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(^{3}He,d) Reaction to Bound and Quasibound Levels in ^{93}Tc†

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The ^{92}Mo(^{3}He,d)^{93}Tc reaction has been studied at 35-MeV bombarding energy. Several $T_<$ levels are observed below 6-MeV excitation energy, and evidence is presented for sizable $p_{3/2}{}^{-2}$ and $f_{5/2}{}^{-2}$ components in the ^{92}Mo proton configuration. Four deuteron groups, corresponding to $T_> = \frac{9}{2}$ analogs of low-lying levels in ^{93}Mo are also observed. Distorted-wave Born-approximation calculations were performed, using form factors calculated for a proton quasibound by the Coulomb and centrifugal barrier for the proton-unstable levels ($\geq$4.08-MeV excitation energy). The data are well described by the calculations, and reasonable spectroscopic factors are obtained for both $T_<$ and $T_>$ levels.

I. INTRODUCTION

The structure of nuclei in the $A = 90$ region has been studied quite extensively both theoretically and experimentally. The models used to describe the proton configurations for $Z \geq 39$ in the presence of the $N = 50$ closed shell are usually based on a ^{88}Sr or ^{90}Zr closed core,[1-3] and studies of low-lying levels in this region via proton transfer reactions[4-7] appear to have verified this assumption. We have studied the ^{92}Mo(^{3}He, d)^{93}Tc reaction up to 11-MeV excitation energy to investigate the proton configuration of the ^{92}Mo ground state and the nature of the $T = \frac{9}{2}$ isobaric analog states (IAS), which are also excited in this reaction. Ohnuma and Yntema[4] and Picard and Bassani[5] (referred to as PB in the following discussions) have also studied some of the low-lying $T_<$ levels with the ^{92}Mo(^{3}He, d)^{93}Tc reactions; however, no analysis was made of levels above the ^{93}Tc proton separation energy (4.08 MeV). We have performed distorted-wave Born-approximation (DWBA) calculations for the proton-unstable $T_<$ and $T_>$ states, using a technique reported previously[8] for the analysis of stripping to unbound levels.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A 35.0-MeV ^{3}He beam from the Texas A & M cyclotron was used to bombard a 1.10-mg/cm^2 self-supporting Mo foil enriched to 98.3% in ^{92}Mo. The beam was focused to a 3-mm-diam spot at the center of the 30-in. scattering chamber and collected in a Faraday cup 2 m behind the chamber. A beam-energy spread of ~35 keV was obtained through the use of the $n = \frac{1}{2}$ analyzing magnet. A ΔE-E detector telescope consisting of a 1-mm-thick ΔE detector and a 3-mm-thick E detector was used to detect the deuterons and the elastically scattered helions simultaneously. The beam axis in the scattering chamber was located to within 0.1° by rotating the detector into the "beam" resulting from the few ions produced in the cyclotron with no ion-source arc current and a small filament current. A detector fixed at 35° was used to monitor the current integrator.

Pulses from the ΔE and E detector were routed past time pickoffs and through amplifiers to a power-law identifier circuit where deuteron pulses were selected. The total energy ($E + \Delta E$) pulses were fed through a biased amplifier and stretcher to an analog-to-digital converter which was interfaced to the IBM 7094 computer. The spectra (1024 channels each) were stored in the computer memory and transferred to magnetic tape at the end of each run. Also, four spectra from previous runs were retained in the memory, and the data were reduced on line to absolute, center-of-mass cross sections with the aid of the display oscilloscope. Data for the elastic scattering of ^{3}He from ^{92}Mo were obtained simultaneously by storing pulses from the ΔE detector in a 512-channel analyzer.

A typical deuteron spectrum is shown in Fig. 1. The over-all resolution is about 80-keV full width at half maximum, due mainly to differences in ^{3}He and deuteron energy losses in the target. The levels having excitation energies $\geq$8.39 MeV appear to correspond to isobaric analogs of low-lying levels in ^{93}Mo. An energy calibration was obtained from the ^{12}C(^{3}He, d)^{13}N reaction, and the energies of 24 levels excited in the ^{92}Mo(^{3}He, d)^{93}Tc reaction have been measured. Angular distributions were measured for laboratory angles between 8.5 and 45.5° (Figs. 2–4) with an absolute normalization uncertainty of <±10%. The normalization was checked by comparing the ^{3}He elastic scattering data with optical-model calculations at small angles.

III. DWBA CALCULATIONS

The experimental and DWBA cross sections for spin-zero targets are related by[9]

$$\frac{d\sigma}{d\Omega} = 4.42 C^2 S \sigma_{lj}(\theta) \tag{1}$$

for a given l and j of the transferred particle. Here S is the spectroscopic factor, and C^2 is the isospin Clebsch-Gordan coefficient. The $^{92}_{42}$Mo$_{50}$ target nucleus has isospin $T_0 = 4$, which implies values for C^2 of $2T_0/(2T_0+1) = \frac{8}{9}$ and $1/(2T_0+1) = \frac{1}{9}$ for stripping to $T_<$ and $T_>$ final states, respectively.[10] Values of S extracted for proton stripping to analog states should be comparable to the spectroscopic factors obtained for neutron stripping to the corresponding parent states.

The DWBA calculations were performed using the local zero-range approximation with the computer code DWUCK.[11] Single-particle wave functions, which were used as form factors for stripping to ^{93}Tc bound states, were generated for a given proton binding energy by varying the depth (V_0) of a Woods-Saxon well,

$$V(r) = -V_0 f(r) + \frac{V_0 \lambda_{so}}{r}\left(\frac{\hbar}{2M_p c}\right)^2 \left(\frac{df}{dr}\right) \vec{1}\cdot\vec{\sigma} + V_C(r), \tag{2}$$

where

$$f(r) = (1 + e^{(r - r_0 A^{1/3})/a})^{-1}$$

with $r_0 = 1.25$ F, $a = 0.65$ F, and $\lambda_{so} = 25$. Levels in ^{93}Tc above 4.084-MeV excitation energy are

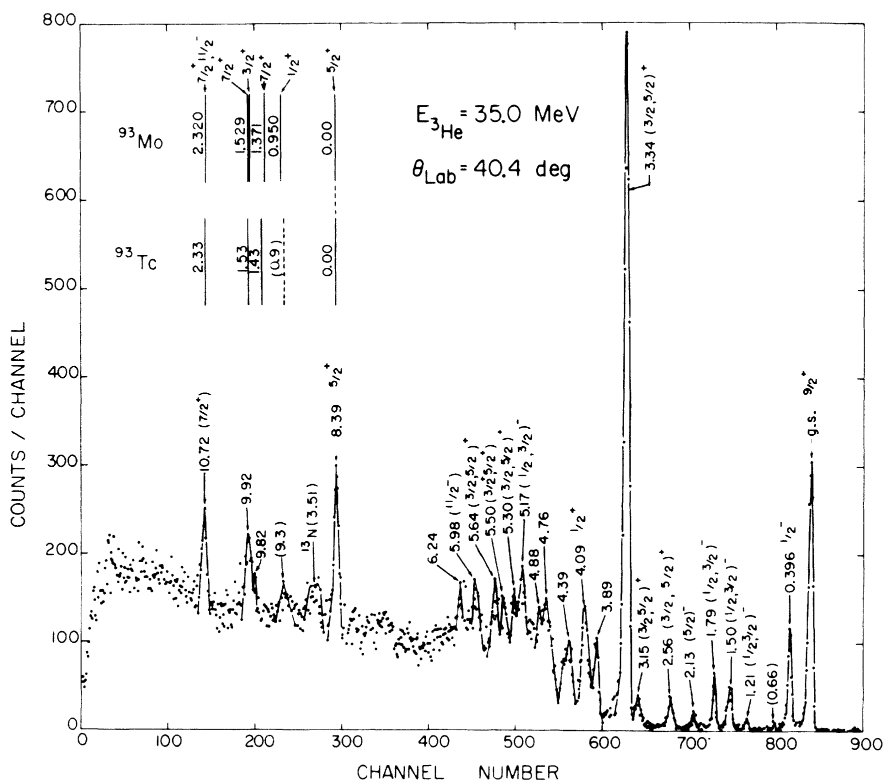

FIG. 1. Deuteron spectrum for the ^{92}Mo(^{3}He, d)^{93}Tc reaction at a lab angle of 40.4°. All levels above 4.084-MeV excitation energy are proton unstable. Level diagrams of ^{93}Mo* and ^{93}Tc*–8.39 MeV are shown in alignment with deuteron groups corresponding to isobaric analog states.

technically unbound with respect to proton emission, but are "quasibound" by the combined Coulomb and centrifugal barrier. DWBA form factors were generated for these levels by varying V_0 in Eq. (2) to minimize the ratio of the exterior amplitude to the interior amplitude of the wave function for a proton having a given (l, j) at the actual binding energy (negative for unbound levels). The wave function was normalized by setting

$$\int_0^{R_{\mathrm{TP}}} U_{lj}^2(r)\,dr = 1\,,$$

where $U_{lj}(r)$ is the radial form factor and R_{TP} is the exterior classical turning radius. The DWBA calculations were then performed in the same manner as for bound states, however, a large upper cutoff radius (~200 F) is required for convergence of the radial integrals if the exterior amplitude of the form factor is large ($\gtrsim$0.01 times the interior amplitude). The computer code DWUCK was modified to include 800 integration points for large radius calculations with a reasonable integration step size ($\lesssim$0.25 F). An analysis of the ^{40}Ca(^{3}He, d)-^{41}Sc reaction[8] has shown that calculations of this type are relatively insensitive to changes in external phase of the form factor, and that the resulting spectroscopic factors are in agreement with those obtained from proton elastic scattering experiments. Huby[12] has recently shown that a "pseudobound" technique similar to the one used here may be derived from the "faithful" calculation of Huby and Mines.[13] A more detailed discussion of the procedure used in the present work is given in Ref. 8.

Deuteron and ^{3}He optical-model parameters used in the DWBA calculations are shown in Table I. The ^{3}He parameters were obtained from optical-model fits to the elastic scattering data using the search program JIB.[14] The deuteron parameters are those obtained by Perey and Perey[15] for $d+{}^{90}$Zr elastic scattering at 25.9 MeV.

IV. DISCUSSION OF RESULTS

A. $T_<$ Levels

The (^{3}He, d) angular distributions measured for $T_<$ levels are shown in Figs. 2 and 3, along with DWBA calculations. Spectroscopic factors and J^π assignments are summarized in Table II.

$l_p = 2$ Levels

The deuteron angular distributions having shapes characteristic of $l_p = 2$ transfers are shown

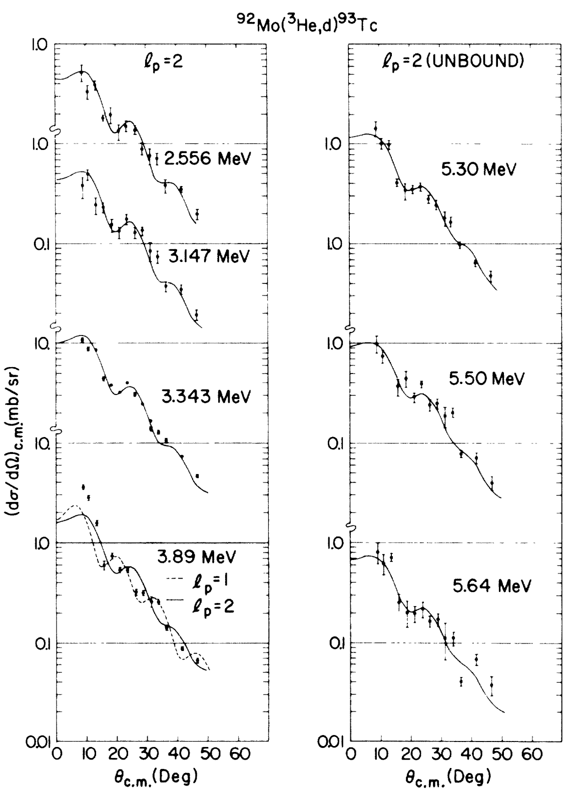

FIG. 2. Deuteron angular distributions for bound and unbound $T_<$ levels in ^{93}Tc corresponding to $l_p = 2$ transfers. The curves are DWBA calculations.

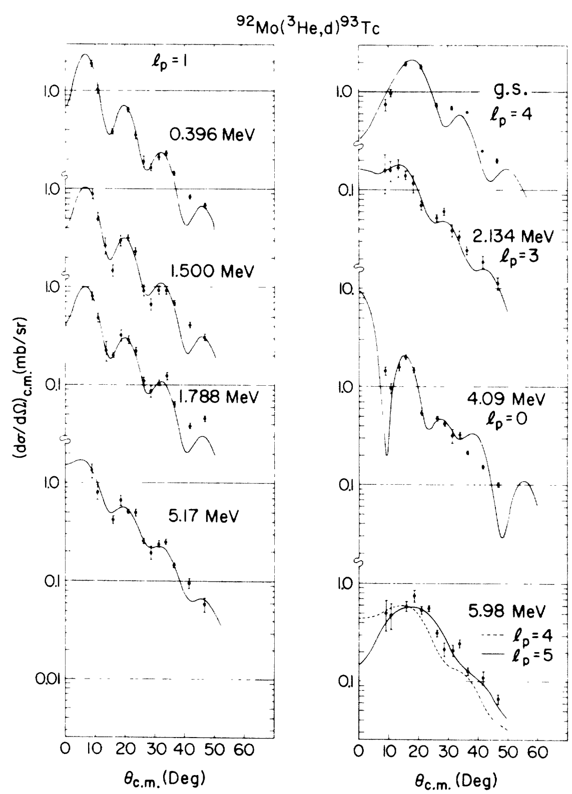

FIG. 3. Deuteron angular distributions for bound and unbound $T_<$ levels in ^{93}Tc. The curves are DWBA calculations.

TABLE I. Potential parameters for DWBA calculations.

Particle	V (MeV)	W (MeV)	$4W_D$ (MeV)	r_0 (F)	a (F)	r_I (F)	a_I (F)	λ_{so}	r_c (F)
^{3}He	157.77	11.71		1.174	0.706	1.596	1.032		1.25
d	95.49		81.08	1.131	0.874	1.376	0.616		1.25
p				1.25	0.65			25.	1.25

in Fig. 2. In a study of the ^{92}Mo(^{3}He, d)^{93}Tc reaction at 18-MeV bombarding energy, PB[5] made $l_p = 2$ assignments for levels at 2.565, 3.360, and 3.910 MeV. Although a deuteron group corresponding to 3.89-MeV excitation energy is well resolved in our spectra, the angular distribution has characteristics differing substantially from our other

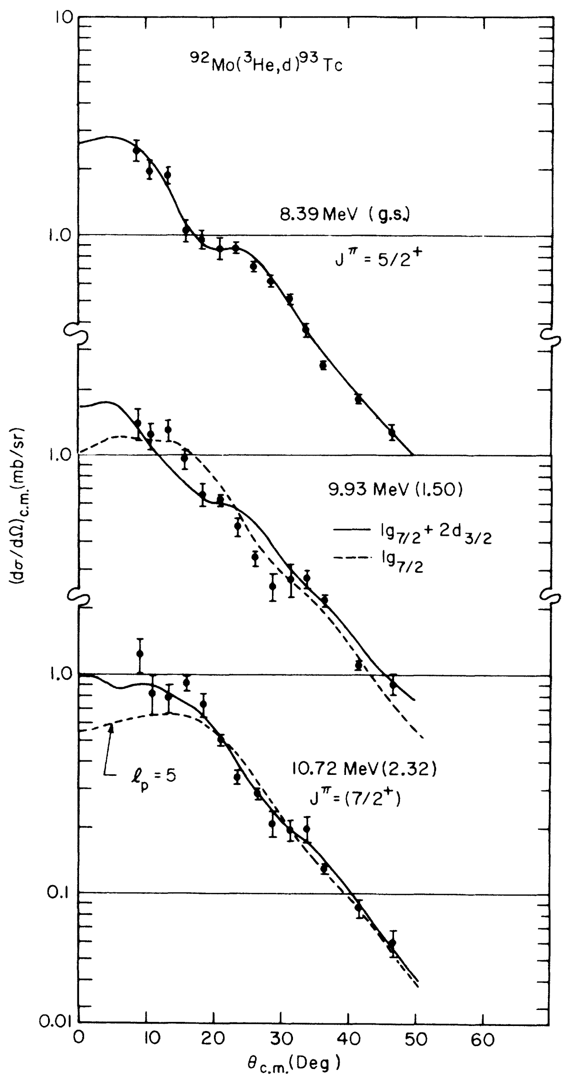

FIG. 4. Deuteron angular distributions for unbound IAS in ^{93}Tc. The curves are DWBA calculations. Excitation energies of corresponding ^{93}Mo parent states are shown in parentheses.

$l_p = 2$ data (Fig. 2) which may indicate the excitation of an unresolved multiplet. However, no combination of two l_p values was found which would provide a resultant DWBA curve consistent with the shape of the experimental distribution. Our $l_p = 2$ assignment for the 3.147-MeV level is in agreement with tentative assignment of PB. The spectroscopic factors obtained are in agreement with those of PB (Table II), although they used a DWBA normalization constant of 7.5 obtained from sum-rule considerations rather than the "Bassel normalization"[9] of 4.42 [see Eq. (1)].

Deuteron groups are observed corresponding to unbound $l_p = 2$ levels at 5.30- and 5.64-MeV excitation. A level at 5.50 MeV is probably due to an $l_p = 2$ transfer also (Fig. 2), although fluctuations in the data make this assignment uncertain. The unbound levels are observed in a region of the spectrum where the peak-to-background ratio is relatively low (Fig. 1). Also, the shape of the background in the vicinity of a given deuteron peak was observed to vary with angle in many cases, thereby making a consistent data analysis rather difficult for these levels. The DWBA curves for the unbound levels are very similar to those calculated for bound states, with a slight decrease in oscillatory structure as the reaction Q value becomes more negative.

$l_p = 1$ Levels

Deuteron groups corresponding to levels at 0.396-, 1.500-, 1.788-, and 5.170-MeV excitation energy were observed to have $l_p = 1$ angular distributions (Fig. 3). Our C^2S values are in agreement with those of PB (Table II) for the first three levels. The unbound level at 5.170 MeV has not been previously assigned. The level at 1.21 MeV, which has been assigned $l_p = 1$ by PB, is very weakly excited in the present work and no meaningful angular distribution was obtained.

The ^{92}Mo(d, ^{3}He)^{91}Nb results of Ohnuma and Yntema[4] indicate the $2p_{1/2}$ proton shell is approximately 70% filled in the ^{92}Mo ground state, while the $2p_{3/2}$ shell is 85% filled. The total $l_p = 1$ strength observed in the (^{3}He, d) reaction, if attributed to the $2p_{1/2}$ shell, is larger than the available hole strength by a factor of 2, which suggests that some of these levels have $J^\pi = \frac{3}{2}^-$. The sum of

TABLE II. Summary of results for $T_<$ states excited in the ^{92}Mo(^{3}He,d)^{93}Tc reaction.

^{93}Tc* (MeV ± keV)	l_p	J^π	C^2S(^{3}He, d) Present work	18 MeV [a]	34 MeV [b]
0.	4	$\frac{9}{2}^+$	0.50	0.67	0.69
0.396 ± 5	1	$\frac{1}{2}^-$	0.28	0.3	0.34
1.21 ± 20	1	$\frac{1}{2}^-$	0.034	0.025 [c]	
		$\frac{3}{2}^-$	0.015	0.01 [c]	
1.500 ± 10	1	$\frac{1}{2}^-$	0.12	0.10	
		$\frac{3}{2}^-$	0.052	0.04	
1.788 ± 10	1	$\frac{1}{2}^-$	0.11	0.12	
		$\frac{3}{2}^-$	0.048	0.05	
2.134 ± 15	3	$\frac{5}{2}^-$	0.045		
2.556 ± 15	2	$\frac{3}{2}^+$	0.037	0.043	
		$\frac{5}{2}^+$	0.019	0.02	
3.147 ± 15	2	$\frac{3}{2}^+$	0.034		
		$\frac{5}{2}^+$	0.018		
3.343 ± 15	2	$\frac{3}{2}^+$	0.78	0.78	
		$\frac{5}{2}^+$	0.41	0.38	
3.89 ± 20	(2)	($\frac{3}{2}^+$)	(0.11)	0.09	
		($\frac{5}{2}^+$)	(0.06)	0.05	
4.09 ± 30	0	$\frac{1}{2}^+$	0.23	0.15	
4.39 ± 40					
4.76 ± 30					
4.88 ± 30					
5.170 ± 15	1	$\frac{1}{2}^-$	0.23		
		$\frac{3}{2}^-$	0.083		
5.302 ± 15	2	$\frac{3}{2}^+$	0.059		
		$\frac{5}{2}^+$	0.032		
5.50 ± 40	(2)	($\frac{3}{2}^+$)	(0.051)		
		($\frac{5}{2}^+$)	(0.028)		
5.64 ± 40	2	$\frac{3}{2}^+$	0.035		
		$\frac{5}{2}^+$	0.019		
5.98 ± 40	(5)	($\frac{11}{2}^-$)	(0.079)		
6.24 ± 40					

[a]See Ref. 5.
[b]See Ref. 4.
[c]It appears there are misprints in Ref. 5, Table 3, concerning the C^2S values for the 1.21-MeV level. The values are consistent with our results and the data of Ref. 5 if they are reduced by a factor of 10.

the $\frac{1}{2}^-$ spectroscopic factors for the 0.396-, 1.500-, and 1.21-MeV levels in the present work (0.43) would account for all the missing $2p_{1/2}$ strength (Table II), while a sum of the $l_p = 1$ strength for the 1.788- and 5.170-MeV levels assuming a spin $J = \frac{3}{2}$ yields a value of 0.13. A definite spin assignment has been made only for the 0.396-MeV level ($J^\pi = \frac{1}{2}^-$).[16]

Other Levels

Angular distributions for four other $T_<$ levels are also shown in Fig. 3. The ^{93}Tc ground state is known to have $J^\pi = \frac{9}{2}^+$,[16] and (^{3}He, d) spectroscopic factors of 0.67[5] and 0.69[4] have been measured previously for this transition. Our value of 0.50 is somewhat smaller than the above results, even though our C^2S values for the low-lying $l_p = 1$ and $l_p = 2$ levels are in excellent agreement with those of PB.[5] A C^2S value of 0.72 is obtained for the ground-state transition in the present work if the form-factor radius parameter is changed from 1.25 to 1.20 F as used by the above authors. However, this would also increase the C^2S values for the other levels by 30–40%.

The angular distribution for the 2.134-MeV level is well described by an $l_p = 3$ DWBA calculation (Fig. 3), and therefore is evidence for a $(1f_{5/2})^{-2}$ component in the ^{92}Mo proton configuration. The fit to the distribution for the 4.09-MeV level confirms the $l_p = 0$ assignment of PB. The angular distribution for the unbound level at 5.98 MeV is best described by an $l_p = 5$ calculation, which would indicate it is probably an $\frac{11}{2}^-$ level.

B. Isobaric Analog States

Levels of ^{93}Tc at 8.39-, 9.82-, 9.92-, and 10.72-MeV excitation energy coincide with expected positions of $T = T_z + 1$ analogs of low-lying levels in ^{93}Mo (see Fig. 1). Angular distributions and DWBA calculations for three of these levels are shown in Fig. 4. The spectroscopic factors [S in Eq. (1)] extracted should be comparable to those obtained from a neutron stripping reaction to the corresponding ^{93}Mo parent states (Table III). Our value of 0.72 for the $2d_{5/2}$ ground-state analog is in good agreement with that obtained for the parent state (0.84) by Moorhead and Moyer[17] via the ^{92}Mo(d, p)^{93}Mo reaction.

TABLE III. Summary of results for $T_>$ states excited in the ^{92}Mo(^{3}He, d)^{93}Tc reaction and comparison with parent states.

^{93}Tc* (MeV ± keV)	$J^{\pi\,a}$	^{93}Tc*-8.39 (MeV)	S(^{3}He, d)	^{93}Mo*[a] (MeV)	$S(d, p)$[a]
8.39 ± 30	$\frac{5}{2}^+$	0.	0.72	0.	0.84
9.82 ± 40	$\frac{7}{2}^+$	1.43	(0.35)[b]	1.371	0.26
9.92 ± 30[c]	($\frac{3}{2}^+$)	1.53	(0.7)[d]	1.502	0.50
	($\frac{7}{2}^+$)		(0.2)[d]	1.529	0.14
10.72 ± 30	($\frac{7}{2}^+$)[e]	2.33	0.52	2.320	0.37[e]

[a]See Ref. 17.
[b]Estimate for weakly excited level.
[c]Unresolved doublet.
[d]Calculated using relative strengths implied by $S(d, p)$ and normalizing the result to the (^{3}He, d) data (solid curve in Fig. 4).
[e]See Ref. 18.

A group which could correspond to the analog of the 0.95-MeV $3s_{1/2}$ level in ^{93}Mo is observed very weakly at only a few angles and no distribution was obtained. An upper limit of <100 μb/sr for the cross section at 33° is indicated by our data, which is consistent with the value of 47 μb/sr calculated with the DWBA code using the appropriate unbound form factor and the spectroscopic factor (0.64) from (d, p) stripping to the parent state.[17] Several closely spaced levels have been observed near 1.5-MeV excitation in ^{93}Mo, and the corresponding deuteron group (9.92-MeV excitation in ^{93}Tc) appears to contain at least two unresolved levels (Fig. 1). The solid curve in Fig. 4 represents a mixture of $2d_{3/2}$ and $1g_{7/2}$ strengths calculated assuming the relative strengths indicated by the parent-state spectroscopic factors[17]; however, the fit to the data is relatively poor. Spin and parity assignments of $\frac{7}{2}^+$ and $\frac{11}{2}^-$ have been made for the parent of the 10.72-MeV level by Hjorth and Cohen[18] and Moorhead and Moyer,[17] respectively. The angular distribution of the analog state appears to be best described by an $l_p = 4$ calculation, and the spectroscopic factor of 0.52 is in reasonable agreement with the value of 0.37 reported by Ref. 18 for the parent state.

It has been suggested that anomalies exist in the magnitudes of experimental cross sections for proton stripping reactions to IAS in the $A = 90$ region[19, 20] and that these anomalies are due to the special structure of the IAS. However, the method used in the present work for performing DWBA calculations to unbound levels provides good agreement with experiment, indicating that the "anomalous" cross sections are in fact a consequence of the reaction mechanism for stripping to unbound levels. A more detailed discussion of this subject is presented elsewhere.[21]

V. SUMMARY AND CONCLUSIONS

The ^{92}Mo ground-state proton configuration has been assumed to be of the form[3, 4]

$$a[(p_{1/2}{}^2)_0(g_{9/2}{}^2)_0] + b[(g_{9/2}{}^4)_0],$$

where a^2 and b^2 are approximately 0.7 and 0.3,

TABLE IV. Comparison of experimental and predicted (d, ^{3}He) hole strength in ^{92}Mo (g.s.).

Orbit	$\sum C^2S_{exp}$ [a]	$\sum C^2S_{pred}$ [b]
$1g_{9/2}$	2.7	3.68
$2p_{1/2}$	1.4	1.14
$2p_{3/2}$	3.4	3.46
$1f_{5/2}$	4.9	5.72

[a] (d, ^{3}He) results of Ref. 4.
[b] Predicted by configuration deduced from (^{3}He, d) results (see text).

respectively. The $2p_{3/2}$ and $1f_{5/2}$ hole strengths observed in this experiment and the (d,^{3}He) work of Ref. 4 suggest, however, that a more realistic configuration would contain sizable $(p_{3/2}^{-2})_0(g_{9/2}^{4})_0$ and $(f_{5/2}^{-2})_0(g_{9/2}^{4})_0$ terms, and that the $(p_{1/2}^{2})_0(g_{9/2}^{2})_0$ coefficient is much smaller than $(0.7)^{1/2}$ [see discussion in Sec. IV A]. The coefficients A_i of the terms in the wave function

$$A_1[(p_{1/2}^2)_0(g_{9/2}^2)_0]+A_2[(p_{1/2}^0)_0(g_{9/2}^4)_0]+A_3[(p_{3/2}^{-2})_0(g_{9/2}^4)_0]+A_4[(f_{5/2}^{-2})_0(g_{9/2}^4)_0]$$

may be determined from the experimental spectroscopic factors from the equation

$$A_i^2=(2J+1)C^2S_J/n_J\,,$$

where n_J is the number of proton holes of spin J in the ith term of the wave function, and C^2S_J is the total spectroscopic strength for spin J. The spin assignments suggested in Sec. IV A for the $l_p=1$ levels result in values of 0.43 and 0.27 for A_2^2 and A_3^2, respectively, while a value of 0.14 is obtained for A_4^2 from the $f_{5/2}$ strength. Using the condition $A_1^2+A_2^2+A_3^2+A_4^2=1$ then yields the result $A_1^2=0.16$ and predicts $C^2S=0.63$ for the total $g_{9/2}$ strength, which is in fair agreement with our result (0.50). This would indicate that the ^{93}Tc ground state has a large $g_{9/2}^5$ component, in contrast to the shell-model calculations of Auerbach and Talmi.[3]

The sum-rule limits predicted by the above configuration for proton pickup are compared with the total strength observed in the ^{92}Mo(d,^{3}He)^{91}Nb reaction[4] in Table IV. The predicted limits are consistent with experiment within the usual DWBA errors. The errors in estimating the $l_p=1$ spectroscopic factors may be abnormally large, since the forward maxima in the $l_p=1$ angular distributions occur at angles smaller than those observed experimentally in either Ref. 4 or the present work. In addition, the relatively strong $l_p=1$ transition to the 5.170-MeV level, which is 3.4 MeV higher in excitation than the next lowest $l_p=1$ level observed, could arise from a proton coupled to a $(p_{3/2}^{-4})_0(g_{9/2}^{6})_0$ term. These factors introduce additional uncertainties in the coefficients A_1, A_2, and A_3, but it appears A_1^2 is certainly <0.4. Similar proton hole strengths in the $f_{5/2}$ and $p_{3/2}$ orbits have been observed in the ^{90}Zr(^{3}He,d)^{91}Nb reaction.[6]

The sum of all $l_p=2$ spectroscopic factors is 0.7 (including C^2S for the IAS) if all levels are assumed to have spin $\frac{5}{2}$. Only small fractions of the $3s_{1/2}$ and $1h_{11/2}$ strengths have been observed, and no $1g_{7/2}$ states have been identified. The unresolved multiplets at 4.39-, 4.76-, 4.88-, and 6.24-MeV excitation energy (Fig. 1) contain a portion of the missing strengths, but the distributions obtained for these groups were such that little or no information could be derived from them.

The DWBA analysis for unbound levels has resulted in good fits to the data and, as is evidenced by the agreement of the IAS spectroscopic factors with those for the parent states, the normalization of the form factor to the exterior classical turning radius appears to be reasonable.

It is apparent that the (^{3}He,d) reaction to unbound $T_>$ states can be described adequately by the DWBA without ascribing any special structure to the IAS (see also Ref. 21). It is necessary, however, that the DWBA form factor used in the calculation properly describe the actual binding energy of the transferred particle.

Note added in proof: It is well known that DWBA spectroscopic factors can be very sensitive to the parameters used in the calculation, and that the shape of the form-factor potential is a major source of uncertainty. Therefore, in order to provide a more meaningful comparison of our (^{3}He,d) spectroscopic factors for the IAS to the (d,p) results, we have performed DWBA calculations for the (d,p) data of Ref. 17 using the optical potentials given there and the same form-factor potential parameters as those used in this work (Table I). The spectroscopic factors obtained are 0.70, 0.38, and 0.56 for the ground, 1.371- and 2.320-MeV levels of ^{93}Mo, respectively. The agreement with our (^{3}He,d) results for the IAS (Table III) is surprisingly good in view of the fact that both (d,p) and (^{3}He,d) spectroscopic factors are also sensitive to uncertainties in optical potentials.

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Energy Levels in ^{156}Gd Populated by 5.4-Day ^{156}Tb

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γ-ray singles and coincidence measurements have been carried out on the decay of ^{156}Tb with Ge(Li) detectors to study levels of ^{156}Gd. A total of 102 transitions were observed, of which 52 were previously unreported. Of these 78 were placed in the decay scheme with levels at: 88.967, 2^+0; 288.16, 4^+0; 584.74, 6^+0; 1129.52, 2^+0; 1154.23, 2^+2; 1242.5, $1^-(0)$; 1248.08, 3^+2; 1258.4, 2^+0; 1276.22, $3^-(0)$; 1297.7, 4^+0; 1319.69, $2^-(1)$; 1355.52, 4^+2; 1366.6, $1^-(1)$; 1462.4, 4^+0; 1468.5, (4^-1); 1510.67, $4^+(4)$; 1539.0, (3^-1); 1622.64, $5^+(4)$; 1852.09, $3^-(2)$; 1943.41, 3^-; 2045.04, $4^-(4)$; 2103.49, 3^-; 2175.6, 2181.5, and 2232.9 keV. The spin, parity, and K assignments are given where known after each level. 12 of these levels are reported in this decay for the first time.

I. INTRODUCTION

Studies of levels in ^{152}Sm and ^{154}Gd which exhibit the rotational and vibrational properties of nuclei with permanently deformed ground states, yet are soft to nuclear deformation, have provided a great wealth of significant information for comparison with the Bohr-Mottelson model. In particular, in recent years the first evidence on β bands[1,2] in deformed rare-earth nuclei and for large $E0$ admixtures[2,3] in $\Delta I = 0$ transitions from these bands[1] came from these nuclei. The first evidence for the failure of the Bohr-Mottelson model to predict branching ratios from the β bands occurred in these nuclei.[4,5] At the same time similar evidence[6] was obtained for the 2^+ level of the β band in ^{156}Gd. These nuclei are spoken of as transitional nuclei because they are in the region where the transition from near spherical to large permanent deformation sets in. Since the ^{156}Gd nucleus is further into the region of strongly deformed nuclei, one may expect to see changes in the level structures of ^{154}Gd and ^{156}Gd.

Thus we have extended our studies of deformed nuclei by carrying out careful γ-ray singles and coincidence measurements on the decay of ^{156}Tb to ^{156}Gd. Since the ground state of ^{156}Tb is 3^-, as is that of ^{154}Eu which decays to ^{154}Gd, one could expect similar levels to be populated. Earlier ^{156}Tb studies[7-11] have reported 13 excited states in ^{156}Gd populated by ^{156}Tb. These studies included electron[7-9] and γ-ray[7,8,10] measurements and low-temperature nuclear-orientation experiments.[11] There are also several earlier studies[12] of the ^{156}Gd levels from the decay of ^{156}Eu which has a 0^+ ground state. The ^{156}Eu decay populates 0^+ and