Particle-Hole Multiplets in Y^{88} and the Mechanism of the (He^3,t) Reaction*

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The reactions $Sr^{87}(He^3,d)Y^{88}$, $Sr^{87}(\alpha,t)Y^{88}$, $Sr^{88}(He^3,t)Y^{88}$, and $Y^{89}(He^3,\alpha)Y^{88}$ were studied and the data were used to construct a level scheme of Y^{88}. Spin and parity assignments are suggested for many new states below 2.5 MeV. The principal components of their wave functions are interpreted in terms of particle-hole multiplets. The angular distributions from the (He^3,t) reaction are not well fitted by distorted-wave calculations. Some systematic patterns of the (He^3,t) reaction mechanism are noted, but the exceptions indicate that the conventional treatment of the (He^3,t) reaction may be far from adequate.

I. INTRODUCTION

With the closure of the $1f$-$2p$ proton shell at $Z=40$, and the $1g_{9/2}$ neutron subshell at $N=50$, ${}_{40}Zr^{90}_{50}$ has often been considered to be a reasonably good closed-shell nucleus. However, the near degeneracy of the $2p_{1/2}$ and $1g_{9/2}$ single-particle orbitals introduces significant configuration mixing in the Zr^{90} ground state.[1-4] Evidence suggests that ${}_{38}Sr^{88}_{50}$ may be a better example of a closed-shell nucleus. Studies[4,5] of the $Sr^{88}(He^3,d)Y^{89}$ reaction reveal that the $2p_{1/2}$ and $1g_{9/2}$ proton orbitals in Sr^{88} are nearly empty. In contrast, the two additional protons in the Zr^{90} ground state are approximately equally distributed between the $p_{1/2}$ and $g_{9/2}$ orbitals.

If closed shells are assumed for the ground state of Sr^{88}, relatively pure multiplets may be expected in ${}_{39}Y^{88}_{49}$ produced by coupling a proton and a neutron hole. The Sr^{88} ground-state configuration and the measured strengths for proton stripping[5] and neutron-pickup[6] reactions on such a target are shown in Fig. 1. (The $l=1$ neutron pickup strengths are probably overestimated by the distorted-wave Born-approximation analysis.[6]) Estimating the centroid energies of the multiplets by adding the single-particle and single-hole energies leads to identification of the multiplets with energies less than 2.5 MeV as shown in Fig. 2. Residual interactions will remove the degeneracies and introduce some configuration mixing.

Isospin considerations prevent some of the multiplets in Fig. 2 from having unique representations in terms of proton particles and neutron holes. These are indicated by dashed lines in the figure. As an example, let us consider the $(g_{9/2}p_{3/2}^{-1})$ multiplet. In Sr^{88} we can excite a $p_{3/2}$ proton into the $g_{9/2}$ orbit and produce these $T=6$ states which may be written as

$$[(p_{3/2})^7{}_{3/2,\,1/2}(p_{1/2})^2{}_{0,1}(g_{9/2})^{11}{}_{9/2,\,9/2}]_{J,\,T}\,.$$

In Y^{88} we have the corresponding excited analog multiplet with $T=6$, as depicted in Fig. 3. Since the analog wave function has three components, there are two possible combinations orthogonal to the analog multiplet, corresponding to two antianalogs of the same configuration but with $T=5$. In addition there is a multiplet in which the 11 $g_{9/2}$ particles are coupled to isospin $\frac{7}{2}$ (as in an idealized ground state of Zr^{89}, for which the two protons are in the $g_{9/2}$ orbit) – in other words, the multiplet

$$[(p_{3/2})^7{}_{3/2,\,1/2}(p_{1/2})^2{}_{0,\,1}(g_{9/2})^{11}{}_{9/2,\,7/2}]_{J,\,T=5}\,.$$

We must also consider a slightly different configuration, which may be written as

$$[(p_{3/2})^7{}_{3/2,\,1/2}(p_{1/2})^4{}_{0,\,0}(g_{9/2})^9{}_{9/2,\,9/2}]_{J,\,T=5}\,.$$

The last two will mix in the same manner as the two 0^+ states in Zr^{90}. The $Sr^{88}(He^3,t)Y^{88}$ reaction should populate only the excited analog and antianalog multiplets, the cross-section ratio of the two antianalogs being dependent on the magnitude of the component corresponding to the first term in the diagram for the analog state in Fig. 3. The way this strength is distributed between the two antianalogs is not predictable without a detailed model, but the sum of the squares of the two coefficients should be $\frac{11}{12}$. The $Zr^{90}(d,\alpha)$ reaction should preferentially populate the last two of the four $T=5$ states, the antianalog states will be populated more weakly. Of course it is quite possible that these multiplets will mix with each other and

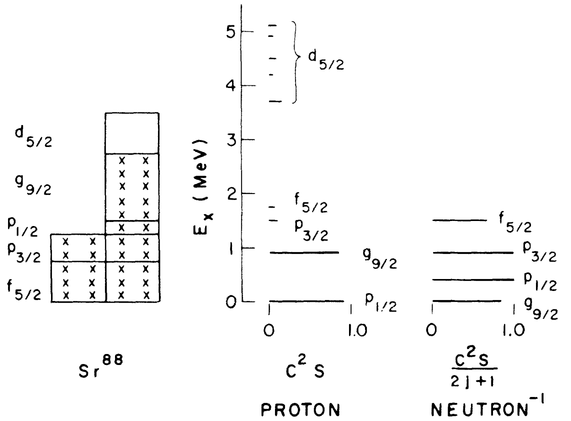

FIG. 1. The Sr^{88} ground-state configuration, and the strengths observed for the reactions $Sr^{88}(He^3,d)Y^{89}$ (Ref. 5) and $Sr^{88}(He^3,\alpha)Sr^{87}$ (Ref. 6).

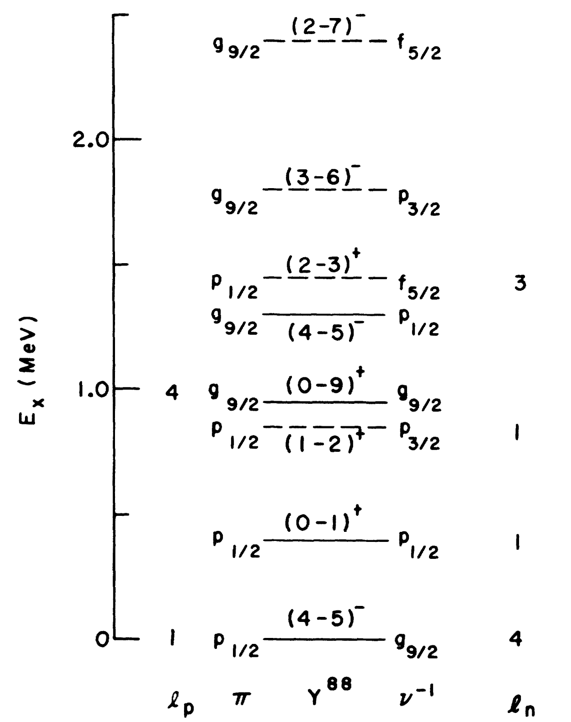

FIG. 2. The particle-hole multiplets in Y^{88} which can be populated by reaction reported here. The multiplets are plotted at their anticipated centroid energies and are shown degenerate. The range of spins is indicated in parenthesis. The symbols π and ν^{-1} label the proton-particle and neutron-hole orbits of the multiplets. The labels are not unique for multiplets shown by dashed lines (see text). The l values expected for proton-transfer and neutron-pickup reactions into Y^{88} are also indicated by l_p and l_n, respectively.

also with other states. Similar sets of states will occur for the $(g_{9/2}f_{5/2}{}^{-1})$ configuration. For the $(p_{1/2})^2{}_0$ and $(g_{9/2})^2{}_0$ states in Y^{88}, we have to keep in mind that there is one analog state

$$[(\tfrac{10}{12})^{1/2}(\nu g_{9/2})^9\pi g_{9/2}(\nu p_{1/2})^2+(\tfrac{2}{12})^{1/2}(\nu g_{9/2})^{10}\nu p_{1/2}\pi p_{1/2}]_{0,6}$$

and one antianalog

$$[(\tfrac{2}{12})^{1/2}(\nu g_{9/2})^9\pi g_{9/2}(\nu p_{1/2})^2-(\tfrac{10}{12})^{1/2}(\nu g_{9/2})^{10}\nu p_{1/2}\pi p_{1/2}]_{0,5}.$$

Y^{88} is thus an intrinsically interesting nucleus for detailed study. Its states can be populated by a variety of reactions. Some of the multiplets can be reached by proton-stripping reactions on Sr^{87} targets or by neutron pickup on Y^{89} targets. These are labeled in Fig. 2 with the appropriate l values expected for direct-reaction transitions. The simplest shell-model configurations are assumed for the target ground states.

The (He^3, t) reaction has been found to be a useful spectroscopic tool for identifying the nuclear levels of simple particle-hole multiplets. These include the states of the $(1f_{7/2})^2$ multiplet,[7–10] the $(1g_{9/2})^2$ multiplet,[11, 12] and the $(g_{9/2}d_{5/2}{}^{-1})$ multiplet,[13] all of which are seen prominently in the low-excitation spectra of the residual nuclei. The angular distributions seem to be characteristic of the orbital angular momentum transfers and thus lead to spin assignments for the states.

Of particular interest is the identification of the $(g_{9/2})^2$ multiplet. Members of this multiplet have previously been observed[11] in Nb^{90}. In the absence of extensive configuration mixing in these nuclei, this multiplet in Y^{88} should show a similar ordering and spacing of levels. It is also expected that the members of the $(g_{9/2})^2$ multiplet should be particularly prominent in the spectra from the (He^3, t) reaction. Distorted-wave (DW) calculations indicate that, for pure configurations and identical L values, states from the $(g_{9/2})^2$ configuration

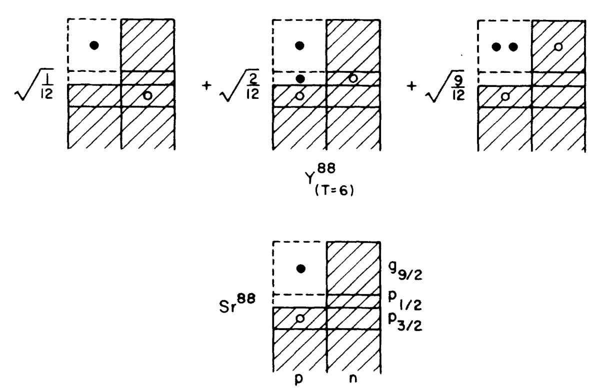

FIG. 3. Schematic representation of a $(p_{3/2}{}^{-1}g_{9/2})$ configuration in Sr^{88} and the isobaric analog of this state in Y^{88}.

would be 2–3 times as intense as those having $(p_{1/2}p_{3/2}^{-1})$ or $(p_{1/2}f_{5/2}^{-1})$ configurations, for example.

Also of interest is an investigation of transitions in the (He^3, t) reaction to multiplets characterized by two different single-particle orbitals. These have not been seen very prominently in the spectra of nuclei for which an identical-orbit multiplet is present in the low-excitation region,[7–12] but they are quite apparent[13] in Nb^{96}. However, these previous studies have been limited to target nuclei in which, in the simplest shell-model configuration, protons and neutrons are matched for all but one orbital. As seen in Fig. 1, there are two such orbitals in Sr^{88} and the multiplets in Fig. 2 have both identical-orbit and nonidentical-orbit configurations.

In the following we report studies of proton-stripping, neutron-pickup, and charge-exchange reactions leading to the nucleus Y^{88}. The results from this and previous studies are used to construct a level scheme and to make spin and parity assignments for many of the states in Y^{88}.

II. EXPERIMENTAL PROCEDURES

Beams of He^3 and He^4 particles were obtained from the Argonne National Laboratory FN tandem accelerator. The reaction products were momentum-analyzed in a split-pole magnetic spectrograph[14] and detected by photographic emulsions placed in the focal plane. Ilford K-1 plates (underdeveloped) were used for recording α particles and Kodak NTB plates for detecting deuterons and tritons. These latter plates were scanned by a computer-controlled plate scanner.[15] Some of them were also scanned manually, as were the Ilford plates.

The experimental conditions relevant to each of the reactions are listed in Table I. The strontium targets were made by evaporating $Sr(NO_3)_2$ onto thin carbon and Formvar backings, and they were kept under vacuum at all times. The yttrium target[16] was a self-supporting foil.

Since absolute cross sections were not the principal interest in this study, the target thicknesses were not measured. The thickness of the yttrium target was already known, but those for the strontium targets were estimated during their preparation. A silicon surface-barrier detector mounted in the scattering chamber at 60° was used as a monitor counter. No deterioration of the targets was observed during any of the experiments.

The data were analyzed by means of a series of computer programs.[17] Levels in Y^{88} were identified by plotting the spectra of each reaction with the Q value as the abscissa and noting the peaks with the same value of Q. Each of the levels identified was observed in at least two reactions. Spectra from three of the reactions are shown in Fig. 4, in this case plotted with excitation energy as the abscissa.

The number of counts in each peak in a spectrum was obtained with the program AUTOFIT.[17] A sample graphical output of the program is shown in Fig. 5. The results of the AUTOFIT analysis were used in plotting the angular distributions. The cross sections for the reactions on the strontium targets are quoted in arbitrary units. However, if the nominal target thicknesses are correct, these should be interpreted as μb/sr. The error in this absolute value is expected to be less than a factor of 2.

Most of the results of this study are summarized in Table II. Many of the spin, parity, and configuration assignments are tentative and should be interpreted in the light of the discussion that follows.

III. DISTORTED-WAVE CALCULATIONS

Calculated angular distributions for each of the reactions were obtained by use of the DW computer code DWUCK.[18] These were principally intended to assist in the identification of the orbital angular momenta transferred in the reactions. The optical-model potentials[5, 6, 19, 20] are listed in Table III.

The angular distributions for the $Sr^{87}(He^3, d)Y^{88}$ reaction were calculated with potential Sets H1-D1. These have also been used in the analysis of (He^3, d) reactions on Sr^{88} and Sr^{86} targets.[5, 21] Other potential sets were also tested. The calcu-

TABLE I. The experimental conditions pertaining to each of the reactions studied in the present investigation. The thicknesses of the strontium targets are estimates and are probably correct within a factor of 2.

Reaction	Energy (MeV)	Target	Enrichment (%)	Thickness ($\mu g/cm^2$)	Resolution width (keV)
$Sr^{87}(He^3, d)Y^{88}$	18	$Sr^{87}(NO_3)_2$	93.3	~100	20
$Sr^{87}(\alpha, t)Y^{88}$	25	$Sr^{87}(NO_3)_2$	93.3	~100	25
$Sr^{88}(He^3, t)Y^{88}$	23	$Sr^{88}(NO_3)_2$	99.8	~100	20
$Y^{89}(He^3, \alpha)Y^{88}$	25	Y^{89}	100.0	110	30

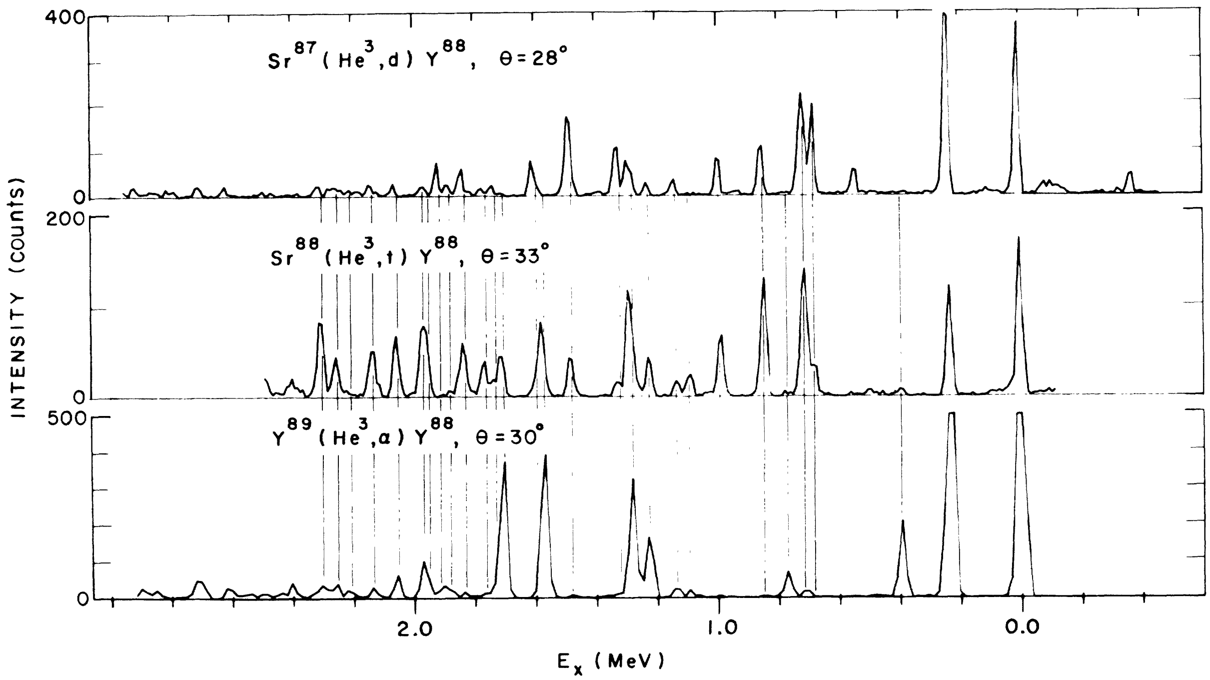

FIG. 4. Spectra from the principal reactions. Each was observed at the indicated angle θ and is plotted against excitation energy in Y^{88}. Thin vertical lines connect the states identified in Y^{88}.

lated absolute cross sections were significantly dependent on the choice of optical potentials and on finite-range and nonlocal corrections, but the relative cross sections and shapes were mostly independent of such effects. Figure 6 shows two states that exhibit $l = 1$ stripping patterns and two that are $l = 4$. The differences were clear enough that states with sufficient yield produced no ambiguities in the assignment of l values. States with $l = 0$, 2, or 3 angular distributions were not expected to be strongly populated, and none were identified.

Relative transition strengths for the proton transfer reactions are given by the expression

$$\frac{d\sigma}{d\Omega} = 4.42\,\frac{2J_f+1}{2J_i+1}\sum_l C^2 S_l\,\frac{\sigma_l(\text{DWUCK})}{2j+1}\,, \tag{1}$$

where J_i, J_f, and j are the total angular momenta of the target nucleus, the final state, and the

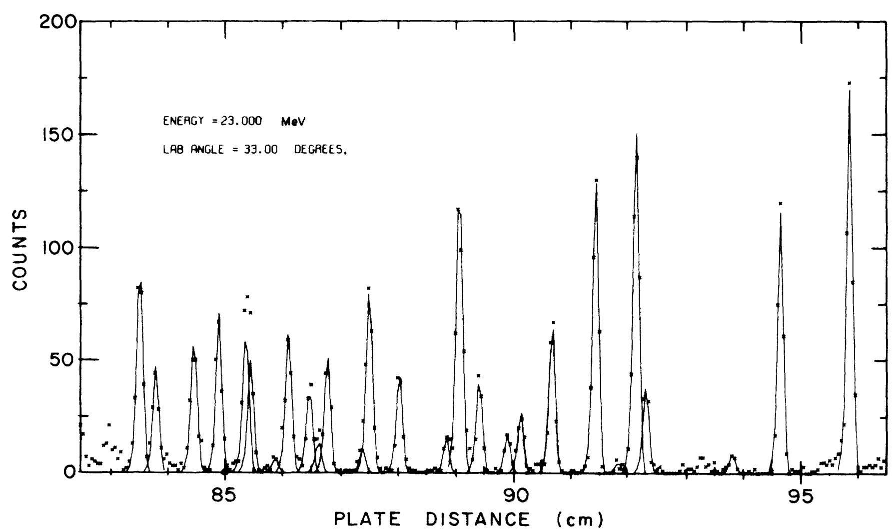

FIG. 5. A typical plot from the program AUTOFIT. The data were obtained for the reaction $Sr^{88}(He^3,t)Y^{88}$.

transferred particle, respectively. Relative values were extracted from the (He^3, d) data by setting $C^2S = 1.0$ for the 1.47-MeV state. As discussed in Sec. IV A *2*, this state is believed to be the $J^\pi = 9^+$ member of the $(g_{9/2})^2$ multiplet and should have a nearly pure configuration. This normalization produced reasonable values for C^2S for other states of Y^{88} and was also in good agreement with the nominal target thickness.

The experimental angular distributions from the (He^3, α) reaction did not show distinctive structures. They were approximately exponential in shape except that the $l = 1$ distributions seemed to flatten at forward angles. This effect was reproduced by the DW calculations, as is shown in Fig. 7. The (He^3, α) reaction is known to have very poor momentum-matching characteristics[6] so that relative spectroscopic strengths for states with different values of l are quite uncertain. The present (He^3, α) data were used primarily for establishing the consistency in the interpretation of the results obtained from the other reactions.

TABLE II. Summary of the principal spectroscopic results for the levels of Y^{88}. The J^π and configuration assignments are believed to be reasonable, but should be interpreted in the light of the text. Only the lowest four levels and the 0.77-MeV state had known assignments before the present study. The maximum experimental cross sections $(d\sigma/d\Omega)_{max}$ have units μb/sr. The values of C^2S for the (He^3, d) reaction are normalized to 1.0 for the 1.48-MeV state. The L assignments for the (He^3, t) reaction are semiempirical, as explained in Sec. III. The abbreviation n.o. means not observed. Configuration assignments in square brackets are especially tentative.

E_x (MeV)	J^π	Principal configuration $\pi\nu^{-1}$	(He^3, d) $d\sigma_{max}$	(He^3, d) l	C^2S	(He^3, α) $d\sigma_{max}$	(He^3, α) l	(He^3, t) $d\sigma_{max}$	(He^3, t) L [a]
0.000	4^-	$(p_{1/2}g_{9/2})$	380	1	0.82	3600	4	58	3, 5
0.234	5^-	$(p_{1/2}g_{9/2})$	510	1	0.83	4500	4	23	5
0.393	1^+	$(p_{1/2})^2$	n.o.			200	1	14	0, 2
0.678	8^+	$(g_{9/2})^2$	140	4	1.18	Weak		9	8
0.712	$\{7^+$ $\{6^+$	$\{(g_{9/2})^2$ $\{(g_{9/2})^2$	190	4	1.04	38		25	6–8
0.767	0^+	$(p_{1/2})^2$	n.o.			97	1	18	0
0.847	5^+	$(g_{9/2})^2$	84	4	1.12	10		27	4, 6
0.989	4^+	$(g_{9/2})^2$	67	4	1.06	Weak		37	4
1.092	$(5^-, 6^-)$		7	(1)		34		8	(4–6)
1.134	$(5)^-$	$[g_{9/2}p_{1/2}]$	49	1	(0.076)	120	4	4	(4–6)
1.225	$\{1^+$ $\{(2^+)$	$\{(p_{1/2}p_{3/2})$ $\{[(g_{9/2})^2 + ?]$	19	4	0.86	280	1	55	0 (+2)
1.282	$\{3^+$ $\{(4^-)$	$\{(g_{9/2})^2$ $\{[g_{9/2}p_{1/2}]$	$\{$ 80	4 +(1)	1.15	380	1	$\{$74	2, 4 +(?)
1.323	$(5, 6)^-$		140	1	(0.2)	Weak		3	(5–7)
1.478	9^+	$(g_{9/2})^2$	150	4	1.0	20		14	8, 10
1.573	2^+	$(p_{1/2}p_{3/2})$	15			660	(1)	28	2
1.598	$()^-$		78	1		Weak		4	
1.705	3^+	$(p_{1/2}f_{5/2})$	8			920	(3, 4)	14	(5–7)
1.732			27	(1)		Weak		5	
1.765			22			23		7	(6–8)
1.832	$()^-$		81	1		43	14	(6–8)	
1.881			43	(1)		53	(3, 4)	2	
1.913	$()^-$		81	1		150	(3, 4)	2	
1.952	2^+	$(g_{9/2})^2 + (p_{1/2}f_{5/2})$	17	(4)	0.39	$\{$290	(3, 4)	38	2
1.971			12					15	
2.056	2^+	$(g_{9/2})^2 + (p_{1/2}f_{5/2})$	16	4	0.37	140	(3, 4)	57	2
2.136			30	(1)		67		10	(6–8)
2.210			n.o.			62		Weak	
2.252			6			100		13	(4–6)
2.305			30			72		16	(5–7)

[a] The L values without parentheses are determined from the J^π values in column 2; those with parentheses are based on empirical calibration.

A full discussion of the DW calculations for the (He^3, t) reactions is given in Sec. V. Since these generally could not fit the data, an empirical calibration of the L values associated with the angular distributions was established during the analysis of the data. The L values quoted in Table II for transitions to states with known or presently assigned spins are those required by selection rules. For the other states, the L values are estimates based on the empirical calibration.

IV. PROPERTIES OF Y^{88}

A. Energy Levels

The energy levels of Y^{88} identified in the present study are listed in Table II. Their relative excitation energies are believed to be known to within 5 keV. Some of the levels were only partly resolved from their neighbors and their relative intensities were quite dependent on the reaction. For example, as seen in Fig. 4, the states at 1.57 and 1.60 MeV were not entirely separated. The 1.60-MeV state was more intense in the (He^3, d) reaction, and the 1.57-MeV state was more intense in the (He^3, α) and (He^3, t) reactions.

Three additional levels listed in Table II are also believed to be doublets whose component members are separated by 15 keV or less. These are the levels at 0.712, 1.225, and 1.282 MeV. Although the spectra did not indicate that the widths of these levels were measurably larger than those of other states, their angular distributions and relative intensities showed significant indications of the presence of more than one level. These aspects will be discussed in more detail in Secs. IV B and IV C.

B. Identical-Orbit Multiplets

1. $(p_{1/2})^2$ Multiplet

The principal components of the $(p_{1/2})^2$ multiplet have previously been assigned[6,22,23] at 0.39 MeV ($J^\pi = 1^+$) and at 0.77 MeV (0^+). A portion of the $J^\pi = 0^+$ member is also contained in the analog state at 7.05 MeV. The present data are entirely consistent with these assignments. As expected, these states are not seen in the (He^3, d) reaction, but they are populated by the (He^3, α) reaction with $l=1$ and also by the (He^3, t) reaction.

The $J^\pi = 0^+$ state at 0.77 MeV is thought to be an antianalog state whose wave function has been described in Sec. I. This state should be populated only weakly by the (He^3, t) reaction. It has been previously observed[24] with about 10% of the analog-state cross section and was also seen here weakly. For such a configuration, the expected ratio of the cross section for the 0.39-MeV state to that for the 0.77-MeV state in the (He^3, α) reaction is 3.6. The observed ratio of 2.7 is evidence for configuration mixing in the 1^+ state.

2. $(g_{9/2})^2$ Multiplet

Simple calculations indicate that the $J^\pi = 8^+$ member of the $(g_{9/2})^2$ configuration, known[11,25] to be the ground state in Nb^{90}, should lie near 600 keV in Y^{88}. States of this multiplet should be populated by the (He^3, d) reaction on Sr^{87} via $l=4$ transitions. If the states have relatively pure configurations, the (He^3, d) cross sections should be proportional to $(2J_f+1)$.

Eight levels with $l=4$ stripping patterns are identified in Table II for the (He^3, d) reaction, the lowest level occurring at 0.678 MeV. Those below 1.8 MeV were also observed to be very prominent in the spectra of the $Sr^{87}(\alpha, t)Y^{88}$ reaction. The (α, t) reaction is expected to favor the transfer of large l values, and this selective enhancement corroborated the identification of the l value assigned to these levels. Furthermore, the relative transition strengths (corrected for effects dependent on Q value) were quite similar for the two reactions.

Tentative assignments of these states as mem-

TABLE III. The optical potentials used for the DW calculations. The notation is standard. V and W are the depths of Fermi-shaped wells, and W' is the strength of a derivative Fermi shape.

Label	Particle	V (MeV)	W (MeV)	W' (MeV)	r_0 (F)	a (F)	r' (F)	a' (F)	r_C (F)	V_{so} (MeV)
D1[a]	d	98.0		18.0	1.10	0.85	1.40	0.70	1.30	6.0
H1[a]	He^3, t	170.0	20.0		1.14	0.75	1.60	0.80	1.40	
H2[b]	He^3, t	159.6	21.4		1.22	0.695	1.50	0.79	1.40	
H3[c]	He^3, t	152.0	19.6		1.24	0.684	1.48	0.771	1.25	
A1[d]	α	207.0	28.0		1.30	0.65	1.30	0.52	1.40	
Bound state		e			1.20	0.70			1.25	$\lambda = 25$

[a]Reference 5.
[b]Reference 19.
[c]Reference 20.
[d]Reference 6.
[e]Adjusted to reproduce the binding energy of each level.

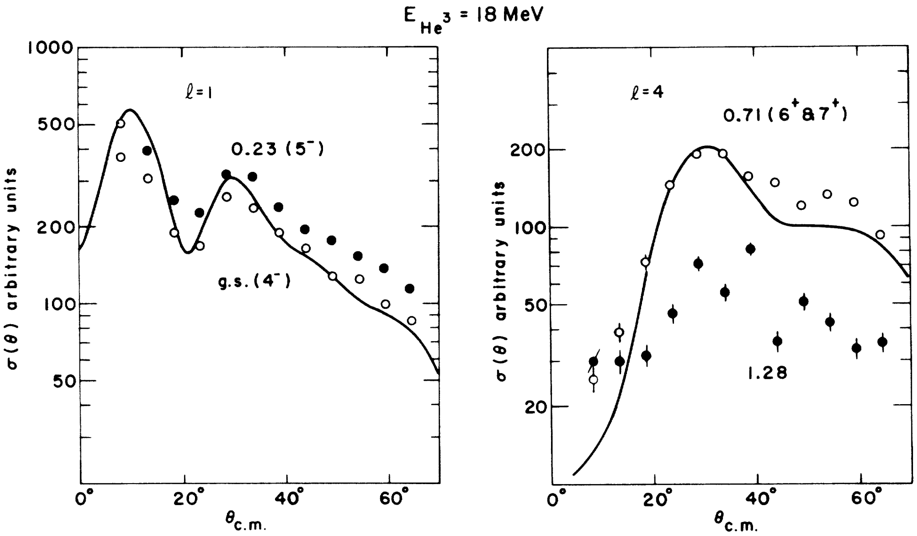

FIG. 6. Four angular distributions for levels in Y^{88}, two each for $l=1$ and $l=4$ stripping patterns in the $Sr^{87}(He^3, d)Y^{88}$ reaction. The curves are DW calculations.

bers of the $(g_{9/2})^2$ multiplet were made on the basis of the yields of the (He^3, d) reaction. These are indicated in Fig. 8, where the data are normalized to the 1.47-MeV state, which is assumed to have $J^\pi = 9^+$.

The transition strengths did not provide a unique association of the levels with states of the $(g_{9/2})^2$ configuration since they did not form a perfect $(2J+1)$ pattern. In particular, the strength for the 0.71-MeV state was exceptionally large and those for the 1.23- and 2.06-MeV states were too small. Additional information was provided by the angular distributions of the $Sr^{88}(He^3, t)Y^{88}$ reaction. These could be readily ordered so that the maximum cross section occurred at successively larger angles, as shown in Fig. 9. On the assumption that the spins have the same ordering as is suggested by the DW calculations and by previous studies of

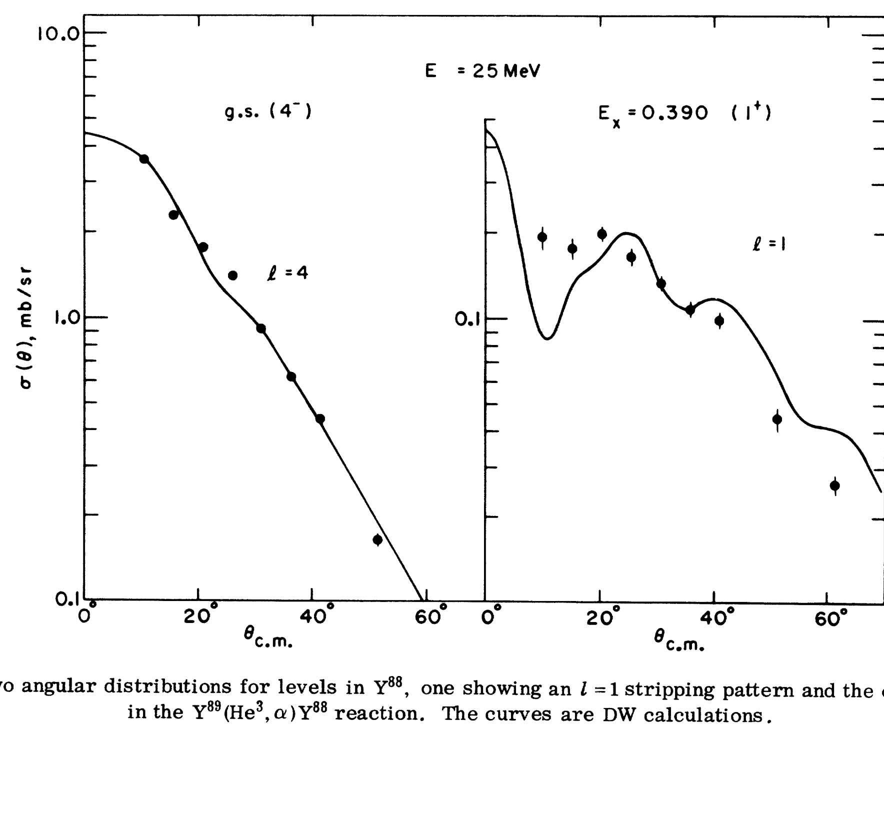

FIG. 7. Two angular distributions for levels in Y^{88}, one showing an $l=1$ stripping pattern and the other an $l=4$ in the $Y^{89}(He^3, \alpha)Y^{88}$ reaction. The curves are DW calculations.

the (He^3, t) reaction,[7-13] the tentative assignments for the Y^{88} levels were substantiated and ambiguities were resolved.

Thus, even though the observed transition strength in the (He^3, d) reaction is slightly larger for the 0.68-MeV state than for the 1.47-MeV state, the angular distribution of the former in the (He^3, t) reaction is peaked at more forward angles and supports the assignments $J^\pi = 8^+$ and 9^+, respectively. This ordering is also expected from the known levels of Nb^{90}, in which the 9^+ state is about 900 keV above the 8^+ ground state.

The state at 0.71 MeV has a (He^3, t) angular distribution which peaks at an angle between those for the presumed 5^+ and 8^+ members of the multiplet. Its transition strength in the (He^3, d) reaction is much too large for either a 6^+ or a 7^+ state, but it closely matches the sum of the strengths for the two states. In Nb^{90}, both a 6^+ or a 7^+ state are present between the 5^+ and 8^+ states. Hence we infer that the level at 0.712 MeV in Y^{88} is an unresolved doublet whose members have assignments $J^\pi = 6^+$ and 7^+.

The transition strength for the 1.28-MeV state also appears to be unusually large. Although the ratio to the expected value for the (He^3, d) reaction is not significantly larger than the ratios for other states, the (α, t) reaction seems to confirm the excess. Furthermore, as seen in Fig. 6, the angular distribution for this level in the (He^3, d) reaction exhibits deviations from the characteristic $l = 4$ shape. In addition, this level is populated moderately strongly by the Y^{89}(He^3, α)Y^{88} reaction.

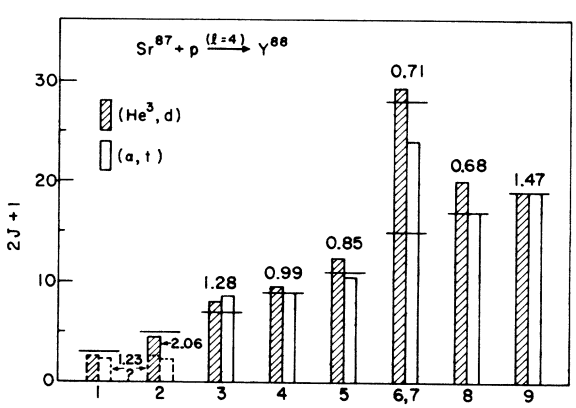

FIG. 8. The transition strengths $(2J_f+1)C^2S$ for levels of Y^{88} populated with $l = 4$ transitions by the (He^3, d) and (α, t) reactions on Sr^{87}. The energies of the states (in MeV) are shown above the bars. Since $C^2S = 1$ for pure configurations, the lengths of the bars for each assigned value of J should be nearly equal to $2J+1$. These values are indicated by horizontal lines. The strength for the 1.23-MeV state may be divided between $J^\pi = 1^+$ and 2^+ states.

This would not be expected if the state has a relatively pure $(g_{9/2})^2$ configuration, as noted in Fig. 2. We believe that this level is also an unresolved doublet. More will be said about this later in this section.

The angular distribution from the (He^3, t) reaction for the 1.23-MeV state shows an oscillatory pattern that is very similar to that for the 0^+ state at 0.77 MeV. The 0^+ strength of the $(g_{9/2})^2$ multiplet is shared between the lowest analog state near 7 MeV and the 0.77-MeV state. Figure 2 shows that no other 0^+ states are available in this excitation region and the 1.23-MeV state most likely has $J^\pi = 1^+$. The most probable configuration for this state is $(p_{1/2}p_{3/2}^{-1})$ since, from the known ordering of levels in Nb^{90}, the 1^+ member of the $(g_{9/2})^2$ multiplet should be located at about 3-MeV excitation. The state is also populated by the (He^3, α)

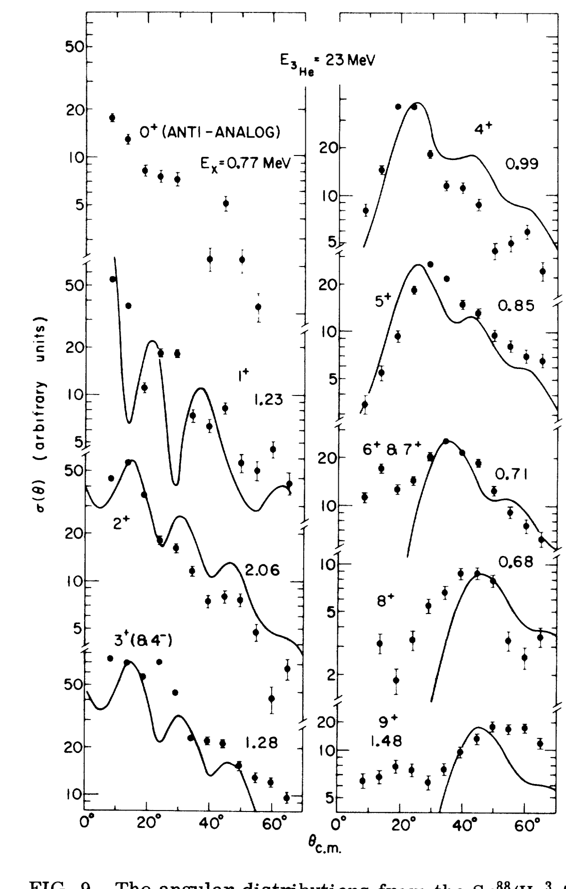

FIG. 9. The angular distributions from the Sr^{88}(He^3,t)-Y^{88} reaction for states believed to be members of the $(g_{9/2})^2$ multiplet. The 0^+ antianalog state, however, is expected to have a main component from the $(p_{1/2})^2$ configuration, the 1^+ state probably has a principal component from the $(p_{1/2}p_{3/2}^{-1})$ configuration, and the 3^+ state may be unresolved from a 4^- state. The curves are DW calculations with microscopic form factors but without tensor terms.

reaction, as would be expected for this configuration, with a strength nearly equal to that for the 1^+ state at 0.39 MeV. In contrast, Fig. 8 indicates that this level also has nearly a full transition strength for $g_{9/2}$ proton transfer. It is impossible for this state to be populated strongly by both the (He^3, d) and (He^3, α) reactions, regardless of the amount of mixing between the two $J^\pi = 1^+$ configurations, and the presence of a third unresolved doublet is strongly suggested. The second member probably has most of the $g_{9/2}$ proton strength and may be a fragment of the $J^\pi = 2^+$ state.

Finally, the transition strength for the $J^\pi = 2^+$ state at 2.06 MeV falls considerably below the expected value. The (He^3, t) angular distribution for the 1.95-MeV state appears to match that for the 2.06-MeV state very well. Undoubtedly the $(g_{9/2})^2$ strength is fragmented among several possible 2^+ states. Hence, the 1.95-MeV state is also assigned $J^\pi = 2^+$ even though it was difficult to resolve it from the 1.97-MeV state in the proton-transfer reactions and thus to verify the presence of $l = 4$ strength.

The presumed $(g_{9/2})^2$ spectra in Y^{88} and Nb^{90} are

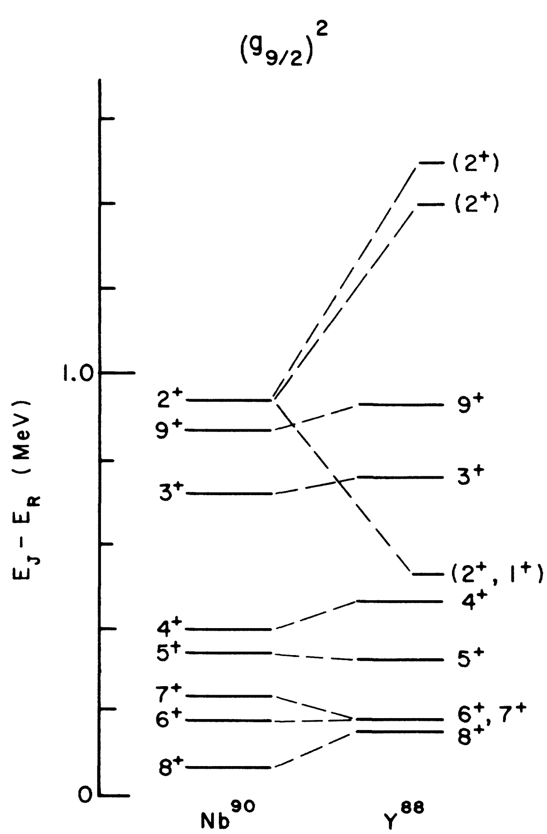

FIG. 10. The energies E_J of the states of the $(g_{9/2})^2$ multiplet in Nb^{90} and Y^{88}, plotted with respect to the expected ground-state particle-hole energy E_R.

compared in Fig. 10. The energies are plotted with respect to the single-particle, single-hole energy in the respective nuclei. It is apparent that the level ordering is the same and that the level spacings are very similar. The greatest discrepancy occurs for the 2^+ states. Two such levels appear to be present in Y^{88} at a much higher relative energy than in Nb^{90}. However, as discussed above, there are indications of $(g_{9/2})^2$ strength for a 2^+ state at much lower energies, so that the centroid may not be significantly different.

C. Nonidentical-Orbit Configurations

1. $(p_{1/2}g_{9/2})$ Multiplets

The ground state of Y^{88} has long been assigned[26] $J^\pi = 4^-$ and a large body of data suggests[6,22,23,27] that the 0.23-MeV state has $J^\pi = 5^-$. These levels are presumed to arise from the $(p_{1/2}g_{9/2}^{-1})$ configuration. The present data are again consistent with these assignments and interpretations. The cross sections are almost exactly proportional to $(2J+1)$ in both the (He^3, d) and (He^3, α) reactions. This indicates nearly equal spectroscopic factors for the proton particle and the neutron hole, respectively, in the two states. The normalized spectroscopic factors in the (He^3, d) reaction suggest, however, that 15–20% of the single-particle proton strength is unavailable because of mixing with other configurations.

Among the other configurations is the $(g_{9/2}p_{1/2}^{-1})$ multiplet, whose centroid is expected to be near 1.3 MeV. The (He^3, t) DW calculations for these conjugate configurations show that the states with the same spins should have the same cross sections. In addition, the two multiplets should have the same order of spins if the configurations are pure. There were, however, no peaks in the spectra of the (He^3, t) reaction with cross sections and angular distributions like those for the ground-state doublet.

Mixing between the two configurations will alter this situation. If the mixing is near 15–20% (as suggested by the proton-transfer measurements) and coherent for the ground-state doublet, this doublet could be enhanced by nearly a factor of 2 and have (He^3, t) cross sections 10 times those of the states of the orthogonal doublet.

Three levels in the energy region near 1.3 MeV have (He^3, d) angular distributions with $l = 1$ shapes, indicating states of negative parity, and (He^3, t) angular distributions with shapes very similar to that of the 5^- state at 0.23 MeV. These are shown in Fig. 11. The level at 1.09 MeV is seen quite weakly in the (He^3, d) reaction and does not seem to be a good candidate for the $J^\pi = 5^-$ state of the $(g_{9/2}p_{1/2}^{-1})$ configuration. Evidence from the

$Zr^{90}(d, \alpha)Y^{88}$ reaction suggests[28] that the 1.32-MeV state has $J^\pi = 6^-$. This spin assignment is consistent with the angular distribution from the (He^3, t) reaction. The remaining level at 1.13 MeV has a proton stripping strength that is about $\frac{1}{10}$ of the strength for the state at 0.23 MeV. This would approximately account for the single-particle strength that appears to be missing from the lower state.

There appears to be no candidate below 1.13 MeV for a second 4^- state. On the other hand, the (He^3, t) angular distribution for the 1.28-MeV state has a shape similar to that of the ground state. The (He^3, d) angular distribution, as noted earlier and shown in Fig. 6, deviates from the usual $l=4$ shape and possibly indicates a weak $l=1$ contribution. This apparent reversal of the ordering of the second 4^- and 5^- states indicates possible additional mixing from higher configurations such as the $(g_{9/2}p_{3/2}{}^{-1})$ configuration.

A significant difficulty for the ground-state doublet is apparent in the data of the (He^3, t) reaction. In Fig. 12 the angular distributions are compared with DW calculations. The data are peaked at more forward angles than the calculations, and the most forward peak of the 4^- state could not be reproduced. This problem is discussed in more detail in Sec. V.

2. $(p_{1/2}p_{3/2}{}^{-1})$ *Multiplet*

The level at 1.23 MeV has already been suggested (Sec. IV B*2*) to be the $J^\pi = 1^+$ member of the $(p_{1/2}p_{3/2}{}^{-1})$ configuration. It was also argued that this level is an unresolved doublet and that the other member may have a fragment of the $J^\pi = 2^+$ state of the $(g_{9/2})^2$ configuration. While such a state would undoubtedly have some $(p_{1/2}p_{3/2}{}^{-1})$ component in its wave function, additional components must lie higher.

The level at 1.57 MeV has considerable strength in the (He^3, α) reaction and its angular distribution appears to have an $l=1$ shape. The value $l=1$ has also been assigned for transitions to this state in earlier studies of the (He^3, α)[6, 22] and (p, d)[29] reactions. The level is weakly populated by the (He^3, d) reaction and its angular distribution in the (He^3, t) reaction is very similar to those for the presumed 2^+ states at 1.95 and 2.06 MeV. All these considerations confirm the interpretation that this state has most of the strength of the $(p_{1/2}p_{3/2}{}^{-1})$, $J^\pi = 2^+$ configuration.

3. $(p_{1/2}f_{5/2}{}^{-1})$ *Multiplet*

The level at 1.70 MeV is also populated strongly by the (He^3, α) reaction and quite weakly by the (He^3, d) reaction. In earlier studies of the (He^3, α) reaction, $l=3$ has been assigned[6, 22] for this state, and the present (He^3, α) data are consistent with this value. The state is thus an excellent candidate for one member of the $(p_{1/2}f_{5/2}{}^{-1})$ configuration expected in this excitation region. Unfortunately, the L value assigned for the (He^3, t) angular distribution from the empirical calibration suggests $L > 4$. However, the DW calculation for a 3^+

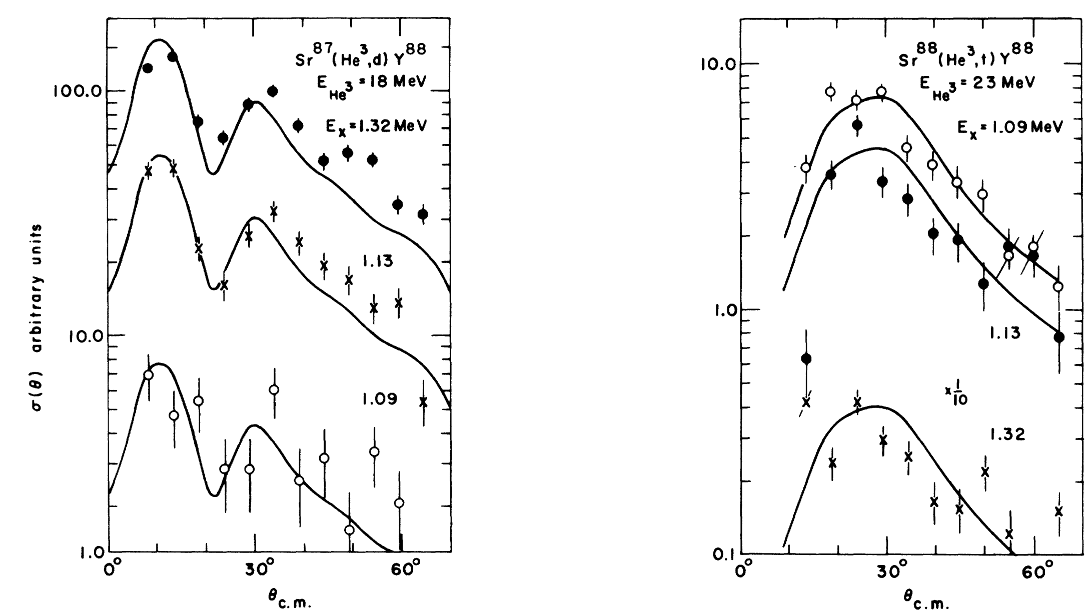

FIG. 11. Angular distributions from the $Sr^{87}(He^3,d)Y^{88}$ and $Sr^{88}(He^3,t)Y^{88}$ reactions for three states of Y^{88}. The curves for the (He^3,d) reaction are $l=1$ DW calculations. The curves for the (He^3,t) reaction were obtained by drawing a smooth line through the data of the 5^- state at 0.23 MeV (Fig. 10) and superimposing it on the data here.

state fits the data quite well. This aspect is discussed in Sec. V. All things considered, no other state could reasonably be an alternative possibility for the 3^+ member of the $(p_{1/2}f_{5/2}{}^{-1})$ configuration – even though fragments of it may be present elsewhere.

The only higher states that have moderately strong (He^3, α) transitions and apparently do not have negative parity are those at 1.95 and 2.06 MeV. Arguments that these are 2^+ states have already been presented. The wave functions apparently have admixtures of $(g_{9/2})^2$ and $(p_{1/2}f_{5/2}{}^{-1})$ configurations.

4. *Other Multiplets*

A number of levels above 1.5 MeV were observed to have $l=1$ angular distributions in the (He^3, d) reaction and thus have negative parity. A few others also were tentatively identified as having $l=1$ angular distributions. These states possibly are members of the multiplets (discussed in Sec. I) whose population in the (He^3, d) and (He^3, t) reactions is not expected to be very strong. In view of the weak cross sections, even tentative assignments are precluded for these states.

D. Summary

The assignments and principal configurations of the states of Y^{88} are summarized in Table II and a level scheme is shown in Fig. 13. The assignments are those indicated by the present data on the basis of the foregoing arguments. Only the assignments of the first four states and of the 0^+ state at 0.77 MeV were known with reasonable confidence[23] prior to the present investigation.

While it is difficult to state the degree of confidence for each of the new spin assignments, we believe that the members of the $(p_{1/2})^2$, $(g_{9/2})^2$, and $(p_{1/2}g_{9/2}{}^{-1})$ multiplets are well identified and those of the $(p_{1/2}p_{3/2}{}^{-1})$, $(p_{1/2}f_{5/2}{}^{-1})$, and $(g_{9/2}p_{1/2}{}^{-1})$ multiplets are only slightly less well known. The data considered together are most consistent with the new spin assignments, and significant difficulties would be created by alternative assignments. Indeed, the only difficulties presented by the present data are related to the mechanism of the (He^3, t) reaction. These are discussed in Sec. V.

The principal disagreement between the assign-

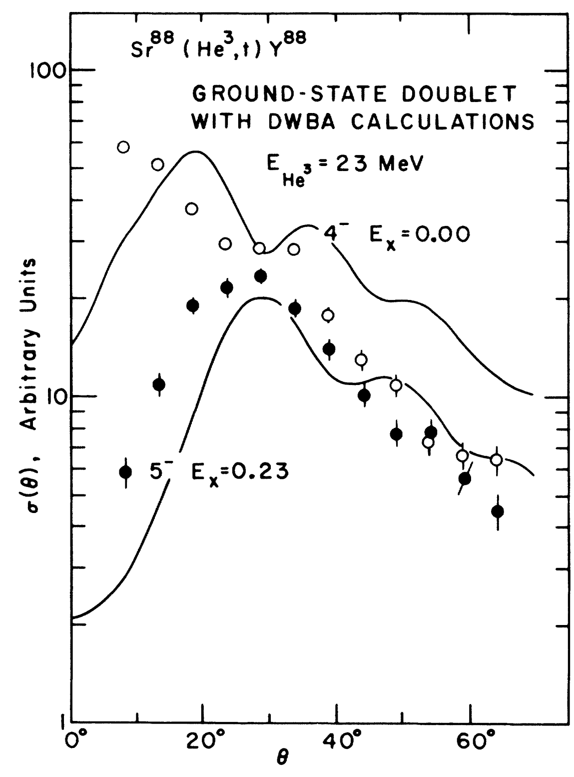

FIG. 12. The angular distributions from the $Sr^{88}(He^3,t)$-Y^{88} reaction for the ground state and first excited state, believed to be members of the $(p_{1/2}g_{9/2}{}^{-1})$ multiplet. The curves are DW calculations (without tensor interactions) and the normalization to the data is the same for both states.

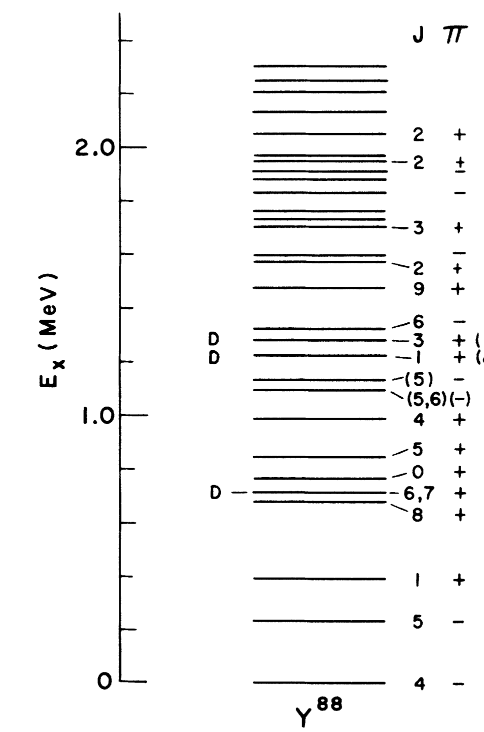

FIG. 13. The level diagram of Y^{88} with spin and parity assignments. With few exceptions, assignments for states above 0.7 MeV were unknown prior to the present study. The symbol D indicates an unresolved doublet (as discussed in the text).

ments in Table II and tentative assignments reported previously concerns the members of the $(p_{1/2}p_{3/2}^{-1})$ multiplet. We reverse the previous ordering[6,22,29] and assign $J^\pi = 1^+$ and 2^+ at 1.23 and 1.57 MeV, respectively. While there quite possibly is a 2^+ state also at 1.23 MeV, we believe that the state observed in neutron-pickup reactions is the 1^+ member of the $(p_{1/2}p_{3/2}^{-1})$ multiplet. The present (He^3, t) data would be inconsistent with the previous ordering.

A second small discrepancy is associated with the level(s) at 0.70 MeV. We assign a 6^+ and 7^+ unresolved doublet at this energy. The $Y^{89}(p, d)Y^{88}$ reaction appears to show[29] $l = 1$ strength to a level at this energy and $J^\pi = 1^+$ has been tentatively assigned. If such a level is also present, it possibly arises from a "forbidden" $(p_{1/2}p_{3/2}^{-1})$ multiplet discussed in Sec. I. It should not be populated by the reactions studied here.

It is apparent that Y^{88} is a much more complex nucleus than had been previously realized. There is a large number of states below 2.5-MeV excitation energy, and even with 20-keV resolution there is evidence for several unresolved doublets. Nevertheless, many of the levels can be readily interpreted as arising from simple particle-hole multiplets. Configuration mixing is present, but this does not appear to destroy the simple understanding of the states.

V. (He^3, t) REACTION MECHANISM

As noted in Sec. IV D, the present (He^3, t) data could not be well fitted with DW calculations. Examples of the fits are shown in Figs. 9 and 12. However, such difficulties did not seriously affect the interpretation of the data since an empirical calibration could be established. Some of the serious discrepancies between the DW calculations and the data have been discussed in a previous article.[30] Considered together they imply a serious defect in our current understanding of the reaction mechanism.

A. Systematics of the Data

Before discussing the DW calculations in detail, we shall note two general systematic features of the (He^3, t) data. Each feature, however, has some specific exceptions.

First, it has been observed previously[8,9] that the angular distributions for even-parity states with odd J are very similar to those for states with the next higher even J. This feature is also consistent with some of the present data, although it is complicated by the presence of unresolved doublets. It has been attributed[12,31] to a tensor term in the charge-exchange interaction.

A more general statement would be that all angular distributions for transitions to unnatural-parity final states (from spin-zero targets) should show this feature. Indeed this is generally the effect of the tensor term in the DW calculations. However, our experimental result for the 4^- ground state of Y^{88} shows that this generalization is wrong, the angular distribution being quite different from that to the 5^- first excited state at 0.23 MeV. The DW calculations with a tensor term here again predict that the $L = 5$ cross section should dominate over the $L = 3$ cross section, and therefore that the 4^- and 5^- states should have similar angular distributions. The failure to fit the data raises serious doubts about the validity of the tensor term in the effective interaction, since such a term cannot arbitrarily be included for some configurations and not for others.

Since most of the data hitherto have been for transitions in which the neutron was replaced by a proton in the same orbit $[(f_{7/2})^2$ and $(g_{9/2})^2]$, one might conclude that the rule for unnatural-parity transitions applies only in these identical-orbit cases. However, in the $Zr^{96}(He^3, t)Nb^{96}$ reaction,[13] in which a $d_{5/2}$ neutron was replaced by a $g_{9/2}$ proton, the unnatural-parity states are populated by

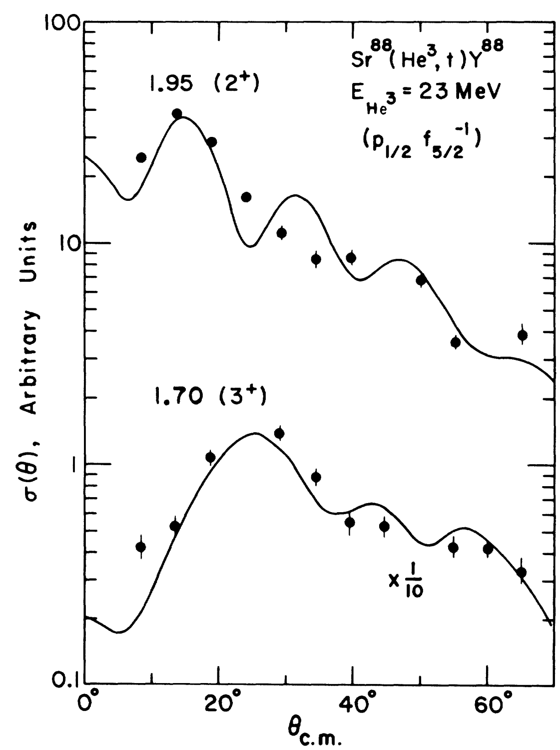

FIG. 14. The angular distributions for the probable 2^+ and 3^+ doublet of the $(p_{1/2}f_{5/2}^{-1})$ multiplet in Y^{88}. The curves are DW calculations without a tensor term in the effective interaction.

the higher L values. This agrees with the pattern for the $(j)^2$ transitions but contrasts with the observation of the $(p_{1/2}g_{9/2}^{-1})$ states in Y^{88}.

It is also interesting to note that microscopic DW calculations without a tensor term can predict that unnatural-parity transitions for some configurations will proceed with the higher of the allowed L values. This is the case for all transitions between states in which both the proton and the neutron are in shell-model orbits with $j = l - \frac{1}{2}$.[32] In Sec. IV C *3* we tentatively identified the 1.70- and 1.95-MeV states with the 3^+ and 2^+ members of the $(p_{1/2}f_{5/2}^{-1})$ configuration, respectively. In Fig. 14, DW calculations with purely central interactions are compared with the data. The transition to the 3^+ state is calculated to proceed mainly by $L=4$ and indeed, in these cases, very good fits are obtained. In fact, if a tensor interaction were included, the $L=2$ contribution to the 3^+ state would be sharply enhanced so that the good agreement with the data would be destroyed.

Note added in proof: It is possible to get the same good fits to the 3^+ state with a tensor term if mixing with the $(g_{9/2})^2$ configuration is allowed. Such calculations are considered specious, since the unmixed results do not even reproduce the most striking feature of the data: The first maximum of the $(g_{9/2})^2$ 4^+ state at 0.98 MeV occurs at a *smaller* angle than that for this 3^+ state.

The second anomalous feature in (He^3, t) reactions is the fact that, as has already been noted,[30] the experimental angular distributions peak at angles ~5° farther forward than do the DW calculations. This feature could not be eliminated by any reasonable choice of distorting parameters. It is clearly present for natural-parity states whose L values are unique, and it also appears to be present for the unnatural-parity transitions, though in the latter case the issue is somewhat clouded by the question of mixed L values and the tensor-force questions raised above. It is interesting to note that for the 1.70- and 1.95-MeV states mentioned above there appeared to be no sign of such an angular shift.

B. DW Calculations

The formalism for the charge-exchange (He^3, t) reaction with microscopic form factors is presented in the literature[31-33] and will not be repeated here. The DW calculations were done by use of the computer program DWUCK.[18] Microscopic form factors were used. The effective interaction included central, spin-flip, and tensor terms. These were treated with the same procedure as Refs. 31 and 32.

The optical potentials are listed in Table III. In general, the same potentials were used for both the He^3 and t channels. However, an isospin correction was also investigated for potential set H2 in the manner of Drisko, Roos, and Bassel.[19] The effects of such a correction were entirely negligible. The mixed potential set H2-H3 was also tried. While the choice of optical potentials strongly affected the cross sections, it did not significantly affect the shapes of the angular distributions and produced no angular shifts. The set H1-H1 was used for the final calculations.

C. Discussion

None of the DW calculations were able to satisfactorily reproduce the data in the present study. More discussion of the detailed investigations related to these calculations has been given elsewhere.[30] A tensor term can explain the preference for the higher allowed L value shown by some transitions to unnatural-parity states, but it fails for others. It is not needed when both values of j are equal to $l - \frac{1}{2}$, and it fails completely for the odd-parity states of Y^{88}.

The angular shift seems to be present for most states except that it does not seem to be required for the two $(p_{1/2}f_{5/2}^{-1})$ final states, for which $j = l - \frac{1}{2}$. It does, however, appear to hold for the odd-parity states. It is very difficult to find an explanation for this shift. It appears to be independent of any reasonable optical potential.

It thus may be necessary to consider various corrections to the usual DW calculations or to look for new terms in the charge-exchange interaction. Many of the possible corrections have been reviewed elsewhere,[32] and it appears unlikely that they could account for the present difficulties.

A correction that may be significant, and which has not been considered in detail, results from spin-orbit coupling. The sum over L and S in the expression for the cross section becomes coherent if spin-orbit terms are included in the elastic scattering channels and the form factor. For the latter, such a term could arise from the $\vec{L} \cdot \vec{S}$ terms in the nucleon-nucleon potential.

It is conceivable that the coherence brought about by the spin-orbit interactions could account for some of the phenomena, but it appears unlikely to account for all of them. The effects should be most noticeable when two values of L are involved, but it would hardly appear to matter in cases in which only one is present, as for the 5^- states of Y^{88}. It certainly does not matter for the natural-parity states of identical-orbit multiplets, which have only one term $(S=0)$ anyway.

An interesting feature is illustrated in Fig. 15. The sum of $L=1$ and $L=3$ curves is compared with the data for the 4^- state, and the sum of $L = 3$ and $L = 5$ curves is compared with the data for the 5^- state. The fit to the 5^- state, for which only $L = 5$ is allowed by the selection rules, is exceptionally good. The fit to the 4^- state is not as good, but appears to be a considerable improvement over the fit ($L = 3$) shown in Fig. 12. In both cases, the fits were achieved by incoherently adding cross sections calculated for L values two units less than those allowed by selection rules. (DW curves with L values only one unit less than allowed values could not produce good fits.)

An explanation of this phenomenon is not offered, and it should be regarded as a phenomenological comment with no apparent theoretical basis. Since the mass-3 particles can have a spin momentum change of at most one unit, the total angular momentum change of the nucleus can differ from the orbital angular momentum transfer by only one unit. Mechanisms for obtaining an extra two units of L, such as transitions between the ${}^{3/2}D_{1/2}$ and ${}^{1/2}S_{1/2}$ components of the wave functions of the mass-3 particles, are incapable of explaining this effect in zero range. Indeed, consideration of such transitions with central forces, and ignoring exchange effects, shows[34] that they may be described by an effective tensor interaction. It remains to be seen what finite-range calculations may produce. As an example with possible relevance, we cite the (Li^7, t) reaction connecting $J^\pi = 0^+$ states: It proceeds with an apparent $L = 0$ transition, though a zero-range calculation would require $L = 1$ because of the $\frac{3}{2}^-$ ground state of Li^7.[35]

This admixture of forbidden lower L values is, in effect, the angular shift we have already discussed here and elsewhere.[30] One may describe the transition to the 4^- state as being fitted by $L = 3$ and $L = 5$ DW curves (*without* a tensor interaction) with an angular shift of about 7°. This would be consistent with DW calculations for other states.[30] The explanation is less satisfactory for the transition to the 5^- state, since the experimental maximum in the angular distribution seems broader than that for the calculated $L = 5$ curve.

It is possible that the (He^3, t) reaction to $T_<$ states is dominated by a two-step or other second-order process and that the analogy to inelastic scattering is not valid except for the quasielastic process to ground-state analogs. The reaction has been applied to a large range of nuclei over a broad range of bombarding energies. The essential characteristics of the reaction, such as the dependence of the angular distributions on the angular momentum transfers and the sensitivity to nuclear configurations, have been noted throughout the entire range of investigation. In addition, the nuclear-structure information which has been extracted has been found to be very consistent with the results obtained from other, better understood, reactions.

In conclusion, the present study has shown the (He^3, t) reaction to be very useful in probing the structure of Y^{88}, particularly when it is used in

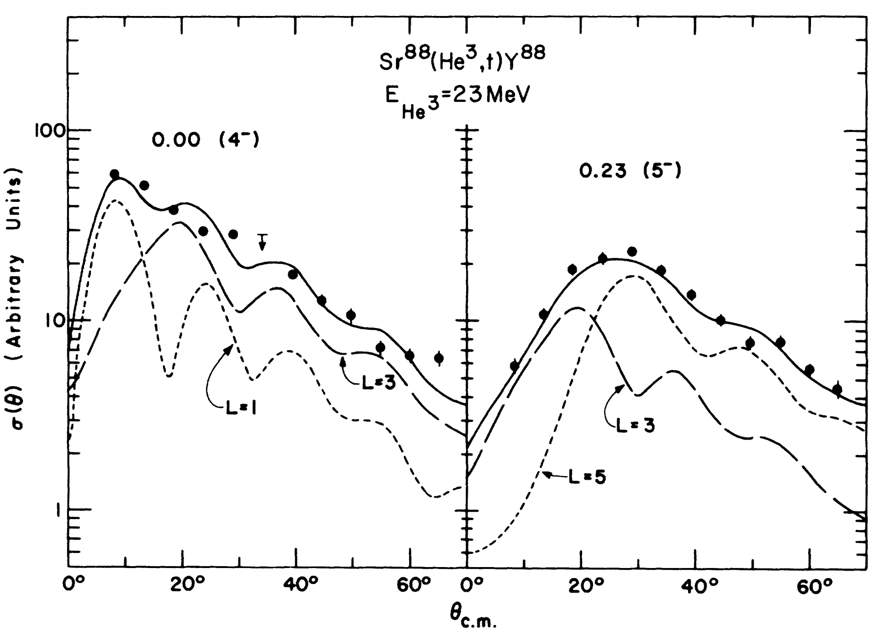

FIG. 15. The angular distributions for the $(p_{1/2}g_{9/2}^{-1})$ ground-state doublet in Y^{88}. The dashed curves are DW calculations for L values allowed and not allowed by the conventional stripping selection rules. The solid curves are their sums.

conjunction with other reactions. Systematic features of the (He^3, t) data appear in a comparison with DW calculations and are noted here, but some interesting exceptions are found. The persistent inability of the DW calculations to reproduce the data presents a sharp challenge to the current understanding of the (He^3, t) reaction mechanism.

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[1]S. Bjornholm, O. B. Neilsen, and R. K. Sheline, Phys. Rev. 115, 1613 (1959).

[2]B. F. Bayman, A. S. Reiner, and R. K. Sheline, Phys. Rev. 115, 1627 (1959).

[3]S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga, Phys. Letters 10, 195 (1964).

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

[5]J. Picard and G. Bassani, Nucl. Phys. A131, 636 (1969).

[6]G. Bassani and J. Picard, Nucl. Phys. A131, 653 (1969).

[7]J. J. Schwartz, D. Cline, H. E. Gove, R. Sherr, T. S. Bhatia, and R. H. Siemssen, Phys. Rev. Letters 19, 1482 (1967); R. Sherr, T. S. Bhatia, D. Cline, and J. J. Schwartz, to be published.

[8]G. Bruge, A. Bussiere, H. Faraggi, P. Kossanyi-Demay, J. M. Loiseaux, P. Roussel, and L. Valentin, Nucl. Phys. A129, 417 (1969).

[9]S. I. Hayakawa, J. J. Kraushaar, P. D. Kunz, and E. Rost, Phys. Letters 29B, 327 (1969).

[10]H. Ohnuma, J. R. Erskine, J. P. Schiffer, J. A. Nolen, Jr., and N. Williams, Phys. Rev. C 1, 496 (1970).

[11]R. C. Bearse, J. R. Comfort, J. P. Schiffer, M. M. Stautberg, and J. C. Stoltzfus, Phys. Rev. Letters 23, 864 (1969).

[12]S. I. Hayakawa, W.L. Fadner, J. J. Kraushaar, and E. Rost, Nucl. Phys. A139, 465 (1970).

[13]J. R. Comfort, J. V. Maher, G. C. Morrison, and J. P. Schiffer, Phys. Rev. Letters 25, 383 (1970).

[14]J. E. Spencer and H. A. Enge, Nucl. Instr. Methods 49, 181 (1967).

[15]J. R. Erskine and R. H. Vonderohe, Nucl. Instr. Methods 81, 221 (1970).

[16]The authors are indebted to L. Parrish for lending them this target.

[17]J. R. Comfort, Argonne National Laboratory Physics Division Informal Report No. PHY-1970B, 1970 (unpublished).

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[19]R. M. Drisko, P. G. Roos, and R. H. Bassel, J. Phys. Soc. Japan, Suppl. 24, 347 (1968).

[20]J. C. Hafele, E. R. Flynn, and A. G. Blair, Phys. Rev. 155, 1238 (1967).

[21]J. V. Maher, J. R. Comfort, and G. C. Morrison, Phys. Rev. C 3, 1162 (1971).

[22]C. M. Fou and R. W. Zurmühle, Phys. Rev. 176, 1339 (1968).

[23]C. D. Goodman, Bull. Am. Phys. Soc. 15, 572 (1970).

[24]C. D. Goodman, P. G. Roos, and D. G. Kamke, Bull. Am. Phys. Soc. 14, 121 (1969).

[25]J. A. Cooper, J. M. Hollander, and J. O. Rasmussen, Nucl. Phys. A109, 603 (1967).

[26]*Nuclear Data Sheets*, edited by K. Way *et al.* (National Academy of Sciences – National Research Council, Washinton, D. C., 1960).

[27]C. D. Goodman, Oak Ridge National Laboratory Report No. ORNL-3800, 1965 (unpublished).

[28]J. R. Comfort, J. V. Maher, G. C. Morrison, and H. T. Fortune, Bull. Am. Phys. Soc. 15, 574 (1970).

[29]C. D. Goodman, C. A. Ludemann, and P. G. Roos, Oak Ridge National Laboratory Report No. ORNL-4217, 1967 (unpublished).

[30]J. R. Comfort, J. P. Schiffer, A. Richter, and M. M. Stautberg, Phys. Rev. Letters 26, 1338, (1971).

[31]E. Rost and P. D. Kunz, Phys. Letters 30B, 231 (1969).

[32]P. Kossanyi-Demay, P. Roussel, H. Faraggi, and R. Schaeffer, Nucl. Phys. A148, 181 (1970).

[33]V. A. Madsen, Nucl. Phys. 80, 177 (1966).

[34]S. Yoshida, private communication.

[35]P. Neogy, W. Scholz, J. Garrett, and R. Middleton, Phys. Rev. C 2, 2149 (1970).