used in ^{99}Mo calculations.

State	Energy (MeV)	V^2
$3s_{1/2}$	0.0	0.38
$2d_{3/2}$	0.6	0.56
$2d_{5/2}$	0.3	0.55
$1g_{7/2}$	0.5	0.33
$1g_{9/2}$	3.3	0.90

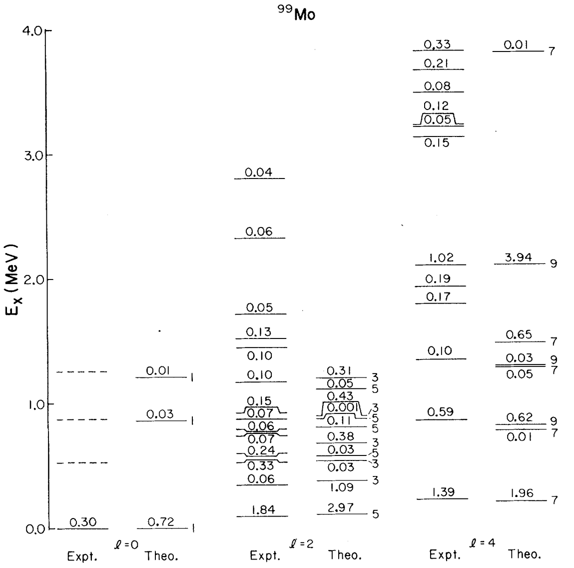

FIG. 7. Comparison of the experimentally observed $l = 0$, 2, and 4 energy levels with the theoretical predictions for ^{99}Mo. The experimental and calculated spectroscopic factors are indicated in the middle of the lines and the theoretical predictions for $2J$ are indicated on the right of the line. The dashed lines are experimental levels taken from other work.

IV. CONCLUSIONS

The (p, d) and (d, t) reactions have been used to excite the neutron hole states of ^{99}Mo. A DWBA analysis was used to make l assignments and to obtain spectroscopic factors for levels up to 4.3 MeV in excitation. The results obtained in the present study agreed well with previous studies, but many new levels above 2.1 MeV have been identified. Although most of the $l = 2$ strength is observed, only a fraction of the $l = 1$ and 4 strength is observed. The ground state of ^{100}Mo appears to contain a significant mixture of $3s_{1/2}$, $2d_{3/2}$, $2d_{5/2}$, and $1g_{7/2}$ orbitals.

A quasiparticle core-coupling model was used to predict the properties of ^{99}Mo. The calculated energy levels and spectroscopic factors are in reasonable agreement with the data for low-lying $l = 0$, 2, and 4 levels up to ~2 MeV in excitation. Since we couple only the ground and the first 2^+ states with the neutron states, this model is not capable of reproducing the levels at high excitation energies. The higher states are probably of a more complicated nature, perhaps involving contributions from higher phonons. However, it is rather interesting to find that such a simple-minded model is successful in reproducing the low-lying levels of ^{95,97,99}Nb and ^{97,99}Mo.

An interesting aspect of the present study is that the levels above 2.1 MeV can be divided into three distinct groups of weakly excited levels, one corresponding to mainly $l=4$ levels and two corresponding to mainly $l=1$ levels. These levels, along with other weakly excited unresolved levels at higher excitation, are being analyzed as groups to obtain some gross features. This could shed some light on the missing $l=1$, 3, and 4 strengths.

ACKNOWLEDGMENTS

The authors wish to thank Dr. T. Kishimoto for several discussions and R. Weber for his assistance in taking and analyzing the data.

[†] Work supported in part by the National Science Foundation and the Robert A. Welch Foundation.

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