Energy Levels in Sc^{49} from $Ca^{48}(He^3,d)Sc^{49}$ and Other Reactions Proceeding from Ca^{48}†

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The $Ca^{48}(He^3,d)Sc^{49}$ reaction at $E_{He^3}=12.00$ MeV has been studied with a broad-range magnetic spectrograph. Twenty-four energy levels have been identified up to an excitation energy of 7 MeV. Distorted-wave Born-approximation calculations have been used to assign l values and extract spectroscopic factors for most of the transitions. Some information obtained with the $Ca^{48}(He^3,\alpha)Ca^{47}$, $Ca^{48}(d,t)Ca^{47}$, $Ca^{48}(d,p)Ca^{49}$, and $Ca^{48}(\alpha,p)Sc^{51}$ reactions is also given.

INTRODUCTION

THE energy-level structure of Sc^{49} is expected to be particularly simple because of the closed shell at Ca^{48}.[1] The structure of such nuclei near closed shells is of interest because it can provide valuable information on the location of single-particle states. With the level structures of Ca^{41},[2] Sc^{41},[3,4] and Ca^{49},[5] Sc^{49} completes the information on nuclei in this region of the periodic table. The (He^3,d) reaction is well described as a direct process analogous to the (d,p) reaction but adding a proton instead of a neutron. An analysis of the reaction within the framework of the distorted-wave Born approximation (DWBA) yields quantitative information about the spectroscopic factors of the final states.

EXPERIMENTAL METHOD

The energy levels of the nucleus Sc^{49} were studied with the 12.0-MeV He^3 beam of the Argonne tandem Van de Graaff accelerator and the Argonne broad-range magnetic spectrograph.[6] Evaporated targets[7] of Ca^{48} about 90 and about 16 μg/cm^2 thick on C backings about 30 μg/cm^2 thick were used. The He^3 beam was obtained by accelerating the singly charged He^3 beam in a small Van de Graaff accelerator and allowing the beam to pass through a charge-exchange canal where an appreciable fraction of the beam was neutralized. This neutral beam was aimed at another charge-exchange canal in the high-voltage terminal of the tandem accelerator from which the charged fraction was accelerated. The doubly charged He^3 component of the beam was then selected by magnetic analysis. Typically, beam currents between 0.1 and 0.3 μA were used.

Measurements were obtained at laboratory angles of 10°, 15°, 20°, 30°, and 40°. Eastman NTA plates were used as detectors in the broad-range spectrograph. These were scanned carefully in order to select only deuteron tracks in the emulsion. The peaks observed along the focal plane of the magnet were analyzed in terms of Q values for the reactions. Peaks due to contaminants were eliminated by observing the dependence of particle energy on the scattering angle.

Absolute cross sections were obtained by measuring the yield of elastically scattered He^3 ions at 10° and assuming this to be well approximated by Rutherford scattering. The error in this assumption is believed to be small compared with other uncertainties in the measurement.

One high-yield exposure at 10° was obtained with a relatively thick target (about 90 μg/cm^2) for an integrated beam charge of 1290 μC. All angles were measured with a target thickness of about 16 μg/cm^2 and an integrated beam charge of 800 μC. Additional data were obtained in the vicinity of the very weak groups at $\sim$2.3 and $\sim$3.5 MeV excitation at a bombarding energy of 11 MeV.

ANALYSIS OF THE (He^3,d) DATA

DWBA calculations were performed with the Oak Ridge National Laboratory computer code TSALLY.[8] The parameters are listed in Table I. The angular distributions are quite insensitive to small changes in the choice of distorting parameters.

Typical calculated angular distributions are shown in Fig. 1; transitions with different l values are clearly

TABLE I. Optical-model parameters.

Incident particle	V (MeV)	W (MeV)	R_0 (F)	a (F)	R_0' (F)	a' (F)	R_c (F)
He^{3}[a]	146.3	9.2 (volume)	1.07	0.754	1.81	0.592	1.25
d[b]	112.0	18.0 (surface derivative)	1.00	0.900	1.55	0.47	1.25

[a] R. Bassel (private communication).
[b] Parameters derived from Ca^{40} by R. H. Bassel, R. M. Drisko, G. R. Satchler, L. L. Lee, Jr., J. P. Schiffer, and B. Zeidman, Phys. Rev. 136, 960 (1965).

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] A preliminary report of this work was presented by J. R. Erskine, J. P. Schiffer, and A. Marinov, Bull. Am. Phys. Soc. 9, 80 (1964).
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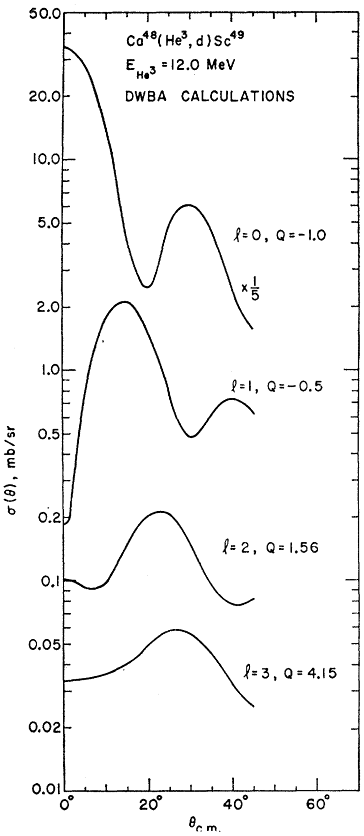

FIG. 1. Angular distributions calculated by use of the DWBA and the computer code TSALLY. The parameters used are listed in Table I. The quantity plotted is $\sigma(\theta)$ as defined in the text.

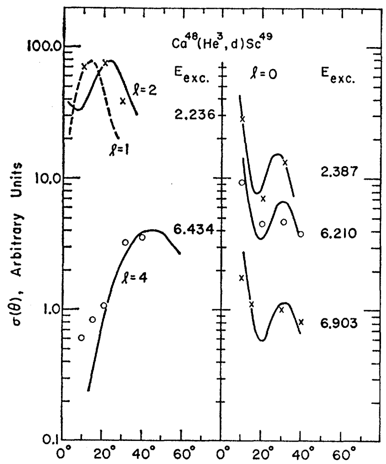

FIG. 3. Observed angular distributions for states other than $l=1$ or 3, for which l-value assignments are given. The lines represent DWBA calculations; experimental errors are less than 20%.

distinguishable. The cross sections with a 6-F cutoff were used, since with no cutoff or a cutoff of 4 F the calculated cross section for the ground state showed no sign of the observed peak at 30°. However, at the angle at which the experimental cross section peaked, the calculated cross sections for every final state changed by less than 10% when cutoff radii were varied from zero to 6 F.

Figures 2 and 3 compare the data with the calculated distributions. The information extracted from this analysis is listed in Table II together with the best excitation energies and peak cross sections obtained from the present experiment. A ground-state Q value of 4.150±0.012 MeV was measured for the $Ca^{48}(He^3,d)Sc^{49}$ reaction. The uncertainty in this Q value and the 5–12-keV uncertainties in the excitation energies arise chiefly from the uncertainty in the stopping correction. Our measurement of 3.092±0.005 MeV for the energy of the first strong $l=1$ state seriously disagrees with the

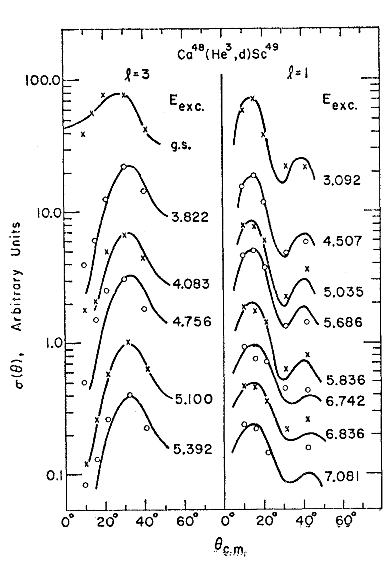

FIG. 2. Observed angular distributions for $l=1$ and $l=3$ transitions. The lines represent DWBA calculations; experimental errors are less than 20%.

TABLE II. Summary of experimental results.

Q value[a] (MeV)	Excitation[b] energy (MeV)	Peak[c] cross section (mb/sr)	l	J^π	$(2J+1)S$ [c]	S' [c]
4.150	0.0	1.9	3	$(\frac{7}{2}-)$	8.0	1.0
	2.233	0.15	(2)	$(\frac{3}{2}+)$	0.15	0.05
	2.382	0.04	(0)	$(\frac{1}{2}+)$	0.008	0.005
	3.092	14.3	1	$(\frac{3}{2}-)$	2.4	0.68
	3.819	0.3	3	$(\frac{5}{2}-)$	0.6	0.15
	3.923	0.03				
	4.004	0.1				
	4.080	0.4	3	$(\frac{5}{2}-)$	0.8	0.20
	4.507	9.6	1	$(\frac{3}{2}-)$	1.1	0.31
	4.756	0.3	3	$(\frac{5}{2}-)$	0.4	0.10
	5.035	2.0	1	$(\frac{1}{2}-)$	0.21	0.13
	5.100	1.0	3	$(\frac{5}{2}-)$	1.4	0.35
	5.392	0.4	3	$(\frac{5}{2}-)$	0.6	0.15
	5.686	4.8	1	$(\frac{1}{2}-)$	0.47	0.30
	5.836	1.2	1	$(\frac{1}{2}-)$	0.12	0.08
	6.024	0.07				
	6.210	0.2	(0)	$(\frac{1}{2}+)$	0.01	0.006
	6.434	0.2	(4)	$(\frac{9}{2}+)$	0.6	0.06
	6.555	0.5	1	$(\frac{1}{2}-)$	0.05	0.03
	6.742	0.6	1	$(\frac{1}{2}-)$	0.06	0.04
	6.836	1.7	1	$(\frac{1}{2}-)$	0.17	0.11
	6.903	1.7	(0)	$(\frac{1}{2}+)$	0.12	0.07
	7.044	0.1				
	7.081	1.5	1	$(\frac{1}{2}-)$	0.15	0.10

[a] The uncertainty for the ground-state Q value is estimated to be 12 keV.
[b] The uncertainties in these excitation energies are estimated to be 5 keV for the 3.092- and 4.507-MeV levels, 10 keV for the other states below 4.5 MeV, and 12 keV for all other states.
[c] The uncertainties in these numbers are estimated to be 20%.

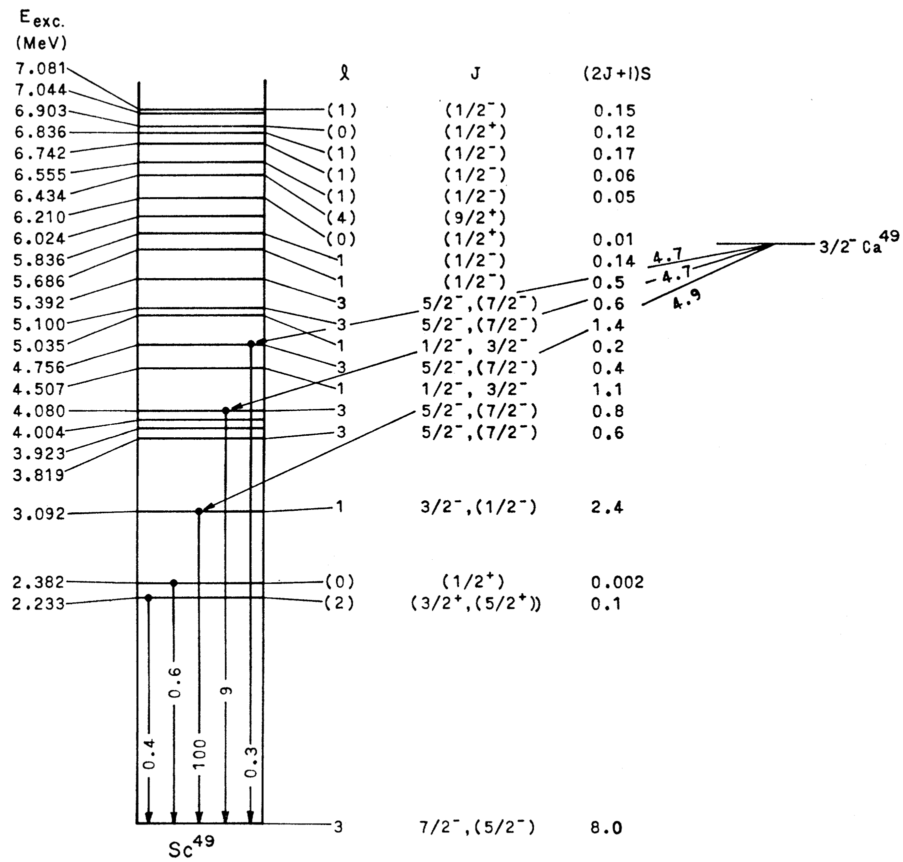

FIG. 4. The energy levels of Sc^{49} as determined in the present experiment. Data from β^- decay of Ca^{49} are also shown. The l values, probable spins, and $(2J+1)$ times the spectroscopic factors are also given.

measurement of Chilosi *et al.*[9] who report 3.079 ± 0.001 MeV from a study of gamma radiation in the β decay of Ca^{49}. No evidence has been found for a state at 3.50 MeV reported from a study of gamma rays in the $Ca^{48}(p,\gamma)Sc^{49}$ reaction[10]; if present, such a state would be populated with a cross section of less than 0.01 mb/sr. The spectroscopic factors given were obtained from the DWBA calculations by assuming the ground-state transition to have $J^\pi=\frac{7}{2}^-$ and to be of single-particle strength. In this way a normalization constant $x=4.17$ was obtained. Here x is defined by $d\sigma/d\Omega=x(2J+1)S\sigma(\theta)$, where $\sigma(\theta)$ is the cross section calculated by the TSALLY code[8] and $d\sigma/d\Omega$ is the measured cross section.

The assignment of spins to states in Sc^{49} is necessarily uncertain because no gamma-ray correlation measurements have been made, and our angular distributions are too incomplete to attempt an analysis in terms of a J dependence.[11]

Some reasonable tentative assignments can be made on the basis of systematics and the results from the β decay of Ca^{49} to Sc^{49}.[9,12,13] This information is summarized in Fig. 4. One would certainly expect $J^\pi=\frac{7}{2}^-$ for the ground state of Sc^{49} (the $1f_{7/2}$ single-particle state of the shell model). This is, in fact, the assignment from the $l=3$ angular distribution and the lack of a β^- transition which would proceed if this state had $J^\pi=\frac{5}{2}^-$. The next shell-model state expected is the $2p_{3/2}$ state which probably is the state at 3.092 MeV. This assignment is supported by the $l=1$ transition to this state with a large spectroscopic factor and a strong β^- transition. The two states at 2.233 and 2.382 MeV were seen as one group in the proton pickup reaction[14] $Ti^{50}(d,He^3)$-Sc^{49} and appeared to have a mixed $l=2$ and $l=0$ angular distribution. They are very weak in the present experiment. The angular distribution of the 2.233-MeV state appears to be consistent with an $l=2$ transition and the 2.382-MeV state with an $l=0$ transition. One would therefore tentatively identify these as the $1d_{3/2}$ and $2s_{1/2}$ hole states.

The logft values for the β^- transitions to the 3.819- and 4.080-MeV states[12,13] are consistent with the $\frac{5}{2}^-$ as-

[9] G. Chilosi, G. D. O'Kelley, and E. Eichler, Bull. Am. Phys. Soc. **10**, 92 (1965).
[10] J. Dubois and S. Maripuu, Phys. Letters **8**, 349 (1964).
[11] A. G. Blair (private communication).
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[14] J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964).

signment to these states. The next state (at 4.507 MeV) is excited with an $l=1$ transition, which allows spin assignments of $\frac{1}{2}^-$ or $\frac{3}{2}^-$. The spectroscopic factor of 1.1 suggests that if the spin were $\frac{1}{2}^-$, this transition would exhaust more than half of the $2p_{1/2}$ sum-rule strength. One would therefore expect that the logft value for the β decay would be very similar to the ones observed for the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states. This β transition is not observed, and from a review of the published data one would guess an upper limit of perhaps 5.5–6. This is quite inconsistent with a $2p_{1/2}$ single-particle state. On the other hand, with a $\frac{3}{2}^-$ assignment, the wave function of the second strongest $\frac{3}{2}$ state may not overlap sufficiently with the Ca^{49} ground state to give a large β-decay matrix element; a single-particle $\frac{1}{2}^-$ state would have to have such overlap. We therefore tentatively assign $\frac{3}{2}^-$ to this state. This is also the assignment suggested by Armstrong and Blair[15] from the J dependence of the angular distribution

An assignment of $\frac{1}{2}^-$ appears to be a reasonable guess for all the higher $l=1$ states and $\frac{5}{2}^-$ for all the $l=3$ states. The lack of a β decay to the $l=3$ state at 3.819 MeV is not surprising for the reasons discussed above: The fact that the $1f_{5/2}$ single-particle state is fragmented among many actual levels implies that some, but not all, of them must show up in β decay.

On the basis of these assignments, one can use a prescription suggested by Satchler[16] to correct the spectroscopic factors for the slight J dependence of the cross sections as calculated by the code TSALLY. The procedure for applying this correction is to multiply the calculated $l=3$ cross section by 1.2 for a $\frac{7}{2}^-$ state, by 0.8 for a $\frac{5}{2}^-$ state, by 1.06 for a $\frac{3}{2}^-$ state, by 0.94 for a $\frac{1}{2}^-$ state, and by 0.9 for a $\frac{3}{2}^+$ state. The values of S' listed in Table II include this correction. The normalization factor x, discussed above, now becomes 3.48, which is to be compared with the factor 3.8 found for other (He^3,d) reactions, and a factor[16] of 4.4 calculated from reasonable wave functions for He^3 and the deuteron.

The values of S' were used to calculate mean values of single-particle energies $\bar{E}_J$ by use of

$$\bar{E}(J)=\sum_i S_i(J)E_i(J)/\sum_i S_i(J)$$

and spreading widths W_J from the relation

$$W(J)=\left[\frac{\sum_i S_i(J)[E_i(J)-\bar{E}(J)]^2}{\sum_i S_i(J)}\right]^{1/2}.$$

The sums of S_i should be equal to 1.0 if all components of the single-particle state are included. In Sc^{49} it is expected that for the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ single-particle states, the isobaric analog states will occur at much higher excitation energies and their spectroscopic factors will be

$$\sum S'_{T=9/2}=1/(2T_0+1)=\tfrac{1}{9},$$

where T is the isobaric spin of the final states and T_0 is the isobaric spin of the target. These states are the analogs of the states in Ca^{49} and have been observed as resonances in the proton scattering on Ca^{48} at excitation energies in Sc^{49} of 11.45, 13.55, 15.57, and 15.97 MeV.[17] The sums of spectroscopic factors for the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ transitions observed in the present experiment should therefore be

$$\sum S'_{T=7/2}=1-1/(2T_0+1)=8/9.$$

The values of $\sum S'$, $\sum S'/(8/9)$, $E_J(T=\frac{7}{2})$, and the spreading width $W_J(T=\frac{7}{2})$ are given in Table III.

TABLE III. Characteristics of single-particle states in Sc^{49} with $T=\frac{7}{2}$.

State	$\Sigma S'_i$	$\Sigma S'_i/(8/9)$	$\bar{E}_J$ (MeV)	W_J (MeV)
$1f_{7/2}$	1.00		0.0	0.0
$2p_{3/2}$	0.99	1.11	3.54	0.66
$1f_{5/2}$	0.95	1.07	4.69	0.69
$2p_{1/2}$	0.85	0.96	6.04	0.58

The spectroscopic factors are reasonable in view of a ±20% uncertainty in cross sections and additional uncertainties in the method of normalizing the DWBA calculations. Considering the different bombarding energies and the different parameters used in the analysis, they are in remarkable agreement with those of Ref. 18. Minor disagreements with Ref. 18 regarding some of the weak levels do not alter the conclusions of the present work, although the higher resolution of the present experiment would perhaps tend to make the present assignments the more plausible ones.

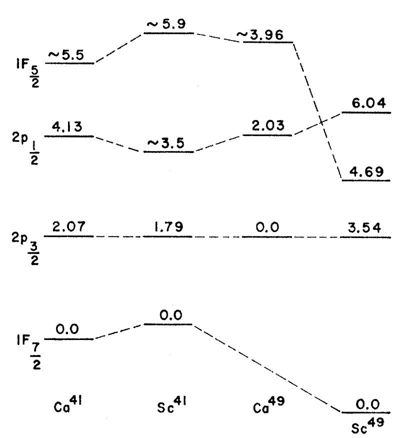

FIG. 5. Single-particle energies (Refs. 8, 10, 11) in Ca^{41}, Sc^{41}, Ca^{49}, and Sc^{49}. The energies shown for the $1f_{5/2}$ states in the first three nuclei are lower limits. The levels are drawn relative to the $2p_{3/2}$ energies. The numbers shown are excitation energies in MeV.

[15] D. D. Armstrong and A. G. Blair, Phys. Rev. **140**, B1226 (1965).
[16] R. H. Bassel (private communication, 1965).
[17] K. W. Jones, L. L. Lee, Jr., A. Marinov, and J. P. Schiffer, Bull. Am. Phys. Soc. **10**, 479 (1965).
[18] D. D. Armstrong and A. G. Blair, Phys. Letters **10**, 204 (1964).

A comparison of the single-particle energies in Sc^{49} with those found in Ca^{41}, Sc^{41}, and Ca^{49} in Fig. 5 reveals that the $1f_{5/2}$ and $1f_{7/2}$ energies are lower in Sc^{49}, relative to the $2p$ states, than they are in the other nuclei. It would seem that the $1f$ proton state is affected by the filling of the $1f_{7/2}$ neutron state; the $1f_{5/2}$ neutron state apparently is not so affected. Macfarlane has pointed out to us that from this one may deduce that there is a stronger attraction in the $T=0$ than in the $T=1$ two-particle state.

OTHER REACTIONS WITH A Ca^{48} TARGET

A number of other reactions which used a Ca^{48} target were also studied. The ground-state Q values are summarized in Table IV for all the reactions studied, including the $Ca^{48}(d,\alpha)K^{46}$ reaction which was previously reported.[7]

TABLE IV. A summary of the ground-state Q values of various reactions measured with a Ca^{48} target.

Reaction	Q value (MeV)	Uncertainty (MeV)
$Ca^{48}(He^3,d)Sc^{49}$	4.150	0.012
$Ca^{48}(He^3,\alpha)Ca^{47}$	10.630	0.012
$Ca^{48}(d,t)Ca^{47}$	−3.699	0.010
$Ca^{48}(d,p)Ca^{49}$	2.917	0.007
$Ca^{48}(\alpha,p)Sc^{51}$	−5.860	0.020
$Ca^{48}(d,\alpha)K^{46}$	1.915	0.015

Alpha-particle groups from the $Ca^{48}(He^3,\alpha)Ca^{47}$ reaction were observed on the plates along with deuterons from the $Ca^{48}(He^3,d)Sc^{49}$ reaction. The Q value of the ground-state group was measured to be 10.630±0.012 MeV. A strong group corresponding to an excited state in Ca^{47} was observed near 2.59 MeV. Further investigation of the latter group with the $Ca^{48}(d,t)Ca^{47}$ reaction revealed that this group was a 24-keV doublet consisting of levels at 2.584±0.005 and 2.608±0.005 MeV excitation. These two levels may be the $1d_{3/2}$ and $2s_{1/2}$ hole states which are expected in this region. This identification is supported by the good agreement between these energies and those of two weak states seen in the $Ca^{46}(d,p)Ca^{47}$ reaction and by the $l=0$ angular distribution for the 2.608-MeV state.[19] The 2.013-MeV state seen with the $Ca^{46}(d,p)Ca^{47}$ reaction[19,20] as a strong $l=1$ transition was not seen here; since this is most likely the $2p_{3/2}$ state, one would not expect it to be populated. The ground-state Q value of the $Ca^{48}(d,t)Ca^{47}$ reaction was measured to be −3.699±0.010 MeV.

The $Ca^{48}(d,p)Ca^{49}$ reaction was also investigated. A ground-state Q value of 2.917±0.007 MeV was measured. Excited states were observed at 2.027(4), 3.357(4), 3.589(4), 4.001(4), 4.020(7), 4.078(10), 4.278(10), 4.423(10), and 5.394(5) MeV, the values in parentheses being the uncertainty (keV) in these measurements. These excitation energies are in substantial agreement with the measurements of Kashy *et al.*[5] except for the 3.357-MeV level which differs by more than the stated uncertainties. A number of other groups observed above 4.8-MeV excitation seemed to have the proper kinematic behavior to be identified as Ca^{49} levels. However, these states probably were states in Ca^{41} which came from a small Ca^{40} impurity in our target.

The isotope Sc^{51} is observed here for the first time in the study of the $Ca^{48}(\alpha,p)Sc^{51}$ reaction. A ground-state Q value of −5.860±0.020 MeV was measured. Four excited states were found at excitations of 0.860, 1.070, 2.330, and 3.020±0.030 MeV. There is probably one more strong level at an excitation of 2.660±0.050 MeV. A preliminary report on this reaction has already been given.[21]

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[21] J. R. Erskine and A. Marinov, Bull. Am. Phys. Soc. **10**, 479 (1965).