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$(f_{7/2})^{-3}$ Configuration States in ^{45}Ca.*

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ABSTRACT

The ^{48}Ca $(^3$He,^{6}He$)^{45}$Ca has been studied at 70 MeV bombarding energy and angular distributions to strongly populated states in ^{45}Ca up to 5 MeV of excitation have been obtained. Evidence for $(f_{7/2})^{-3}$ configuration states at 0.17, 1.43, 1.56, 1.89 and 2.88 MeV is discussed. The experimental $(f_{7/2})^{-3}$ spectrum is compared to calculations based on the $(f_{7/2})^{-2}$ spectrum of ^{46}Ca.

NUCLEAR REACTION ^{48}Ca$(^3$He,^{6}He), $E_{^3He}$=70 MeV, measured $(E_{^6He},\theta)$; enriched target, deduced excitation energies.

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I. INTRODUCTION

There has been a great interest in the description of nuclei with Z and N between 20 and 28 in terms of the spherical shell-model with a suitable residual interaction between nucleons in a $(f_{7/2})^n$ configuration outside the A=40 closed shell.[1,2] The simplest systems to check the basic assumptions of such a model are the $(f_{7/2})^{\pm 3}$ configuration states. ^{45}Ca is the least known of these nuclei. The present paper intends to fill this gap.

Since all $(f_{7/2})^{-3}$ levels, except for the $7/2^-$ state, have seniority v=3, these states are expected to be very weakly excited in single-nucleon transfer reactions, but strongly in the ^{48}Ca$(^3$He,^{6}He$)^{45}$Ca reaction. The single-particle or single-hole states in ^{45}Ca have been studied by Rapaport, et al.[3] and Yntema[4] via ^{44}Ca(d,p)^{45}Ca and ^{46}Ca(d,t)^{45}Ca. The comparison of these results to those obtained in the present ^{48}Ca$(^3$He,^{6}He) reaction yields evidence for all of the high-spin members of the $(f_{7/2})^{-3}$ configuration states in ^{45}Ca.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The ^{48}Ca$(^3$He,^{6}He$)^{45}$Ca reaction was performed with a 70 MeV ^{3}He particle beam from the Michigan State University Cyclotron. The reaction products were detected in a position sensitive detector system on the focal plane of an Enge split-pole magnetic spectrograph. The detector system consisted of two resistive-wire proportional counters backed by a plastic scintillator. The two proportional counters provided reduntant information of the energy loss in the gas, while the signal from the plastic scintillator was employed to give both time of flight in the spectrograph and light-output information.

The target was made by evaporating metallic calcium, enriched to 97% in ^{48}Ca, onto a thin carbon foil. The metallic calcium was reduced from $CaCO_3$ by means of Zr powder as a part of the evaporation process. The target was kept under vacuum at all times. The thickness was about 130 $\mu g/cm^2$.

Figure 1 shows two ^{6}He spectra taken at 10° and 24°. The resolution was about 30 keV full width at half maximum. Although the level density in ^{45}Ca is quite high in the 2 to 5 MeV excitation energy range,[5] only relatively few states are strongly excited. The excitation energies of the levels observed in the present experiment are given in Table I.

Angular distributions were obtained over the region from 6° to 35°. They are displayed in Figs. 2-4. Error bars reflect only statistical uncertainties. The accuracy of the absolute differential cross section is estimated to be about ±25%.

III. DISCUSSION

In the (^{3}He,^{6}He) reaction, the selection rules allow the transfer of the three neutrons either with seniority v=1 or v=3. The $(f_{7/2})^{-3}$ configuration states in ^{45}Ca with the spins $3/2^-$, $5/2^-$, $7/2^-$, $9/2^-$, $11/2^-$ and $15/2^-$ have, except for the $7/2^-$ state, seniority v=3. All can be excited in the ^{48}Ca(^{3}He,^{6}He) reaction. Assuming a $(f_{7/2})^8$ neutron configuration for the ground state of ^{48}Ca, the three-neutron pick-up spectroscopic factors for these states are proportional to $(2J_f+1)$. Furthermore,

high values of the transferred orbital angular momentum are kinematically favored due to momentum mismatch. Hence, the high spin members of the $(f_{7/2})^{-3}$ configuration should be populated strongly. On the other hand in direct single-neutron transfer reactions, the transitions to seniority v=3 states are forbidden except in the case of configuration mixing. Accordingly, the fact that a state is strongly populated in the ^{48}Ca(^{3}He,^{6}He) reaction and very weakly in the ^{44}Ca(d,p) and ^{46}Ca(d,t) reactions can be used as evidence for the $(f_{7/2})^{-3}$ configuration of this state; it is, however, not unique. In addition from a comparison with the level scheme of the other $(f_{7/2})^{\pm 3}$ configuration nuclei ^{43}Ca, ^{51}V and ^{53}Mn, where these states are already established, the six members of the $(f_{7/2})^{-3}$ configuration are expected to lie below 3 MeV of excitation[6] with the spin sequence in good agreement with the calculations.[7]

The ground state of ^{45}Ca, already known to be predominantly $(f_{7/2})^{-3}$ $J^{\pi}=7/2^-$ by the single neutron transfer reactions ^{44}Ca(d,p) and ^{46}Ca(d,t), is one of the strongest excited states in the ^{48}Ca(^{3}He,^{6}He) reaction. The shape of the angular distribution (see Fig. 2) points to a large angular momentum transfer. A predominant $(f_{7/2})^{-3}$ configuration has been suggested for the $(5/2^-)$ state at 0.174 MeV on the basis of its very weak population in the single-neutron transfer reactions,[3,4] whereas for the $3/2^-$ state at 1.435 MeV it is based on the γ-ray deexcitation.[8] Our ^{48}Ca(^{3}He,^{6}He) data support both of these assignments. As expected the cross section decreases for transitions to states with the smaller spin values. The observed ℓ_n=1 single-neutron stripping and pick-up strength to the $3/2^-$ state at 1.435 MeV shows that significant mixing with the $[(f_{7/2})^4_0(p_{3/2})^1]_{3/2}$ single-particle configuration exists. The states at 1.562 and 2.877 MeV are strongly excited in the $^{48}Ca(^3He,^6He)$ reaction with angular distributions pointing to large L-transfers (see Fig. 3). The excitation of the 1.584 MeV state which is only 26 keV apart from the 1.558 MeV state must be weak, since its population would have resulted in a broadening of the corresponding peak in the spectra which is not seen. The absence of any single-neutron transfer strength together with the strong excitation in the $^{48}Ca(^3He,^6He)$ reaction suggests that the 1.562 and 2.877 MeV states belong to the $(f_{7/2})^{-3}$ configuration. The peak labeled 1.89 MeV in the spectra of Fig. 1 is broader than the others indicating that two or more states are excited. Around this energy there are two states known from the single-neutron transfer reactions, at 1.882($3/2^+$) and 1.900($3/2^-$) MeV. The level at 1.882 MeV is characterized as a $[(f_{7/2})^6_0 d^{-1}_{3/2}]$ hole state by a very strong ℓ_n=2 pick-up strength observed in the $^{46}Ca(d,t)^{45}Ca$ reaction. This type of state is also expected to be excited in the $^{48}Ca(^3He,^6He)^{45}Ca$ reaction. However, a comparison of its cross section to that observed for the $^{42}Ca(^3He,^6He)^{39}Ca$ ground state transition, where we also have a $d_{3/2}$ hole configuration, indicates that only about 25% of the 1.89 MeV peak strength in ^{45}Ca is accounted for by the $3/2^+$ state of 1.882 MeV. The contribution from the 1.900($3/2^-$) state can be ruled out, since this state has

predominantly a $[(f_{7/2})^4 p_{3/2}]$ single-particle character as shown by the $^{44}Ca(d,p)^{45}Ca$ reaction and cannot be strongly excited in the $^{48}Ca(^3He,^6He)$ reaction. The aforementioned and the fact that the centroid of the peak shifts slightly to higher excitation energies with increasing angle, where the contribution from the 1.882($3/2^+$) MeV state becomes smaller, leads us to suggest that there is a third state in this excitation energy region of ^{45}Ca which is populated in the $^{48}Ca(^3He,^6He)$ reaction. This is supported by the shape of the angular distribution (shown in Fig. 2) which is similar to that of the 1.56 MeV transition and dissimilar to the above mentioned $^{42}Ca(^3He,^6He)^{39}Ca$ ground state transition. We think that this new state belongs also to the $(f_{7/2})^{-3}$ configuration.

Figure 5 shows a comprehensive survey of the present and previous results about ^{45}Ca. On the basis of an overall consistency with the available data we suggest that the states 0.174, 1.435, 1.562, 1.895 and 2.877 MeV belong to the $(f_{7/2})^{-3}$ configuration with $J^\pi=5/2^-$, $3/2^-$, $11/2^-$, $9/2^-$ and $15/2^-$, respectively. Since the interpetation of the data is not unique, our assignments have to be considered as somewhat uncertain. Neglecting configuration mixing the energies of the states belonging to the $(f_{7/2})^{-3}$ configuration in ^{45}Ca can be predicted from the energies of the $(f_{7/2})^{-2}$ configuration states of ^{46}Ca[9] using the coefficient of fractional parentage technique.[10] The results are shown in Table II and Fig. 5 and compared to the experimental data. The agreement is excellent with the exception of the $3/2^-$ member. The known mixing with the $[(f_{7/2})^4_0 p_{3/2}]$ single-particle configuration is likely to be responsible for this discrepancy.

Besides the $(f_{7/2})^{-3}$ configurations states, one expects that hole states with $[(f_{7/2})^{-2}_{J}s^{-1}_{1/2}]$, $[(d_{3/2})^{-2}_{J}f^{-1}_{7/2}]$ or $[(s_{1/2})^{-2}_{0}f^{-1}_{7/2}]$ configurations are excited. The $[(f_{7/2})^{-2}_{0}s^{-1}_{1/2}]_{1/2^+}$ hole state at 2.39 MeV, which is characterized by a strong ℓ_n=0 transition in the ^{46}Ca(d,t) reaction, is also strongly excited in the ^{48}Ca(^{3}He,^{6}He) reaction (see Fig. 3). Also shown is the ^{42}Ca(^{3}He,^{6}He) angular distribution of the transition to the $1/2^+$ state at 2.47 MeV of ^{39}Ca. Both angular distributions exhibit the same shape which can be attributed to a L=0 transfer. There are other strongly excited transitions observed corresponding to levels at 2.79, 3.67, 3.85 and 4.29 MeV. Their angular distributions are displayed in Fig. 4. It should be noted that the transition to the 4.29 MeV state is the strongest observed in the ^{48}Ca(^{3}He,^{6}He) reaction. Since there is no other detailed experimental information available, it is difficult to infer the nature of these states except that they probably belong to the aforementioned hole configurations.

The distorted-wave Born approximation (DWBA) description of the (^{3}He,^{6}He) reaction is to date not fully developed although several tries have been made to reproduce the differential cross sections of the ^{13}C(^{3}He,^{6}He)^{10}C reaction measured by Kashy, et al.[11] The results of the DWBA analysis of Delic and Kurath[12] showed that the ^{13}C(^{3}He,^{6}He)^{10}C reaction can be interpreted as a direct three-neutron cluster transfer. In the present work, the angular distributions were only used as an empirical aid in determining a high orbital angular momentum transfer. It is hoped that the data presented here will be useful as three-nucleon transfer reaction theory continues to improve.

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TABLE I.--Energy levels of ^{45}Ca observed in the $^{48}Ca(^{3}He,^{6}He)$ reaction, compared with previous data. The excitation energies measured in the present experiment have an estimated uncertainty of ±8 keV for levels up to 2.5 MeV of excitation and ±12 keV for higher excited states.

Present data	Compilation[a]		$^{44}Ca(d,p)^{45}Ca$[b]		$^{46}Ca(d,t)^{45}Ca$[c]	
E_x(MeV)	E_x(MeV)	J^{π}	E_x(MeV)	(2J+1)S	E_x(MeV)	C^2S
0.000	0.000[d]	$\frac{7}{2}^-$	0.000	3.4	0.000	6.2
0.174	0.1745[d]	$\frac{5}{2}^-$	0.176			
1.435	1.4347[d]	$\frac{3}{2}^-$	1.433	0.47	1.435	0.15
1.562	1.558		1.558			
	1.584		1.584			
	1.882	$\frac{3}{2}^+$	1.886	0.15	1.886	3.3
1.895						
	1.900	$\frac{3}{2}^-$	1.904	2.56	1.900	<0.08
	....					
2.389	2.393[d]	$\frac{1}{2}^+$	2.396	0.11	2.393	0.9
	....					
2.786						
	2.842	$\frac{3}{2}^-$		0.46	2.842	0.15
2.877						
	....					
3.041	3.035		3.035			
	....					
3.348						
	....					
3.485						

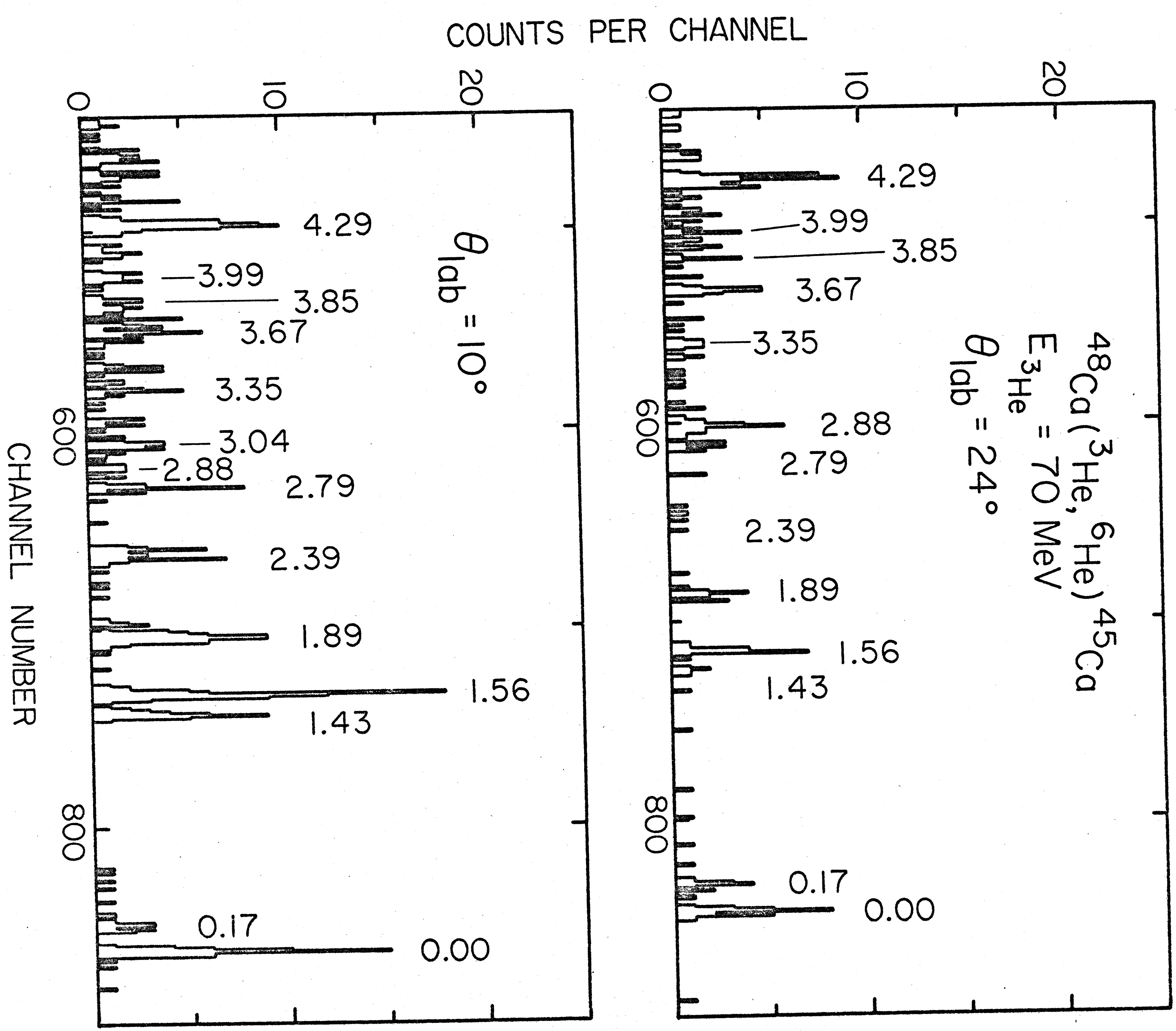
TABLE I.--Continued.

Present data E_x(MeV)	Compilation[a] E_x(MeV)	J^π	$^{44}Ca(d,p)^{45}Ca$[b] E_x(MeV)	(2J+1)S	$^{46}Ca(d,t)^{45}Ca$[c] E_x(MeV)	C^2S
3.675						
	....					
3.846	3.845		3.845			
3.993	3.993		3.993			
	....					
4.288	4.286		4.286			
	....					

[a]Reference 5.
[b]Reference 3.
[c]Reference 4.
[d]Levels used as calibration

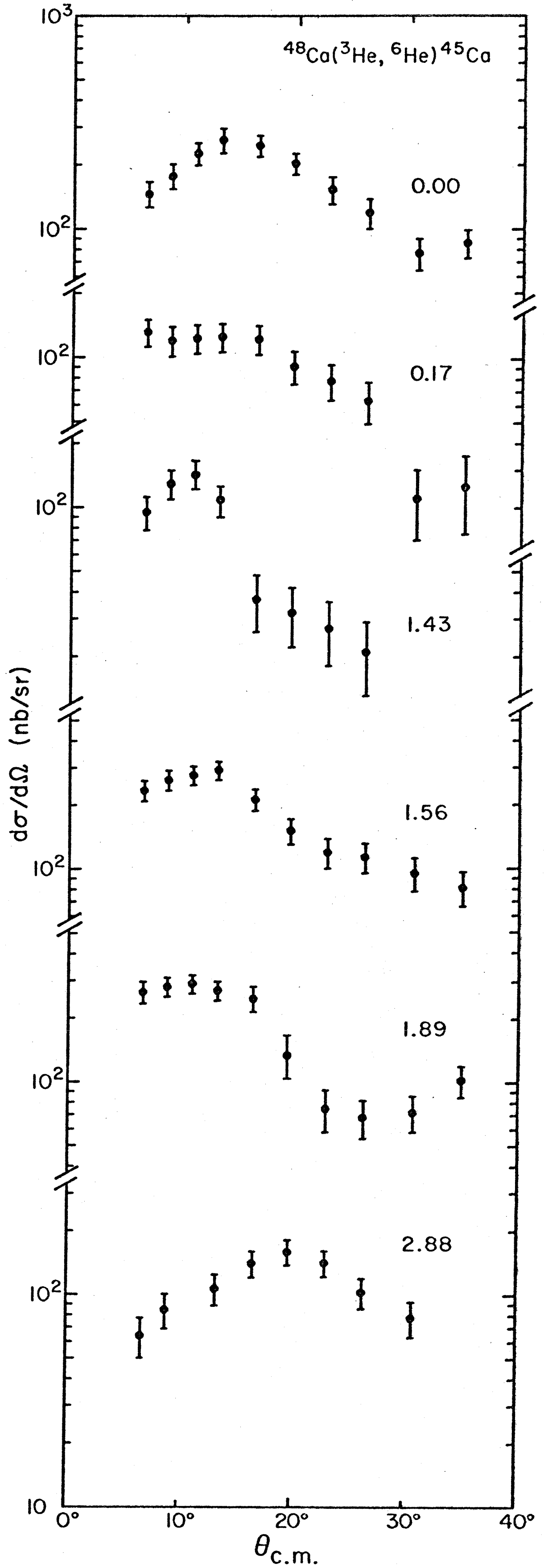
Table II. Energies in MeV of the $(f_{\frac{7}{2}})^{-3}$ states in ^{45}Ca.

State	$\frac{3-}{2}$	$\frac{5-}{2}$	$\frac{7-}{2}$	$\frac{9-}{2}$	$\frac{11-}{2}$	$\frac{15-}{2}$
Expt.	1.435	0.174	0.0	1.895	1.562	2.877
Theor.	1.221	0.151	0.0	1.927	1.616	2.936

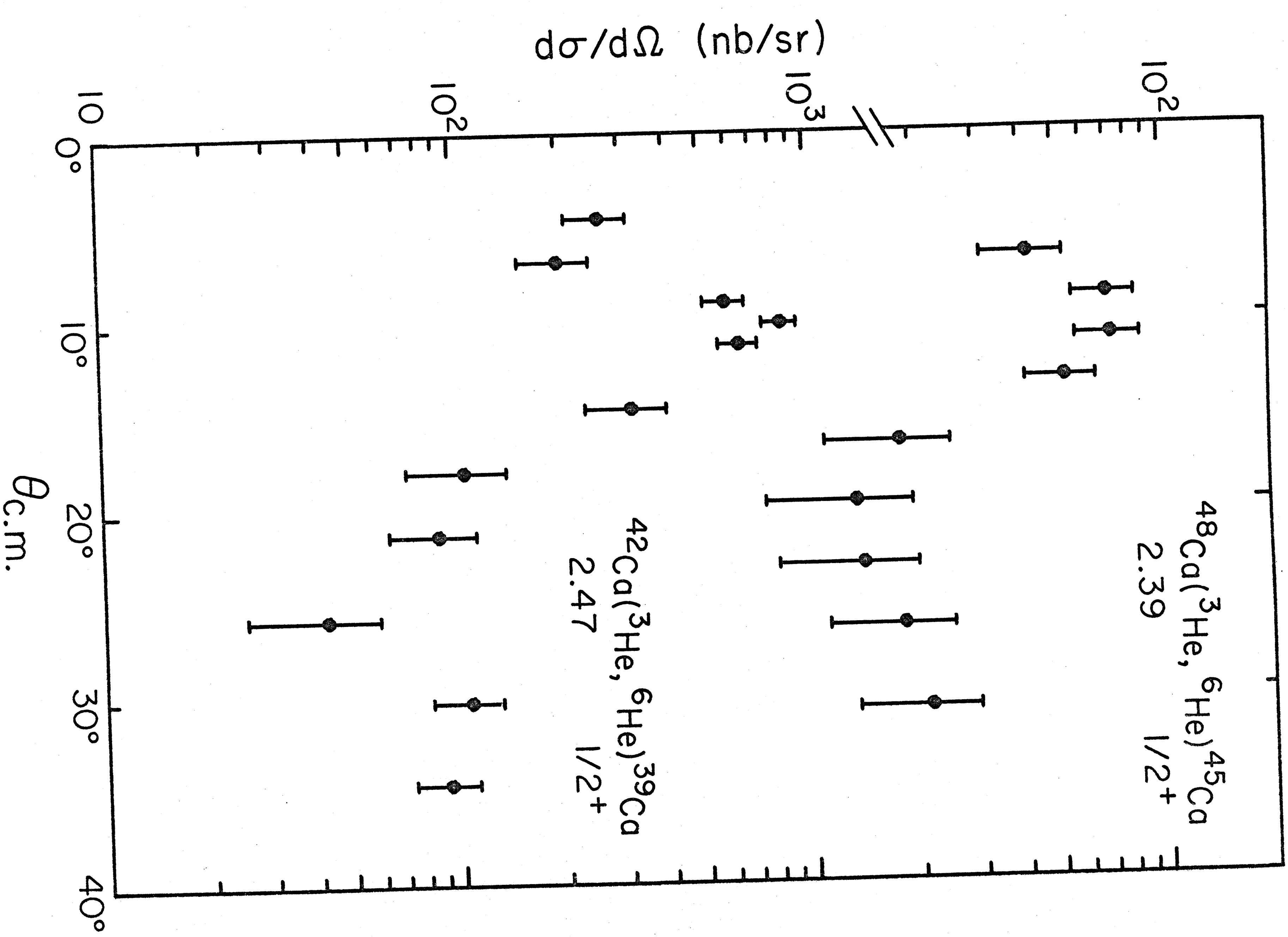


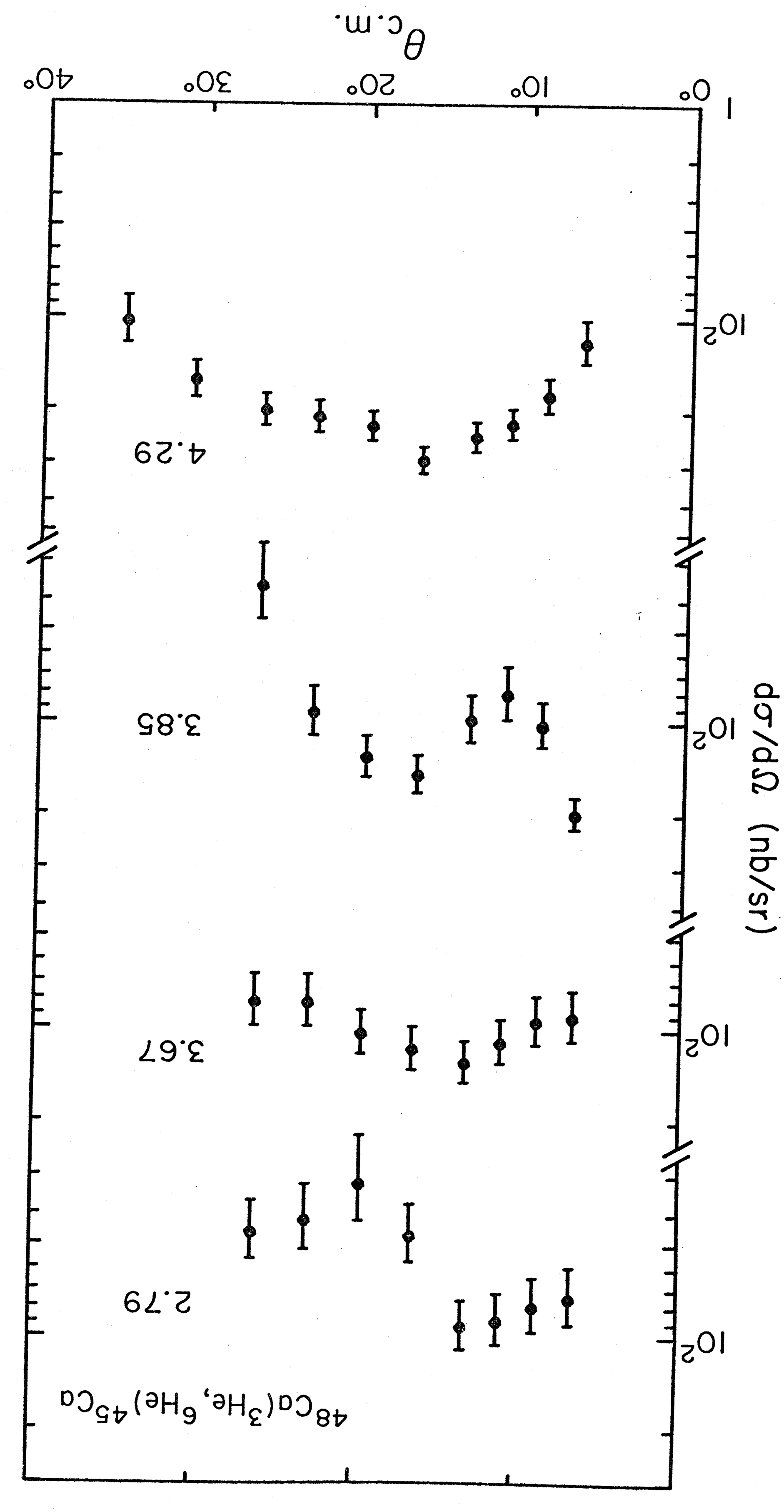
COUNTS PER CHANNEL
CHANNEL NUMBER
0
10
20
600
800
θ_{lab} = 10°
4.29
3.99
3.85
3.67
3.35
3.04
2.88
2.79
2.39
1.89
1.56
1.43
0.17
0.00
$^{48}Ca(^{3}He, ^{6}He)^{45}Ca$
$E_{^3He}$ = 70 MeV
θ_{lab} = 24°

71-1799

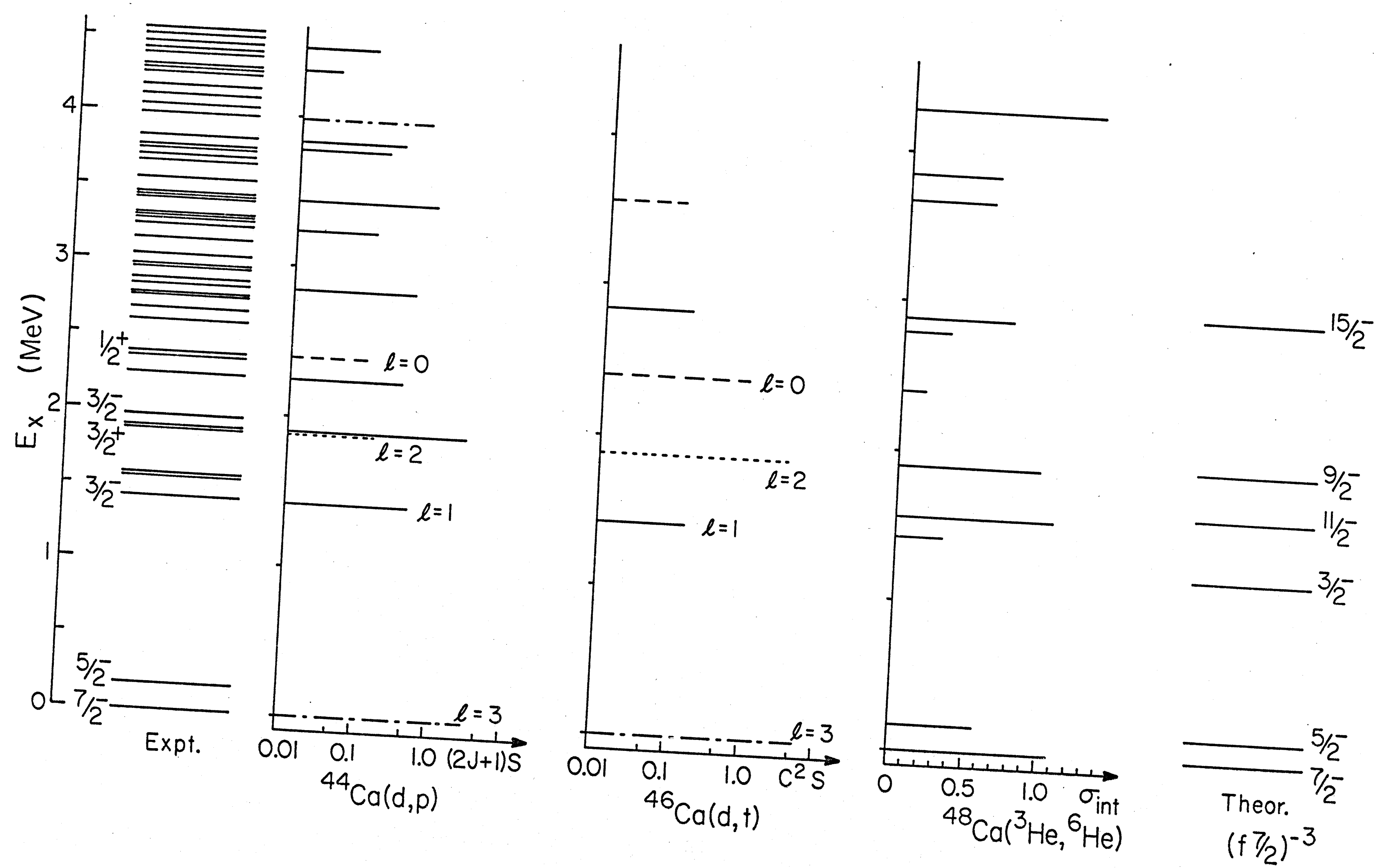


$^{48}Ca(^{3}He, ^{6}He)^{45}Ca$
0.00
0.17
1.43
1.56
1.89
2.88
$d\sigma/d\Omega$ (nb/sr)
$\theta_{c.m.}$


dσ/dΩ (nb/sr)
10
10²
10³
10²
0°
10°
20°
30°
40°
θc.m.
48Ca(3He, 6He)45Ca
2.39
1/2+
42Ca(3He, 6He)39Ca
2.47
1/2+



$^{48}Ca(^{3}He, ^{6}He)^{45}Ca$
2.79
3.67
3.85
4.29
$d\sigma/d\Omega$ (nb/sr)
$\theta_{c.m.}$



Ex (MeV)
0
1
2
3
4
7/2−
5/2−
3/2−
3/2+
3/2−
1/2+
Expt.
ℓ=3
ℓ=1
ℓ=2
ℓ=0
0.01 0.1 1.0 (2J+1)S
44Ca(d,p)
ℓ=3
ℓ=1
ℓ=2
ℓ=0
0.01 0.1 1.0 C2S
46Ca(d,t)
0 0.5 1.0 σint
48Ca(3He, 6He)
7/2−
5/2−
3/2−
11/2−
9/2−
15/2−
Theor.
(f 7/2)-3

FIGURE CAPTIONS

Fig. 1.--Spectra of the $^{48}Ca(^{3}He,^{6}He)^{45}Ca$ reaction at $\theta_{lab}=0°$ and 24°.

Fig. 2.--Angular distributions of the transitions to the state which are suggested to have a predominant $(f_{7/2})^{-3}$ configuration.

Fig. 3.--Angular distribution of the $^{48}Ca(^{3}He,^{6}He)^{45}Ca(2.39)$ transition compared to the $^{42}Ca(^{3}He,^{6}He)^{39}(2.47)$ transition.

Fig. 4.--Miscellaneous other angular distribution of the $^{48}Ca(^{3}He,^{6}He)^{45}Ca$ reaction.

Fig. 5.--Comprehensive survey of the present and previous results about ^{45}Ca.