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States of ^{94}Mo from the ^{95}Mo$(d, t)^{94}$Mo Reaction*

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The ^{95}Mo$(d, t)^{94}$Mo reaction has been studied at 17-MeV incident energy. Energy spectra were measured at 12 angles from 9 to 50° laboratory angle in an Enge split-pole spectrograph. The energy resolution was 8 keV. 77% of the expected extracore pickup strength is accounted for by the six strongest $l=2$ transitions. The spectroscopic sums for final $J^\pi = 0^+$, 2^+, and 4^+ among these six levels are fully consistent with those predicted by the assumption of pure $(d_{5/2})^3 \rightarrow (d_{5/2})^2$ transitions. Angular distributions were measured for an additional 16 levels up to 3.7 MeV excitation. Seven of these levels have not been previously reported. The existence of a ^{94}Mo level at 1.746 MeV is confirmed in this experiment.

[NUCLEAR REACTIONS ^{95}Mo(d, t), $E_d = 17.0$ MeV; measured $\sigma(E_t, \theta)$, 8-keV resolution. ^{94}Mo deduced levels, l_n, S; DWBA analysis. Enriched target.]

I. INTRODUCTION

There is increasing evidence that $^{88}_{38}$Sr$_{50}$ is a better closed-shell nucleus than $^{90}_{40}$Zr$_{50}$ and that the low-lying states of nuclides having $Z = 38$ to 44 can be interpreted in terms of the filling of the next few shell-model subshells outside an inert ^{88}Sr core. In particular, the states of the molybdenum isotopes have been treated in a number of shell-model calculations using a ^{88}Sr or ^{90}Zr core, with bases selected from the next few higher subshells.[1] The spectroscopic information from the ^{95}Mo$(d, t)^{94}$Mo reaction provides an important check for these calculations. The comparison of the experimental (d, t) l-transfer values and spectroscopic factors with theory is straightforward. The configuration $(2d_{5/2})^n$ is predicted in the calculations to be the dominant neutron configuration in the low-lying states of both ^{95}Mo and ^{94}Mo. Pickup from a $(2d_{5/2})^3$ configuration results in a unique distribution of transition strength over states of each possible final-spin J; thus various sums of the (d, t) spectroscopic factors can provide interesting comparisons with theory.

The ^{95}Mo$(d, t)^{94}$Mo reaction can provide other important information. The $\frac{5}{2}^+$ (g.s.) analog resonance in ^{95}Tc has been studied extensively. Its partial width decay amplitudes to the various low-lying states of ^{94}Mo have recently been measured.[2] The squares of these amplitudes for a given subshell j should have the same relative proportion as the spectroscopic factors S_j for neutron pickup leading to the same levels. The (d, t) reaction at 17.0 MeV, where Coulomb barrier effects are expected to be unimportant, can provide accurate relative spectroscopic factors for this comparison.

II. EXPERIMENTAL METHOD

The ^{95}Mo$(d, t)^{94}$Mo reaction was studied using a 17.0-MeV deuteron beam from the University of Pittsburgh three-stage tandem Van de Graaff accelerator. Details of the beam transport system have been described previously.[3] The beam was focused through a slit 0.5 mm wide and 2.0 mm high, located 2 cm in front of the target. Current on this slit, and on an antiscattering slit placed between it and the target, were monitored at all times during the experiment. The currents were small enough to allow measurements down to 9° laboratory angle. The target was fabricated by evaporation of 35-μg/cm^2 molybdenum metal, enriched to 96.4% ^{95}Mo, onto a 20 μg/cm^2 carbon backing. Tritons were detected in the focal plane of an Enge split-pole spectrograph. As the expected variation of cross section from state to state at a given angle was very large, two exposures were made at each angle, one of 2400-μC and one of 240-μC integrated beam charge.

The exposed plates were scanned at the Argonne automatic plate scanning facility.[4] Spot checks of the automatic scanning were made by the Pittsburgh manual scanning group. Also, excitation regions having very weak groups were scanned manually at all angles. Throughout, the results of the two different exposures at each angle were used as a check of internal consistency. Agreement was very good within the known dynamic range of each scanning method.

The energy spectra were analyzed using the peak-fitting program AUTOFIT.[5] Angular distributions for the range 9–50° were extracted for 22 levels up to 3.7-MeV excitation energy.

The excitation energies tabulated in Table I were obtained by calibration of the focal plane at two angles using the previously studied ^{93}Nb(d, t)^{92}Nb reaction.[6] This calibration was then used to compute excitation energies of all levels at each angle.[7] The rms deviation of level energy measurements at 12 angles was typically 2 keV, and agreement with previous work was good. The absolute level energies are believed to be accurate to ±0.3%.

Relative normalization of the (d, t) cross sections was obtained by charge integration and by simultaneous detection of elastically scattered deuterons in a pair of NaI(Tl) monitors kept fixed at $\theta = \pm 38°$ throughout the experiment. Absolute normalization of the data was obtained by target-thickness measurements using deuteron elastic scattering at 11.8 and 17.0 MeV. The elastic scattering cross sections at 11.8 MeV were taken from the work of Mairle and Schmidt-Rohr[8] and those at 17.0 MeV from an optical-model prediction using the parameters shown in Table II.[9] In addition, a third cross-check of the target thickness was made possible by a strong impurity group from the ^{96}Mo(d, t)^{95}Mo reaction, using the known composition of the target and the published cross sections of Diehl *et al.*[10] Agreement among all these determinations was very good, and the uncertainty in the absolute normalization is at most 15%.

TABLE I. Summary of the results. The differential cross sections listed in the fourth column are those of the most forward maximum of the best DWBA fit, with the exception of $l = 0$ transitions, for which they represent the second maximum. For the 2.538-MeV level, the cross sections are those of the DWBA fits mixed to give the solid curve shown in Fig. 7. The fifth column shows the neutron-pickup spectroscopic factors for each level; the $l = 0$, 1, 2, 3, and 4 strengths were calculated assuming $3s_{1/2}$, $2p_{1/2}$, $2d_{5/2}$, $1f_{5/2}$, and $1g_{9/2}$ transitions, respectively.

Level No.	E_x (MeV)	l_n	$\left(\frac{d\sigma}{d\Omega}\right)_{\max}$ (mb/sr)	C^2S_{lj}
0	0.0	2	4.07	0.51
1	0.874	2	1.52	0.25
2	1.578	2	3.24	0.66
3	1.746	2	0.05	0.01
4	1.869	2	0.70	0.16
5	2.073	2	0.89	0.22
6	2.301	2	1.11	0.30
7	2.398	0	0.03	0.005
8	2.426	4	0.02	0.06
9	2.538	1,3	0.09, 0.02	0.02, 0.05
10	2.571	2	0.06	0.02
11	2.811	0	0.15	0.03
12	2.876	2	0.11	0.04
13	2.972	0	0.19	0.04
14	2.999	0	0.10	0.02
15	3.136	2	0.05	0.02
16	3.171	0	0.10	0.02
17	3.378	4	0.04	0.20
18	3.407	0	0.08	0.02
19	3.462	1	0.08	0.02
20	3.602	2	0.02	0.01
21	3.650	2	0.03	0.02

Typical energy spectra are shown in Fig. 1. Shown are both the short and long exposure for 12° laboratory angle. The short exposure spectrum shows the strong dominance of the six strongest transitions. The numbers identifying the peaks correspond to those of Table I. Energy resolution was 8 keV for all exposures made.

Groups from reactions on light impurities presented no problem in this experiment. Only one such group was observed, and it quickly moved out of range with increasing angle. Groups from other isotopes of molybdenum, however, were a more serious problem and prevented the simple assignment of observed weak high-lying levels as new levels in ^{94}Mo. The levels accepted for analysis in this work were checked for any possible interference from the (d, t) reactions on the known impurity isotopes, all of which have been studied.[10, 11]

In particular, the weak group labeled 3 in Fig. 1 can be identified as a level in ^{94}Mo, at excitation energy 1.746 ± 0.006 MeV. This level almost certainly corresponds to the 1.74-MeV $J^\pi = 0^+$ state reported in a study of the ^{94}Mo($n, n'\gamma$) reaction.[12]

III. RESULTS AND DISCUSSION

A. Distorted-Wave Analysis

The distorted-wave Born-approximation (DWBA) calculations were made using the code DWUCK.[13] The calculations were standard single-neutron-pickup calculations, using both the nonlocal and finite-range corrections available in the code. The correction parameters employed were $\beta_d = 0.54$, $\beta_t = 0.25$, and $R = 0.845$, as suggested in the instructions for use of the code.[13] The bound-state geometrical parameters and the entrance- and exit-channel optical-model parameters are presented in Table II. The deuteron optical-model parameters were those of Childs, Daehnick, and Spisak,[9] corresponding to 17.0-MeV deuteron scattering from ^{93}Nb. The triton parameters were those of Flynn *et al.*,[14] corresponding to 20-MeV triton scattering from ^{94}Zr.

The DWUCK calculations with finite-range and nonlocality corrections were performed with the standard (d, t) normalization value of 5. The use of this value is supported by previous experience and theoretical considerations.[10, 15] Finite-range and nonlocality corrections lead to spectroscopic

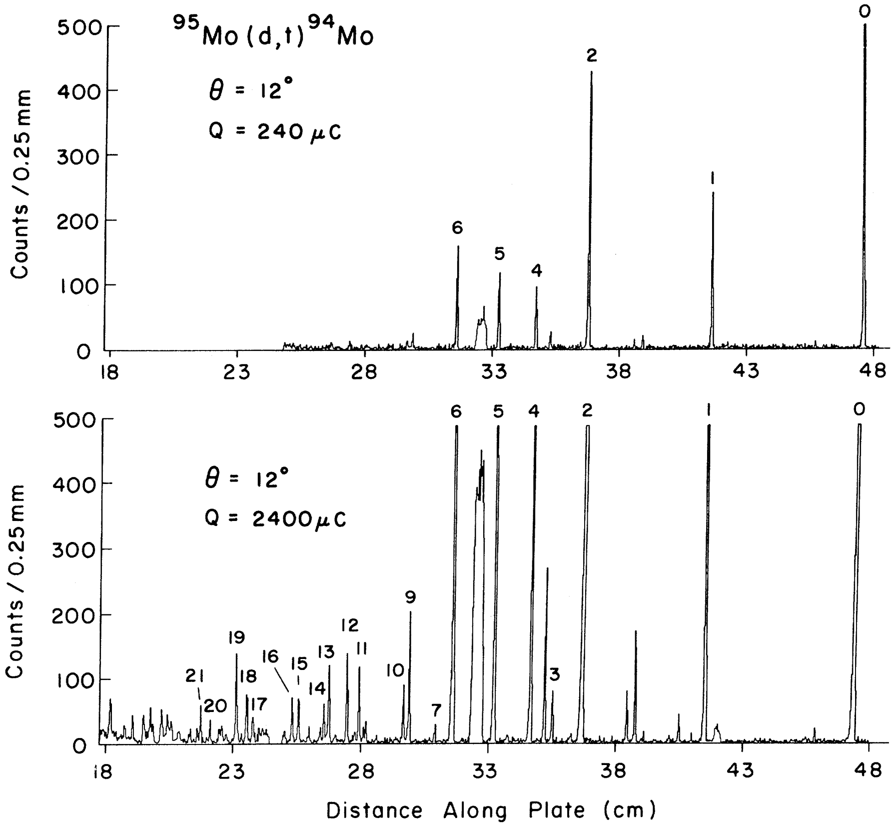

FIG. 1. Typical spectra from the ^{95}Mo$(d,t)^{94}$Mo reaction at 17 MeV. The spectra shown are plotted with a linear vertical scale to emphasize the domination of the spectra by six very strong low-lying levels. The numbering of the levels corresponds to that in Table I.

factors C^2S about 20% smaller than those obtained from corresponding zero-range calculations without these corrections. This reduction in spectroscopic strength is reasonable as zero-range calculations with the standard normalization have often exceeded spectroscopic sum limits by large amounts.[10, 15]

B. Strong $l = 2$ Transitions

Figure 2 shows the angular distributions of the six strong transitions seen to dominate the spectra in Fig. 1. The solid curves are DWBA predictions for $2d_{5/2}$ pickup. The spectroscopic factors C^2S are presented in Table I; C stands for the usual isospin vector coupling coefficient. Summing these factors gives 2.11 particles; thus more than 77% of the expected extracore pickup strength is found in these six levels. Addition of the strengths of six additional weaker transitions brings the total $l = 2$ strength to 2.24 particles, or 82% of the pure-configuration value $3C^2 = 2.75$. This value is subject to some uncertainty due to mixture of $2d_{3/2}$ pickup strength in this sum. The results of Diehl *et al.*,[10] comparing (d,p) and (d,t) cross sections for states of neighboring Mo isotopes,

TABLE II. Bound-state and optical-model parameters used in the DWBA calculations.

	Source	V (MeV)	r_0 (fm)	a_0 (fm)	W (MeV)	$4W_D$ (MeV)	r_i (fm)	a_i (fm)	r_c (fm)	λ_{so}
Bound states	···	a	1.17	0.75						25
^{95}Mo + d	Ref. 9.	90.2	1.20	0.75	···	59.2	1.30	0.71	1.15	···
^{94}Mo + t	Ref. 14.	171.	1.16	0.732	17.	···	1.542	0.774	1.40	···

[a] Adjusted to give the correct separation energy.

indicate that some 0.3–0.5 units of $2d_{3/2}$ pickup strength may be expected. This admixture is sufficiently small to warrant the interpretation of the strong $l=2$ transitions in terms of $(2d_{5/2})^n$ configurations.

The pickup of one of three $2d_{5/2}$ neutrons results in a unique distribution of transition strengths to $J^\pi=0^+$, 2^+, and 4^+ final states, based on the coefficients of fractional parentage (cfp) for $(\frac{5}{2})^2$, $J=0$, 2, and 4 in the antisymmetrized $(\frac{5}{2})^3$, $J=\frac{5}{2}$ target wave function. If the protons in the ^{95}Mo ground state are assumed to be in a pure seniority-zero configuration, summed strength for final spin J is

$$C^2\sum_\alpha S^{J,\alpha}_{d_{5/2}}=3C^2[(\tfrac{5}{2})^2(J)\tfrac{5}{2}\,\tfrac{5}{2}|\}(\tfrac{5}{2})^3\,\tfrac{5}{2}]^2,$$

where the quantity in square brackets is the cfp for spin J. Figure 3 shows the experimental spectroscopic sums for final spins 0^+, 2^+, and 4^+ among these six transitions, compared with the theoretical ones. The cfp's were taken from the work of de-Shalit and Talmi.[16] The final-state spins assumed were taken from a (p,t) study.[17] The theoretical sums have been scaled by a factor 0.82, as only this fraction of the total $l=2$ strength expected is observed in this experiment. The good agreement seen in Fig. 3 supports the interpretation that these six strong transitions are dominated by the $(2d_{5/2})^n$ components of the initial and final states. The observed concentration of strength in these few states provides interesting structural information. The ground state receives all the $J^\pi=0^+$ strength expected in this model, and is presumably very similar in structure to the target ground state. Fragmentation into three $J^\pi=2^+$ states is not surprising, as there are several 2^+ states of similar excitation energy expected.[1] Finally, the large spectroscopic factor for the second excited state, and the observation of only one other strong $J^\pi=4^+$ level, is indicative of the dominance of the $\nu(2d_{5/2})^2{}_{4^+}$ configuration for this level.

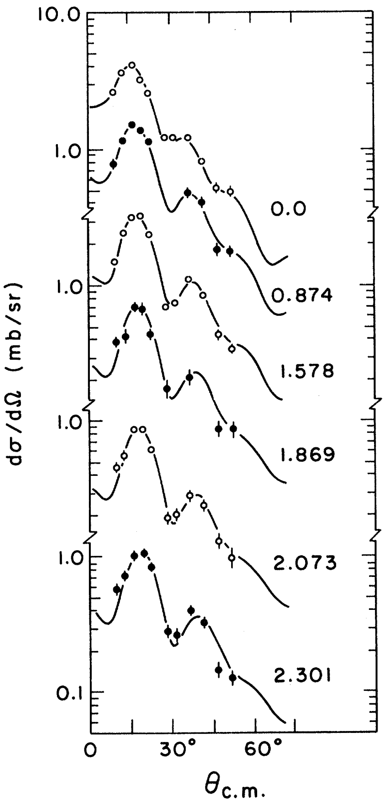

FIG. 2. Angular distributions of the six strongest transitions in the ^{95}Mo(d,t)^{94}Mo reaction. The solid curves are DWBA fits, corresponding to pure $2d_{5/2}$ neutron pickup. Note that a Q-value dependence of the minimum near 28° is fitted by the calculations.

C. Other Even-Parity Levels

Figure 4 shows the angular distributions for six additional weaker $l=2$ transitions. The level at 1.746 MeV has been previously observed only in the $(n,n'\gamma)$ reaction,[12] where it was assigned $J^\pi=0^+$. This state is expected from several shell-model predictions,[1] and it is interesting that it was not observed in previous (p,t),[17,18] (^{3}He,d),[19] and (p,p')[20] studies.

The level at 2.571 MeV has been observed previously in the (p,t)[17] and (^{3}He,d)[19] reactions. Several previous investigations have determined a level near 2.87 MeV,[21] but the spin limits placed

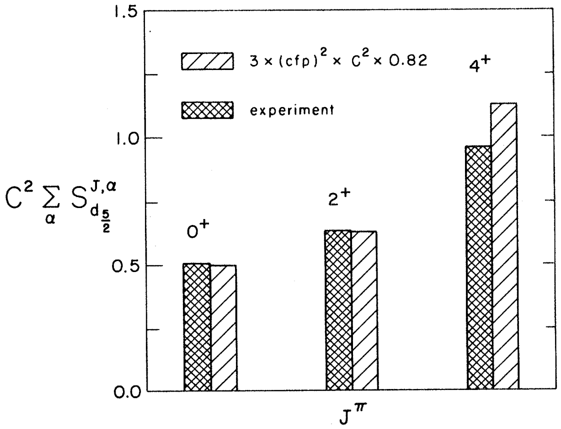

FIG. 3. Sums of spectroscopic factors for known $J^\pi=0^+$, 2^+, and 4^+ levels among the six shown in Fig. 2, compared with the sum-rule prediction based on the assumption of pure $(2d_{5/2})^3\to(2d_{5/2})^2$ pickup transitions. Details of the calculation are presented in the text.

by these studies make it unlikely that the levels observed are the same level as the 2.876-MeV state observed in the present study. Finally, the levels at 3.136, 3.602, and 3.650 MeV have not been previously observed.

Figure 5 shows the angular distributions of six $l=0$ transitions. The solid curves shown are DWBA predictions for $3s_{1/2}$ pickup. The sum of the spectroscopic factors for these six transitions is 0.13. As can be seen in the Figure the data and the calculations are shifted in angle with respect to each other by 3°. Spectroscopic factors were calculated by shifting the calculations 3° towards smaller angles and normalizing visually to the data. Spin limits of $J^\pi=2^+, 3^+$ can be placed on all of these levels. Two levels, at 2.398 and 3.407 MeV, have been previously assigned spins $J^\pi=2^+$ from a study of the ^{96}Mo(p,t)[17] reaction. The levels at 2.811, 2.972, 2.999, and 3.171 MeV were not observed in either of two recent (p,t) studies of ^{94}Mo.[17,18] This fact strongly suggests a $J^\pi \simeq 3^+$ assignment for all of these four levels.

Figure 6 shows two transitions dominated by $l=4$ transfer. The solid curves are $1g_{9/2}$ distorted-wave predictions. These transitions represent only a small amount of $1g_{9/2}$ pickup strength. More than this observed total of 0.26 particles is expected on the basis of shell-model systematics; however, the dynamics of the (d,t) reaction favors $l=2$ over $l=4$ transitions to such a degree that there could well be considerable $l=4$ strength hidden by the dominant $l=2$ transitions. Even a transition with equal $2d_{5/2}$ and $1g_{9/2}$ spectroscopic factors would be difficult to distinguish from a pure $2d_{5/2}$ transition. The observed dominance of $l=4$ for the levels at 2.426 and 3.378 MeV may therefore signify forbiddenness of direct $2d_{5/2}$

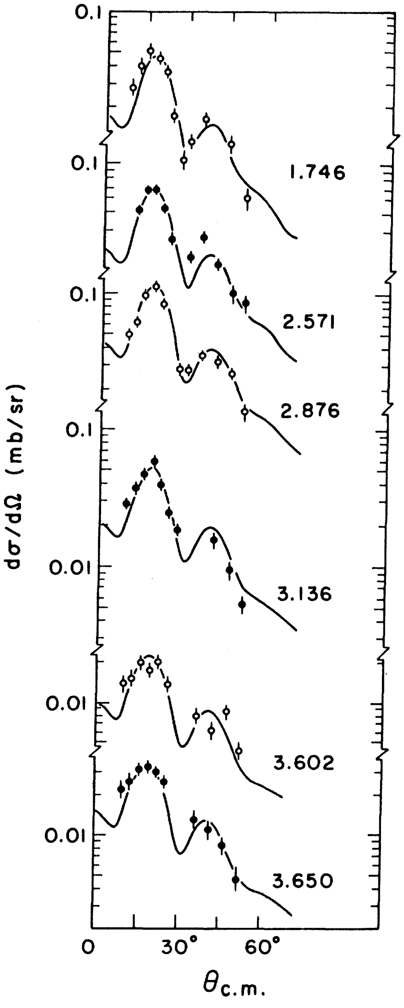

FIG. 4. Angular distributions for six additional weaker $l=2$ transitions. The curves are DWBA predictions.

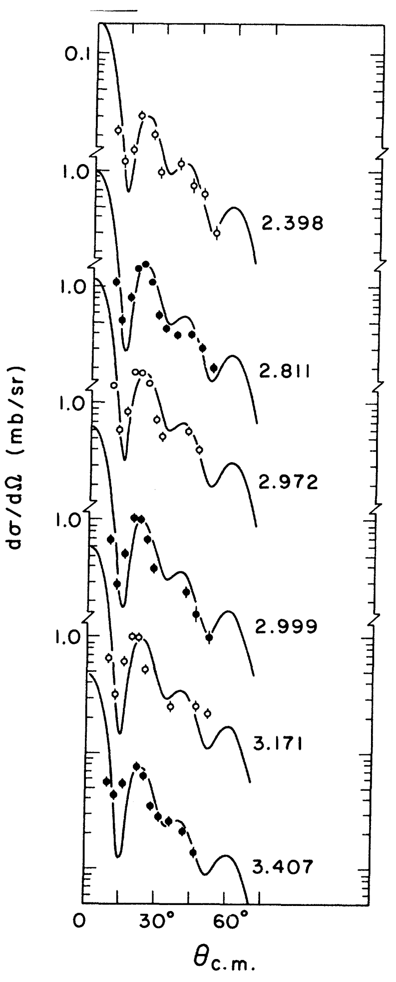

FIG. 5. Observed $l=0$ transitions in the ^{95}Mo$(d,t)^{94}$Mo reaction. The solid curves are DWBA predictions.

transfer. The simplest explanation is the assignment of $J_f \geq 6$. This interpretation would substantiate a previous assignment of $J^\pi = 6^+$ for the 2.426-MeV level.[22] If the level at 3.378 MeV is the same as the 3.375-MeV level observed in the (p, t) reaction,[17] then it too is likely to have $J^\pi = 6^+$.

D. Odd-Parity Levels

Figure 7 shows the two transitions observed to have odd-l transfer. The curve for the 2.538-MeV level is a mixture of $2p_{1/2}$ and $1f_{5/2}$ distorted-wave calculations. The relative strengths of the two components are expressed in terms of spectroscopic factors in Table I. Levels assigned both $J^\pi = 3^-$ and 5^- have been reported[20, 17] at this energy, and it has been suggested[17] that there is a close doublet of levels. No evidence of doublet structure was seen for this level in the (d, t) spectra.

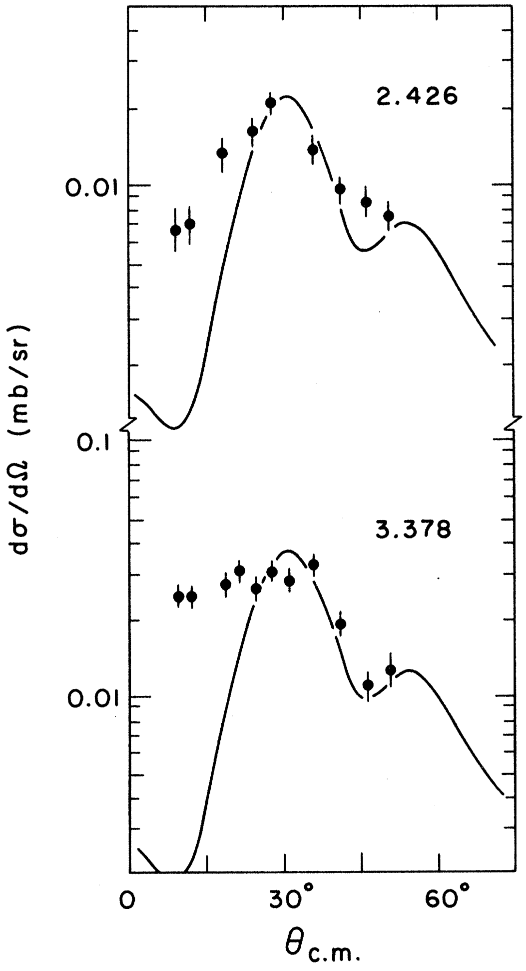

FIG. 6. Observed $l=4$ transitions in the ^{95}Mo$(d, t)^{94}$Mo reaction. The solid curves are DWBA predictions.

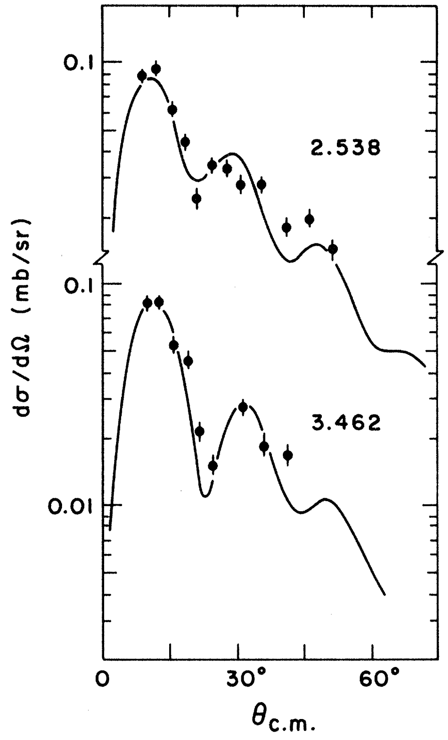

FIG. 7. Transitions to odd-parity levels in ^{94}Mo. The curve for the 2.538-MeV level is a mixture of $l=1$ and 3 DWBA predictions. The relative mixture in terms of spectroscopic factors is given in Table I. The curve for the 3.462-MeV level is a pure $2p_{1/2}$ pickup calculation.

IV. SUMMARY AND CONCLUSIONS

Figure 8 shows the distribution of spectroscopic strength for $l=0$ to 4 as a function of excitation energy for the range 0.0 to 3.7 MeV. The distribution for $l=2$ shows the concentration of the

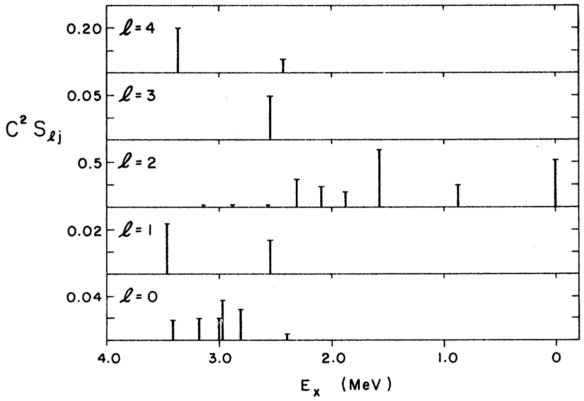

FIG. 8. Distribution of spectroscopic strength as a function of excitation energy in the ^{95}Mo$(d, t)^{94}$Mo reaction. The $l=1$, 2, 3, and 4 strengths were calculated assuming $2p_{1/2}$, $2d_{5/2}$, $1f_{5/2}$, and $1g_{9/2}$ transitions, respectively.

extracore pickup strength in the six strongest transitions. The structural implications of this concentration are discussed in Sec. III B. Six additional weak $l = 2$ transitions were observed, including one at 1.746 MeV, confirming the existence of a ^{94}Mo level at this energy; three of these $l = 2$ states were previously unobserved. The S_{lj} distribution marked $l = 0$ in Fig. 8 shows a group of six transitions centered slightly above 3.0 MeV excitation. These are interpreted as pickup from a weak $\nu(3s_{1/2})^2 2d_{5/2}$ component in the ^{95}Mo wave function. These states were assigned spin-parity ranges $J^\pi = 2^+$, 3^+. Four of them were not observed in the (p, t) reaction,[17, 18] in strong support of a $J^\pi = 3^+$ assignment. A known[22] $J^\pi = 6^+$ level at 2.42 MeV was populated by an $l = 4$ transition. The second $l = 4$ transition seen in Fig. 8 coincides in energy with a level tentatively assigned $J^\pi = 5^-$ in a (p, t) study[17]; however, no combination of odd-l transfers, including $l = 5$, could fit the (d, t) data for this level. This level is most likely also $J^\pi = 6^+$. Two odd-parity transitions were observed in this reaction. The level at 2.538 MeV required a mixture of $l = 3$ with its predominantly $l = 1$ angular distribution, and accounts for the single $l = 3$ level shown in Fig. 8. There was no evidence from the line shapes of a doublet of states at this energy.

As mentioned in the Introduction, the $2d_{5/2}$ spectroscopic factors for the strongest transitions can be used as a reference for measurements of the partial-width decay amplitudes of the $\frac{5}{2}^+$ (g.s.) analog resonance in ^{95}Tc. The squares of the amplitudes for subshell j decay to the various levels of ^{94}Mo should have the same relative proportion as the spectroscopic factors S_j for the same levels. Cue *et al.*[2] have measured the decay amplitudes to the first and second excited states of ^{94}Mo and have observed additional branches to the 1.78- and 2.07-MeV levels. The comparison of these amplitudes with the (d, t) results must take into consideration the probable mixture of $2d_{3/2}$ pickup; what is directly comparable then is the total $l = 2$ strength in the two processes. The ratio of spectroscopic factors for the 1.58- and 0.87-MeV levels is 2.64, based on a pure $2d_{5/2}$ calculation. The j dependence of $l = 2$ spectroscopic factors is in this case small enough such that the uncertainty of the $2d_{3/2}$ admixture results in an uncertainty of this ratio of the order of a few percent. The ratio of the total $l = 2$ decay strength for the same two levels is 3.0,[2] in good agreement with the pickup results. This confirms an earlier comparison by Abramson *et al.*[23] using data from the (d, t) reaction at 12 MeV. As the methods of measurement of the decay amplitudes are developed, further useful comparisons with the (d, t) spectroscopic factors presented in Table I can be made.

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[1] K. H. Bhatt and J. B. Ball, Nucl. Phys. 63, 286 (1965); N. Auerbach and I. Talmi, *ibid.* 64, 458 (1965); S. Vervier, ibid. 75, 17 (1966); K. H. Bhatt, J. B. Ball, and J. C. Parikh, Phys. Rev. 178, 1632 (1969); D. Gloeckner, private communication.

[2] N. Cue, I. Plesser, Z. Vager, and G. F. Wheeler, Nucl. Phys. A192, 581 (1972).

[3] W. W. Daehnick, Phys. Rev. 177, 1763 (1969).

[4] J. R. Erskine and R. H. Vanderohe, Nucl. Instrum. Methods 81, 221 (1970).

[5] J. R. Comfort, ANL Physics Division Informal Report No. PHY-1970B, 1970 (unpublished).

[6] T. S. Bhatia, W. W. Daehnick, and T. R. Canada, Phys. Rev. C 3, 1361 (1971). See also, S. Cochavi and D. B. Fossan, *ibid.* 3, 275 (1971).

[7] J. Childs, University of Pittsburgh, spectrograph focal plane calibration code SPIRO (unpublished).

[8] G. Mairle and U. Schmidt-Rohr, Max Planck Institut für Kernphysik (Heidelberg) Report No. 1965 IV, 113 (unpublished).

[9] J. Childs, W. W. Daehnick, and M. Spisak, Bull. Am. Phys. Soc. 17, 446 (1972); and to be published.

[10] R. C. Diehl, B. L. Cohen, R. A. Moyer, and L. H. Goldman, Phys. Rev. C 1, 2132 (1970).

[11] H. Ohnuma and J. L. Yntema, Phys. Rev. 178, 1855 (1969); W. J. Courtney, J. J. Kent, H. G. Bingham, and H. T. Fortune, Bull. Am. Phys. Soc. 18, 722 (1973).

[12] M. T. McEllistrem, K. Sinram, C. E. Robertson, and J. D. Brandenberger, Bull. Am. Phys. Soc. 16, 1154 (1971).

[13] P. D. Kunz, University of Colorado, distorted-wave Born-approximation computer code and instructions (unpublished).

[14] E. R. Flynn, D. D. Armstrong, J. G. Beery, and A. G. Blair, Phys. Rev. 182, 1113 (1969).

[15] J. E. Holden, J. J. Kolata, and W. W. Daehnick, Phys. Rev. C 6, 1305 (1972). The theoretical derivation of the normalization parameter is found in R. H. Bassel, Phys. Rev. 149, 791 (1966).

[16] A. de-Shalit and I. Talmi, *Nuclear Shell Theory* (Academic, New York, 1963).

[17] J. S. Larsen, J. B. Ball, and C. B. Fulmer, Phys. Rev. C 7, 751 (1973).

[18] A. Moalem, M. A. Moinester, J. Alster, and Y. Dupont, Nucl. Phys. A196, 605 (1972).

[19] M. R. Cates, J. B. Ball, and E. Newman, Phys. Rev. 187, 1682 (1969).

[20] H. F. Lutz, D. W. Heikkinen, and W. Bartolini, Phys. Rev. C 4, 934 (1971).

[21] A summary of references for this level is presented in Ref. 17.

[22] J. Barrette, A. Boutard, and S. Monaro, Can. J. Phys. 47, 995 (1969); C. M. Lederer, J. M. Jaklevic, and J. M. Hollander, Nucl. Phys. A169, 449 (1971).

[23] E. Abramson, G. Engler, Z. Vager, N. Cue, I. Plesser, and G. F. Wheeler, Phys. Lett. 38B, 70 (1972).