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Nucleon Pickup Reactions on ^{46}Ca†

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The ^{46}Ca$(d,t)^{45}$Ca and ^{46}Ca$(d,{}^3$He$)^{45}$K reactions have been investigated at an incident deuteron energy of 22.4 MeV. The angular distributions have been compared with distorted-wave calculations, and the spectroscopic strength has been extracted. The transitions to the $\frac{3}{2}^-$ levels of ^{45}Ca at 1.435 and 2.82 MeV were observed with a total strength $C^2S = 0.3$. The spectroscopic factor of the ground-state transition for the ^{46}Ca$(d,{}^3$He$)^{45}$K reaction was found to be $C^2S = 1.5 \pm 0.3$. This suggests the probability of measurable core-excitation admixtures in the ground-state configuration of ^{45}K.

I. INTRODUCTION

The neutron and proton pickup in the (d, t) and $(d, {}^3$He$)$ reactions induced by 22.3-MeV deuterons incident on all the stable Ca isotopes except ^{40}Ca and ^{46}Ca have been reported recently.[1] Some admixture of $2p_{3/2}$ neutrons was observed in each of the even-A isotopes, but the admixture in ^{48}Ca was significantly smaller than the ones for ^{44}Ca and ^{42}Ca. In the preliminary results reported for the ^{46}Ca$(d, t)^{45}$Ca reaction, the resolution was too poor to permit observation of the transitions to the $\frac{5}{2}^-$ level at 0.176 MeV or to the $\frac{3}{2}^-$ levels at 1.433 and 2.847 MeV, all of which had been observed in the ^{44}Ca$(d,p)^{45}$Ca reaction.[2] The 25-keV width of the incident deuteron beam would make it impossible to separate the $l = 2$ transition to the 1.886-MeV level from the $l = 1$ transition to the 1.90-MeV $\frac{3}{2}^-$ level. However, the same situation existed in the ^{42}Ca$(d, t)^{41}$Ca reaction, for which the angular distributions to the 1.94- and 2.01-MeV levels were not separated. That experiment showed clearly that a fairly large admixture of $l = 1$ is readily detectable. The ^{46}Ca$(d, t)^{45}$Ca reaction was also studied by Bjerregaard, Hansen, and Satchler[3] at an incident energy of 10 MeV.

The production of ^{45}K by proton transfer in the ^{46}Ca$(t, \alpha)^{45}$K reaction has been reported by Santo *et al.*,[4] who normalized the spectroscopic factors by assuming that $C^2S = 4.0$ for the strongest $l = 2$ transition obtained in the ^{48}Ca$(t, \alpha)^{47}$K reaction. The strong ^{40}Ca component in the target material used in the present experiment obviously makes it very difficult to uniquely identify the ^{46}Ca$(d, {}^3$He$)^{45}$K transitions in the present data alone; but it is quite feasible with the aid of the ^{40}Ca$(d, {}^3$He$)^{39}$K results obtained at somewhat higher energy by Hiebert, Newman, and Bassel[5] since both the ground state and the first excited state of ^{45}K occur at deuteron energies at which no ^{39}K levels are strongly excited. As a result, the spectroscopic factors obtained are directly comparable to those obtained for ^{43}K, ^{42}K, and ^{41}K from $(d, {}^3$He$)$ reactions on the other Ca isotopes.[1]

II. EXPERIMENTAL PROCEDURES

The experiment was performed in the 60-in. scattering chamber[6] at the Argonne cyclotron. After magnetic analysis, the energy spread in the 22.4-MeV deuteron beam was about 25 keV. The scattered particles were detected with a (dE/dx)-E telescope of surface-barrier detectors. The target was prepared by evaporating isotopically enriched CaCO$_3$ onto a Formvar backing. The material was enriched to 43.4% in ^{46}Ca; it contained about 5% ^{44}Ca, and the remainder was almost entirely ^{40}Ca. The target thickness was measured by comparing the experimentally measured angular distribution of elastically scattered deuterons with the theoretical angular distribution predicted from the optical-model potential parameters used in the distorted-wave Born-approximation (DWBA) calculations. These parameters fit the elastic deuteron scattering on ^{40}Ca at 21.6 MeV.[7] For the l values encountered in this range of atomic number and deuteron energy, the necessary spectroscopic information can be obtained by measuring the angular distribution between 12 and 30°. The optical-model potential parameters used are listed in Ta-

TABLE I. Parameters of the optical-model potential.

Target + projectile	V (MeV)	r_0 (F)	a_0 (F)	W (MeV)	W' (MeV)	a' (F)	r' (F)	V_{so} (MeV)	r_C (F)
Ca + d	105.0	1.02	0.86	···	60.0	0.65	1.42	6.0	1.3
^{46}Ca + t	176.9	1.139	0.7236	14.7	···	0.769	1.662	0.0	1.4
^{46}Ca + ^{3}He	179.5	1.139	0.86	15.3	···	0.769	1.624	0.0	1.4

ble I. The JULIE calculations[8] were made in the zero-range local approximation without a lower cutoff of the radial integrals. In comparing the theoretical and experimental curves, the normalization constant 3 was used as suggested by Bassel.[9] The resolution width of the detection system was about 75 keV for the (d, t) reaction and about 90 keV for the $(d, {}^3\text{He})$ reaction. The energy calibration is considered accurate to ±10 keV.

III. EXPERIMENTAL RESULTS

A. ^{46}Ca$(d, t)^{45}$Ca Reaction

A spectrum of the ^{46}Ca$(d, t)^{45}$Ca reaction is shown in Fig. 1. The 24° lab angle was chosen since all of the transitions have a measurable cross section at that angle. The ground-state transition of the ^{44}Ca$(d, t)^{43}$Ca reaction is identified. The transition to the $\frac{5}{2}^-$ level at 178 keV is not observed; an upper limit on the possible strength of a transition to this level would be 2% of the ground-state strength. The $\frac{3}{2}^-$ levels at 1.433 and 2.842 MeV are excited, but there is no evidence for any excitation of the 1.56- and 1.58-MeV levels nor of a measurable strength for the transition to the 2.251-MeV level which is probably $\frac{1}{2}^-$. The level at 1.89 MeV is the $\frac{3}{2}^+$ level and the level at 2.396 MeV the $\frac{1}{2}^+$ level. The only other state populated with an appreciable strength is the one at 3.56 MeV. No level in this vicinity is observed in the ^{44}Ca$(d,p)^{45}$Ca reaction. The spectrum appears to contain one $f_{7/2}$, one $d_{3/2}$, two $s_{1/2}$, and two $p_{3/2}$ states. The neutron-pickup spectra from ^{44}Ca and ^{42}Ca had a far greater number of levels, while the spectrum of the ^{48}Ca$(d, t)^{47}$Ca reaction has more the appearance of the ^{45}Ca spectrum.

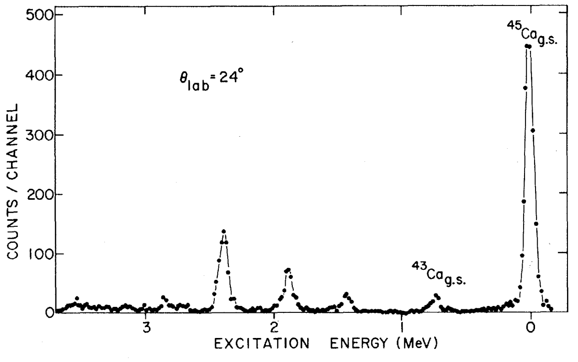

FIG. 1. Spectrum of the reaction ^{46}Ca$(d,t)^{45}$Ca at 24°.

The angular distributions of the six levels excited in this reaction are shown in Fig. 2. The curve for the level at 1.886 MeV should include any con-

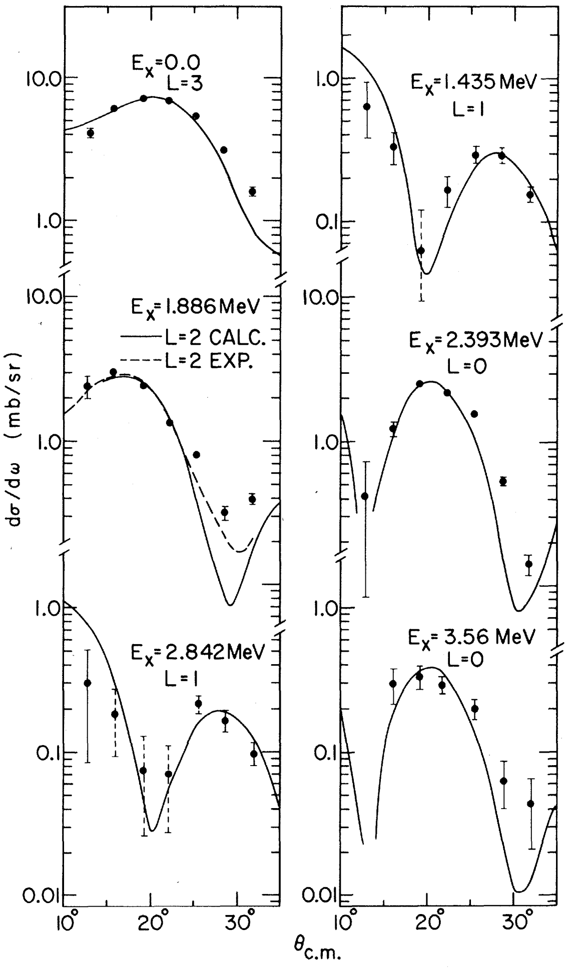

FIG. 2. Angular distributions of groups in the reaction ^{46}Ca$(d,t)^{45}$Ca, together with the calculated distorted-wave curves. For the $l=2$ transition, the empirical pure $l=2$ transition is shown dashed.

TABLE II. Levels in ^{45}Ca from the ^{46}Ca(d, t) reaction.

E_x (MeV)	J^π	l	C^2S for (d,t) Present	(Ref. 3)	$\sum C^2S$ Theor.
0.0	$\frac{7}{2}^-$	3	6.0	6.5	6.0
0.179	$\frac{5}{2}^-$		<0.12	<0.25	
1.435	$\frac{3}{2}^-$	1	0.15		
1.886	$\frac{3}{2}^+$	2	3.3	1.3	3.43
1.900	$\frac{3}{2}^-$		<0.08	<0.04	
2.393	$\frac{1}{2}^+$	0	0.9		1.72
2.842	$\frac{3}{2}^-$	1	0.15		
3.56	$(\frac{1}{2}^+)$?	(0)	0.1		

tribution that may result from excitation of the $\frac{3}{2}^-$ level at 1.90 MeV. For an empirical $l=2$ shape, one can use the experimental $l=2$ transition to the 0.99-MeV level of ^{43}Ca in the ^{44}Ca(d, t)^{43}Ca reaction. This transition has about the same Q value as the ^{46}Ca(d, t)^{45}Ca reaction to the 1.89-MeV level. It is rather obvious that empirically there is at most a small contribution from the 1.90-MeV level. A reasonable upper limit on the contribution from the 1.90-MeV level seems to be half of the strength of the $l=1$ transition to the 1.44-MeV level. The results of comparing the DWBA calculation with the experimental cross sections are summarized in Table II.

B. ^{46}Ca(d, ^{3}He)^{45}K Reaction

This experiment is at the limit of feasibility with the present experimental arrangement. The negative Q value of the ground state and the large admixture of ^{40}Ca in the target make it difficult to obtain reliable data. Therefore spectra were taken only at 16, 21, 24, and 27° in the laboratory system.

The two levels that are relatively unobstructed by the other Ca isotopes and the oxygen in the target are the ground state and 470-keV level. The angular distributions and distorted-wave calculations are shown in Fig. 3. The Q value of the level at 1.08 MeV, which was tentatively assigned a $\frac{7}{2}^-$ spin in the (t, α) experiment, is too negative to allow a good determination of l value and strength for such a weak state in the presence of an overabundance of other Ca isotopes. The results of comparing the DWBA calculations with the experimental results are shown in Table III, together with the results of the ^{46}Ca(t, α)^{45}K experiment.

TABLE III. Levels in ^{45}K from the ^{46}Ca(d, ^{3}He) reaction.

E_x (MeV)	J^π	l	C^2S (d, ^{3}He)	(t, α)	(Ref. 4)
0.0	$\frac{3}{2}^+$	2	1.5	2.25	(3.0)
0.470	$\frac{1}{2}^+$	0	1.0	1.05	(1.4)

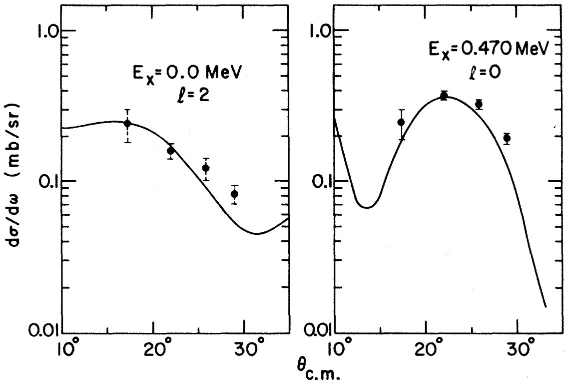

FIG. 3. Angular distributions and distorted-wave calculations for the ground state and first excited state of ^{45}K.

IV. DISCUSSION

The spectroscopic factor for the transitions to the ground state and to the $\frac{3}{2}^+$ state at 1.886 MeV are close to the theoretical expectation. The value of $\sum C^2S$ for the transition to the $\frac{1}{2}^+$ state is of the same order of magnitude as that for the $l=0$ transitions to states in ^{42}Ca, ^{44}Ca, and ^{48}Ca. The theoretical expectation for the transition to the state with the lower T is $\sum C^2S=1.72$. The transitions to the 1.435- and 2.842-MeV $\frac{3}{2}^-$ levels are about equally strong, with $C^2S=0.15$. These levels are equally strongly excited also in the ^{44}Ca(d,p)^{45}Ca reaction, in which the transition to the 1.90-MeV level is about five times stronger. In the ^{46}Ca(d, t)^{45}Ca reaction, however, the transition to the latter level is obviously not separated from the transition to the $\frac{3}{2}^+$ level at 1.886 MeV and was assigned an upper limit $C^2S \leq 0.08$. Here, as in the other Ca isotopes, the intensity ratios of transitions to levels of the same spin are by no means the same in pickup as in stripping reactions; and this difference casts doubt on the practice of assigning J values by comparing relative intensities in stripping and pickup reactions. The value of $\sum C^2S$ for $l=1$ is about the same for ^{46}Ca as for ^{42}Ca and ^{44}Ca. The $^2p_{3/2}$ component in ^{48}Ca was considerably smaller. No indication for an admixture of $^2p_{1/2}$ neutrons in the ground-state configuration was found.

The experimentally obtained values of C^2S for the transitions to the ground state of ^{39}K and the 5.31-MeV $\frac{5}{2}^+$ level of ^{39}K are in excellent agreement with the results reported in Ref. 5. Therefore one can have reasonable confidence in the accuracy of the values of C^2S extracted from the experiment, even though the angular distribution is rather fragmentary and rather large errors are assigned to the experimental points. The value $C^2S = 1.5$ for the ^{45}K ground state is not significantly smaller than the result of the ^{46}Ca(t, α)^{45}K reaction. The value $C^2S = 3.1$ for this transition (Ref. 4) was based on the assumption that $C^2S = 4.0$ for the strongest $l = 2$ transition of the ^{48}Ca(t, α)^{47}K reaction. However, the experimental result for the ^{48}Ca(d, ^{3}He)^{47}K reaction[10] has been quoted as $C^2S = 3.0$. If one uses this normalization, the ^{46}Ca(t, α)-^{45}K reaction yields $C^2S = 2.2$. This is considerably smaller than the results for the ground-state transitions of the ^{42}Ca(d, ^{3}He)^{41}K and ^{44}Ca(d, ^{3}He)^{43}K reactions, which were both fairly close to the theoretical expectation $C^2S = 4.0$. The value $C^2S = 1.0$ for the $l = 0$ transition is also about half the theoretical value $C^2S = 2.0$ obtained from the transitions to ^{43}K and ^{41}K. This result indicates that there probably are appreciable admixtures of core-excited configurations in the ground-state wave function of ^{45}K.

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