PHYSICAL REVIEW C VOLUME 9, NUMBER 2 FEBRUARY 1974

^{96}Mo$(d, p)^{97}$Mo reaction*

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(Received 15 October 1973)

The ^{96}Mo$(d,p)^{97}$Mo reaction was studied with 16-MeV deuterons. Experimental angular distributions were analyzed by use of distorted-wave Born-approximation calculations to determine l values and spectroscopic strengths. The results are compared with previous data and the neutron configurations of ^{97}Mo are examined in comparison with neighboring molybdenum and zirconium nuclei.

[NUCLEAR REACTIONS ^{96}Mo$(d,p)^{97}$Mo, $E = 16$ MeV; measured $\sigma(E_p, \theta)$; ^{97}Mo deduced levels, l_n, G_{lj}.]

I. INTRODUCTION

Approximately 40 levels are known[1] in ^{97}Mo below 4 MeV excitation. Although about 30 J^π assignments were tentatively made, only 7 J^π were unambiguous. This is due in part to the poor resolution in the (p,d), (d,t), and (d,p) experiments. Recent studies of Coulomb excitation,[2] $(\alpha, n\gamma)$,[3] and $(\alpha, 3n\gamma)$[4] show that several low-lying doublets were unresolved in pickup and stripping reactions. The present improved measurements with the (d,p) reaction provide a more precise study of the levels in ^{97}Mo up to approximately 4 MeV excitation.

The low-lying levels in ^{97}Mo, with 42 protons and 55 neutrons, should be well described by configurations involving $(\nu d_{5/2})$, $(\nu g_{7/2})$, and $(\nu s_{1/2})$. The ground state of ^{97}Mo is known[1] to have $J^\pi = \frac{5}{2}^+$. Levels with $J^\pi = \frac{1}{2}^+$ have energies 888.2 and 2065 keV; however, the level at 679.6 keV is only tentatively assigned $\frac{1}{2}^+$. Levels with $J^\pi = \frac{7}{2}^+$ are at 657.92, 1024.53, and 1268.63 keV and several levels have the ambiguous $(\frac{7}{2}, \frac{9}{2})$ assignment. The present study attempts to confirm and elucidate spin and level assignments in ^{97}Mo.

II. EXPERIMENTAL PROCEDURE

A 16-MeV deuteron beam from the Argonne tandem Van de Graaff was used to obtain proton spectra at 15 angles between 8 and 58°. The outgoing protons were momentum-analyzed with a split-pole magnetic spectrograph, and spectra were recorded on Kodak NTB emulsion plates. The exposed plates were scanned by a computer-controlled plate scanner.[5] The target, which had been rolled to a thickness of approximately 200 μg/cm^2, was enriched to ~96% in ^{96}Mo and contamination peaks due to other Mo isotopes were negligible. A typical spectrum is shown in Fig. 1. The overall resolution of the system was 15 keV full width at half maximum and approximately 85 levels were identified up to 4144 keV. The triplet at 690 keV, previously unresolved in pickup and stripping re-

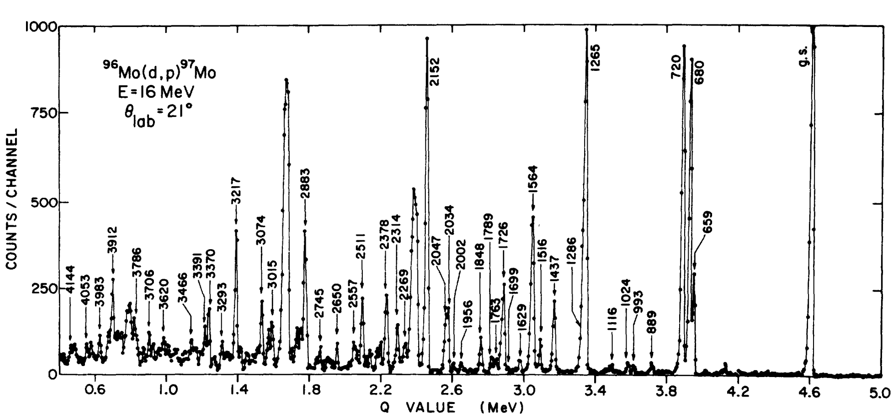

FIG. 1. Typical proton spectrum of the ^{96}Mo$(d,p)^{97}$Mo reaction at $\theta_{lab} = 21°$.

TABLE I. Optical-model parameters used in distorted-wave Born-approximation (DWBA) calculations of ^{96}Mo(d,p)^{97}Mo.

	d	p	Bound-state particle
V (MeV)	110.0	50.0	Adjusted
r_0 (fm)	1.06	1.25	1.20
a (fm)	0.86	0.62	0.70
W (MeV)	···	···	
W_D (MeV)	17.5	9.0	
r_0' (fm)	1.42	1.30	
a' (fm)	0.65	0.60	
r_c (fm)	1.32	1.25	
$V_{\text{s.o.}}$ (MeV)	6.0	0	$\lambda = 25$

actions, was identified in the present experiment.

The data were analyzed with the program AUTOFIT[6] in order to obtain excitation energies (±5 keV) and relative cross sections. The measured angular distributions were compared with distorted-wave calculations for which the optical-model parameters listed in Table I were used in the program DWUCK.[7] The deuteron parameters were taken from the (d, ^{3}He) studies of Ohnuma and Yntema[8] with the exception that the value of

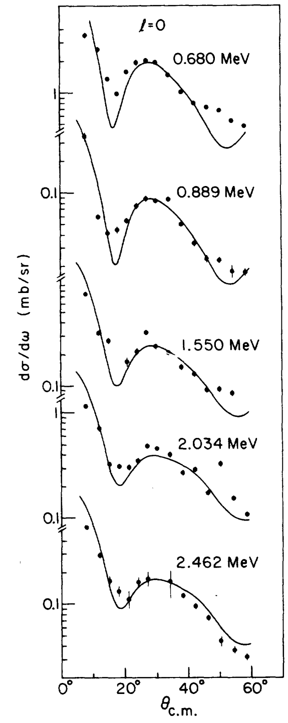

FIG. 3. Angular distributions for levels excited in the ^{96}Mo(d,p)^{97}Mo reaction. The solid lines are the DWBA calculations for $l_n = 0$ transfers.

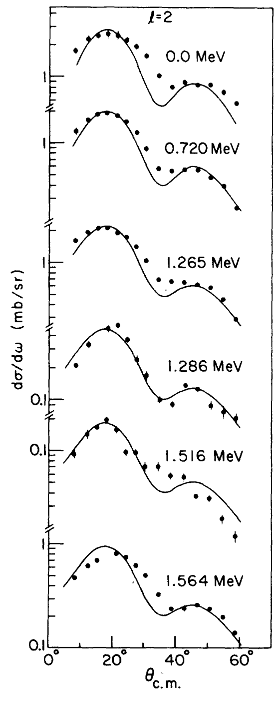

FIG. 2. Angular distributions of the protons leading to excited states in ^{97}Mo observed with the ^{96}Mo(d,p) reaction. The solid lines are the DWBA calculations for $l_n = 2$ transfers.

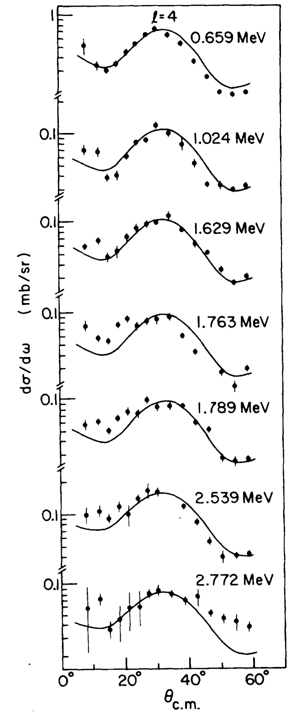

FIG. 4. Angular distributions for levels excited by $l_n = 4$ transfers in the ^{96}Mo(d,p)^{97}Mo reaction. The solid lines are DWBA calculations.

TABLE II. Present results for the ^{96}Mo$(d,p)^{97}$Mo reaction.

E_x (keV)	l_n	J^{π} [a]	G_{lj}
0	2	$\frac{5}{2}^{+}$	1.33
482 ?	(2)	$(\frac{3}{2}^{+})$	0.034
659	4	$\frac{7}{2}^{+}$	5.8
680	0	$\frac{1}{2}^{+}$	0.94
720	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	1.07
753	(2)	$(\frac{3}{2}^{+}, \frac{5}{2}^{+})$	(0.035)
795	(0)	$(\frac{1}{2}^{+})$	(0.012)
889	0	$\frac{1}{2}^{+}$	0.042
993	(2)	$(\frac{3}{2}^{+}, \frac{5}{2}^{+})$	0.031
1024	4	$\frac{7}{2}^{+}$	0.90
1093 ?			
1116	5	$(\frac{9}{2})^{-}$	0.36
1135 ?			
1265	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	1.08
1286	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.26
1437	5	$(\frac{11}{2})^{-}$	3.35
1516	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.095
1550	0	$\frac{1}{2}^{+}$	0.16
1564	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.39
1629	4	$(\frac{7}{2}, \frac{9}{2})^{+}$	0.76
1699	(4)	$(\frac{7}{2}^{+}, \frac{9}{2}^{+})$	(0.18)
1726 [b]	0 + 2 [c]	$\frac{1}{2}^{+} + (\frac{3}{2}, \frac{5}{2})^{+}$	(0.08 + 0.13)
1763	4	$(\frac{7}{2}, \frac{9}{2})^{+}$	0.56
1789	4	$(\frac{7}{2}, \frac{9}{2})^{+}$	0.56
1848	(0)	$(\frac{1}{2}^{+})$	(0.087)
1956	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.026
2002	(4)	$(\frac{7}{2}^{+}, \frac{9}{2}^{+})$	(0.23)
2034	0	$\frac{1}{2}^{+}$	0.23
2047			
2152	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	1.02
2222	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.062
2267			
2315	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.11
2335			
2378	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.18
2745	(1)	$(\frac{1}{2}^{-}, \frac{3}{2}^{-})$	0.085
2772	4	$(\frac{7}{2}, \frac{9}{2})^{+}$	0.45
2833	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.30
2858	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.097
2878	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.091
2904	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.057
2927	(3)		(0.13)
2950 [b]	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.12
2975			
3015	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.10
3035	(2)	$(\frac{3}{2}^{+}, \frac{5}{2}^{+})$	(0.086)
3074	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.14
3096			
3119			
3154	0	$\frac{1}{2}^{+}$	0.081
3192			
3217	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.28
3258			
3293			
3338	4	$(\frac{7}{2}, \frac{9}{2})^{+}$	0.41
3370	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.14
3391	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.10
3466	(2)	$(\frac{3}{2}^{+}, \frac{5}{2}^{+})$	(0.047)
3501			
3547	(4)	$(\frac{7}{2}^{+}, \frac{9}{2}^{+})$	(0.50)
3567	(4)	$(\frac{7}{2}^{+}, \frac{9}{2}^{+})$	(0.41)
3596 [b]			
3620	2	$(\frac{3}{2}, \frac{5}{2})^{+}$	0.065
3659			
3682			
3706	(3, 2)		(0.24, 0.066)
3734			
3786	(2)	$(\frac{3}{2}^{+}, \frac{5}{2}^{+})$	0.12
3892	(3, 2)		(0.15, 0.042)
3912	(2)	$(\frac{3}{2}, \frac{5}{2})^{+}$	(0.17)

TABLE II *(Continued)*

E_x (keV)	l_n	J^{π} [a]	G_{lj}
2411	2	$(\frac{3}{2},\frac{5}{2})^+$	0.060
2429	5	$(\frac{9}{2},\frac{11}{2})^-$	1.04
2462	0	$\frac{1}{2}^+$	0.086
2487	2	$(\frac{3}{2},\frac{5}{2})^+$	0.039
2511	2	$(\frac{3}{2},\frac{5}{2})^+$	0.16
2539	4	$(\frac{7}{2},\frac{9}{2})^+$	0.92
2557	0	$\frac{1}{2}^+$	0.082
2650	2	$(\frac{3}{2},\frac{5}{2})^+$	0.056
2677	2	$(\frac{3}{2},\frac{5}{2})^+$	0.022
2697	2	$(\frac{3}{2},\frac{5}{2})^+$	0.050
3935	(2)	$(\frac{3}{2},\frac{5}{2})^+$	(0.058)
3983	(2)	$(\frac{3}{2},\frac{5}{2})^+$	(0.076)
4025			
4053			
4121			
4144	(2)	$(\frac{3}{2}^+,\frac{5}{2}^+)$	(0.055)

[a] Assignments consistent with Ref. 1 and the present results.

[b] Possible doublet.

[c] A good fit to the measured angular distribution for this state was obtained only with the sum of $l_n = 0$ and $l_n = 2$ calculations.

the imaginary absorption potential had to be increased in order to obtain good fits to $l = 4$ and $l = 5$ angular distributions. The proton parameters were adapted from the Perey and Perey compilation.[9] The spectroscopic strengths $G_{lj} = [(2J_f + 1)/(2J_i + 1)]C^2S_{lj}$ were derived from the differential cross sections by use of the expression

$$d\sigma/d\Omega = 1.53 G_{lj}\,\sigma_{\text{DWUCK}}/(2j+1)\,,$$

where J_i, J_f, and j are the total angular momenta of the target nucleus, the residual nucleus, and the transferred neutron, respectively. The uncertainties in the relative values of G_{lj} are <10%.

III. RESULTS

The excitation energies, l_n transfers, and spectroscopic strengths determined in the present work are shown in Table II. Levels observed in the present study are consistent, within experimental uncertainty, with levels observed in previous ^{96}Mo$(d,p)^{97}$Mo experiments.[10, 11] In addition, the states at 659, 680, and 720 keV observed presently were unresolved in earlier particle-transfer reactions and the values of the l_n transfers observed for this triplet are in agreement with J^{π} adopted from other experiments.[1] The present J^{π} assignments for the 1437- and 2047-keV excitations are inconsistent with earlier values.[10] Also, the present J^{π} for levels at 1516, 1550, 1763, 1956, 2378, 2511, and 2833 keV are in disagreement with the J^{π} adopted[1] for levels, identical within experimental uncertainty, observed in other experiments. The ambiguity could be explained in some cases if the compared levels were not the same configurations.

The ground state and approximately 40 excited states in ^{97}Mo are reached by $l_n = 2$ transfers in

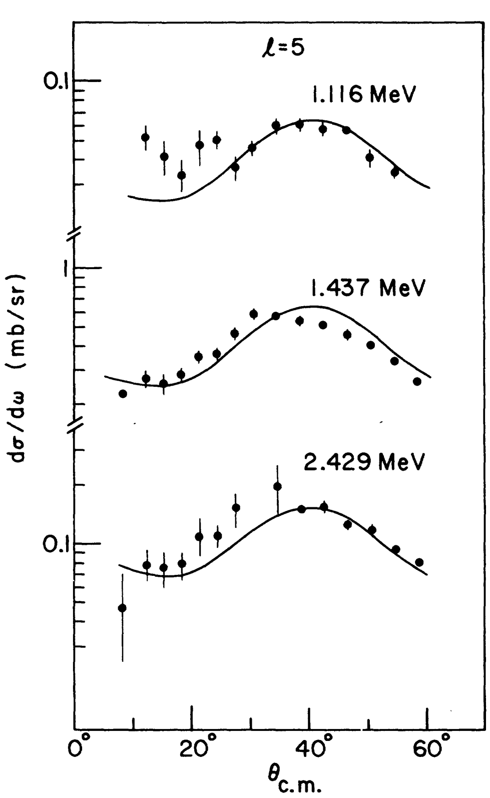

FIG. 5. Angular distributions for levels excited by $l_n = 5$ transfers in the ^{96}Mo$(d,p)^{97}$Mo reaction. The solid lines are DWBA calculations.

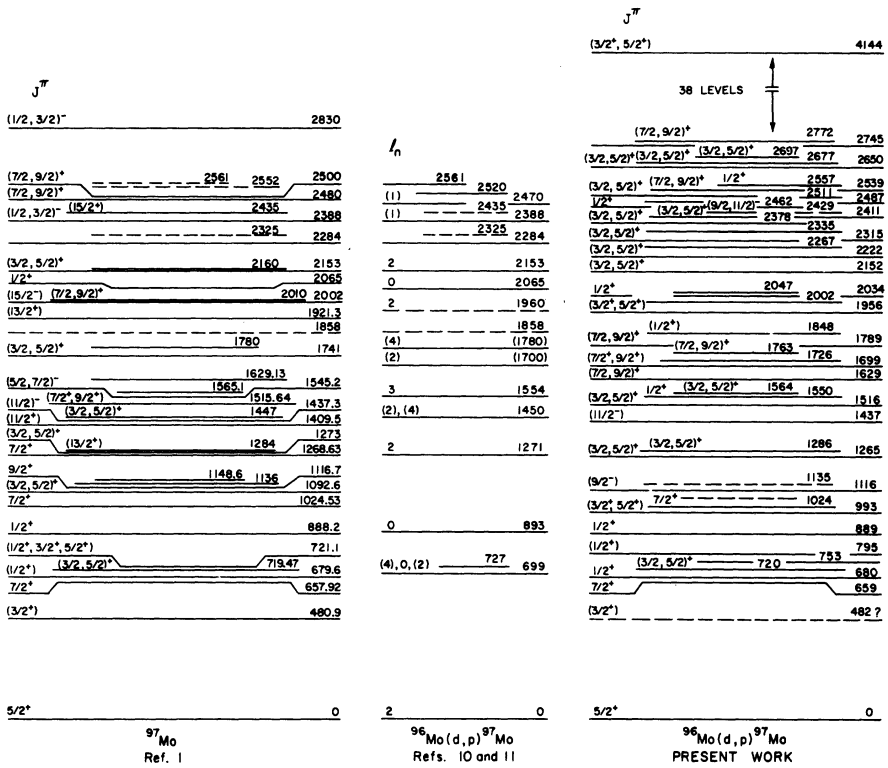

FIG. 6. Energy level schemes of ^{97}Mo. The levels adopted from ^{97}Nb decay, $(\alpha,xn\gamma)$ reactions, Coulomb excitation, and pickup reactions and the previous (d,p) data are compared with the present results.

the (d,p) reaction. Typical angular distributions are shown in Fig. 2. Approximately 56% of the $l_n = 2$ strength is almost equally distributed among the ground state and the 720-, 1265-, and 2152-keV states. The remaining $l_n = 2$ strength is spread over 35 levels up to ~4 MeV excitation. The $l_n = 0$ strength is associated mainly with the 680-keV level (see Fig. 3) and the remaining strength is distributed over nine states below 3.2-MeV excitation. Examples of angular distributions for states reached by $l_n = 4$ and $l_n = 5$ transfers are shown in Figs. 4 and 5. Eight definite and four tentative $l_n = 4$ assignments were made and three $l_n = 5$ transfers were identified.

In Fig. 6, the results of the present work are shown in comparison with earlier (d,p) data and with the levels in ^{97}Mo adopted[1] from the results of experiments with pickup and stripping reactions, Coulomb excitation, $(\alpha, xn\gamma)$ reactions, and ^{97}Nb decay. New low-lying levels observed presently have excitation energies 753, 795[$l_n = (0)$], 993[$l_n = (2)$], and 1550($l_n = 0$) keV. Above 1.6-MeV excitation energy, ~60 new levels were identified. The present results are summarized in Tables

TABLE III. Sums of spectroscopic strengths G_{lj} for states in subshells identified by their l values. The range of excitation energies E_x for which data are available is indicated in the last column.

Target nucleus	l 2	0	4	5	1	3	E_x (MeV)
$^{90}_{40}$Zr$_{50}$	9.47	1.76	9.10	5.24	0.20	0.49	<4.8
^{92}Zr$_{52}$	9.89	2.35	11.72	8.06	0.08	1.53	<4.9
^{94}Zr$_{54}$	6.68	1.77	(2.39)	2.04	(0.60)	(0.49)	<4.0
$^{92}_{42}$Mo$_{50}$	10.5	2.14	3.58	3.96	0.38	···	<3.8
^{94}Mo$_{52}$	8.36	1.60	2.80	3.12	0.12	···	<3.2
^{96}Mo$_{54}$	8.34	1.80	(11.7)	4.75	(0.085)	(0.52)	<4.2

TABLE IV. Centers of gravity (keV) of the states in the subshells indicated by their l values. The range of excitation energies E_x for which data are available is given in the last column.

Target nucleus	l 2	0	4	5	1	3	E_x (MeV)
$^{90}_{40}$Zr$_{50}$	1429	1544	2988	2647	2887	2828	<4.8
^{92}Zr$_{52}$	1254	1198	2137	2388	3340	3884	<4.9
^{94}Zr$_{54}$	1633	1591	(2835)	2027	(2480)	3647	<4.0
$^{92}_{42}$Mo$_{50}$	1200	1646	1598	2320	···	2899	<3.8
^{94}Mo$_{52}$	1132	1308	1230	1949	2520	···	<3.2
^{96}Mo$_{54}$	1734	1321	1447	1630	(2745)	(3564)	<4.2

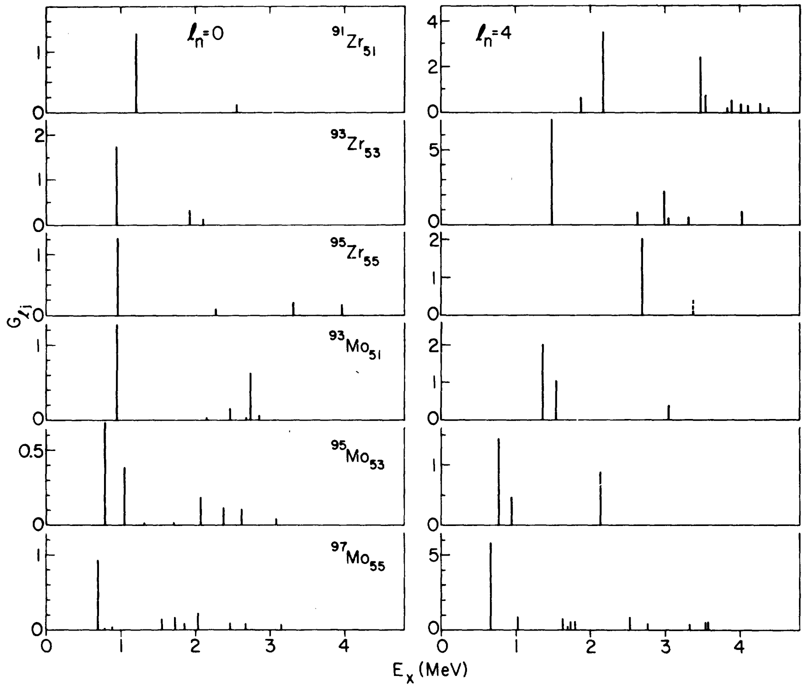

FIG. 7. Comparison of spectroscopic strengths for $l_n = 0$ and $l_n = 4$ transfers to levels in zirconium and molybdenum isotopes.

III and IV, where the sums of spectroscopic strengths and the energy centers of gravity are compared with the data[12-14] for odd-A molybdenum and zirconium nuclei. The sums of strength are consistent with the description in which $2d_{5/2}$, $2d_{3/2}$, $1g_{7/2}$, and $1h_{11/2}$ are the active neutron orbitals in the vicinity of $N = 56$. Table IV and Fig. 7 show the changes in the level energies as pairs of nucleons are added. The $l_n = 0$ strength is more fragmented as pairs of neutrons and pairs of protons are added; however, the centers of gravity are approximately the same. In the case of $l_n = 4$, the centers of gravity change most with the addition of the pairs of protons to the zirconium isotopes. For the molybdenum isotopes, the lowest state observed by $l_n = 4$ transfer decreases in excitation energy as pairs of neutrons are added to $^{93}_{42}$Mo$_{51}$. If this systematic trend exists also for the zirconium isotopes, one would expect a strong $l_n = 4$ transfer to a state at about 1 MeV in ^{95}Zr; however, no such state has been reported in the literature.

The technical assistance of J. Bicek and the cooperation of the group at the tandem are gratefully acknowledged.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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