Energy Levels of Sc^{48} from a Study of Neutrons and Gamma Rays Emitted by the $Ca^{48}(p,n\gamma)Sc^{48}$ Reaction*

C. CHASMAN, K. W. JONES, AND R. A. RISTINEN
Brookhaven National Laboratory, Upton, New York
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Energy levels of Sc^{48} up to 2.5 MeV excitation have been studied by observation of neutrons and gamma rays produced in the $Ca^{48}(p,n\gamma)Sc^{48}$ reaction. Analysis of neutron spectra obtained at $E_p=3.250$ MeV with a He^3-filled proportional counter, and of gamma-ray spectra obtained at various proton bombarding energies with a lithium-drifted germanium gamma-ray detector, shows that the $Ca^{48}(p,n)Sc^{48}$ reaction does not populate the Sc^{48} ground state directly. The ground-state-reaction Q value is found to be -529 ± 10 keV, which implies a mass excess of -44240 ± 14 keV for Ca^{48}. Excited states of Sc^{48} have been established at 131 ± 2, 253 ± 2, 624 ± 3, 1144 ± 3, 1406 ± 3, 2192 ± 3, 2277 ± 3, and 2519 ± 5 keV. Possible spin assignments have been deduced from the gamma-ray branching ratios.

I. INTRODUCTION

PREVIOUS studies[1,2] of the neutrons produced in the $Ca^{48}(p,n)Sc^{48}$ reaction have determined some of the energy levels in Sc^{48}, and have established a reaction Q value[1] of -660 keV for the apparent ground-state reaction. As has been pointed out,[3,4] this reaction Q value is in poor agreement with the Q value of -510 keV deduced from atomic-mass measurements,[5] and may actually correspond to a reaction leading to an excited state of Sc^{48}. The ground-state spin and parity of Sc^{48} are known to be 6+ from β-γ circular-polarization correlation measurements[6,7] following β decay to a 6+ excited state in Ti^{48}. Yntema and Satchler,[8] in a study of the $Ti^{49}(d,He^3)Sc^{48}$ reaction, find evidence for two $d_{3/2}$ proton hole states at excitation energies of 0.77 and 1.40 MeV, and an $s_{1/2}$ hole state at about 2.1 MeV. Very little else is known about the levels of Sc^{48}.

The present experiment was undertaken in an effort to provide more accurate information on the level positions in Sc^{48} and to resolve the discrepancy in the ground-state Q value for the $Ca^{48}(p,n)Sc^{48}$ reaction, as well as to provide information on the gamma-ray decay modes of the excited states. Such information should be of use for comparison with detailed shell-model calculations[9,10] now being made in this mass region. It is also of possible interest with respect to interpretation of experiments on the single and double beta decay of Ca^{48}.

II. NEUTRON MEASUREMENTS

Neutron spectra produced by bombardment of a thin (<1 mg/cm^2) target of 98% $Ca^{48}CO_3$ with 3.25-MeV protons were investigated with a He^3 neutron spectrometer.[11] The spectrometer was a proportional counter, 10 cm diam $\times$38 cm long, filled with He^3 at a pressure of 1.5 atm. Krypton, at a pressure of 3.5 atm, was used as a stopping gas to reduce the range of the protons and tritons produced by the $He^3(n,p)T$ reaction. The effect of He^3 recoils from neutron elastic scattering was eliminated by rise-time discrimination.[12] Two runs were taken, one with collimation of the incident neutron beam to reduce wall effects and one without collimation. Substantially identical spectra were obtained. The neutron energy scale was established by a calibration run on the ground- and first-excited-state neutrons from the $Y^{89}(p,n)Zr^{89}$ reaction and from the $He^3(n,p)T$ thermal peak. A neutron energy spectrum for the collimated run is shown in Fig. 1 with Q values (the value quoted is the average for the two runs) for the numbered peaks as follows: (1) -668, (2) -783, (3) -1168,

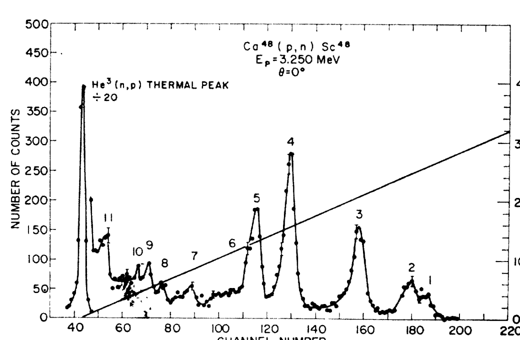

FIG. 1. A neutron energy spectrum taken with a collimated incident-neutron beam. The number near each peak corresponds to an excited state of Sc^{48} as shown in Fig. 6.

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[1] A. J. Elwyn, H. H. Landon, S. Oleksa, and G. N. Glasoe, Phys. Rev. **112**, 1200 (1958).

[2] A. T. G. Ferguson and E. B. Paul, Nucl. Phys. **12**, 426 (1959).

[3] *Nuclear Data Sheets*, edited by K. Way *et al.* (National Academy of Sciences–National Research Council, Washington, D. C.) NRC 61-2; Compilers Comments, NRC 61-2-4.

[4] C. H. Johnson, C. C. Trail, and A. Galonsky, Phys. Rev. **136**, B1719 (1964).

[5] C. F. Giese and J. L. Benson, Phys. Rev. **110**, 712 (1958).

[6] B. van Nooijen, thesis, Technical University of Delft, 1958 (unpublished). Quoted in Nuclear Data Sheets (Ref. 3).

[7] L. G. Mann, D. C. Camp, J. A. Miskel, and R. J. Nagle, Phys. Rev. **137**, B1 (1965).

[8] J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964).

[9] J. D. McCullen, B. F. Bayman, and L. Zamick, Phys. Rev. **134**, B515 (1964).

[10] R. K. Bansal and J. B. French, Phys. Letters **11**, 145 (1964).

[11] A. Sayres, K. W. Jones, and C. S. Wu, Phys. Rev. **122**, 1853 (1961).

[12] A. Sayres and M. Coppola, Rev. Sci. Instr. **35**, 431 (1964).

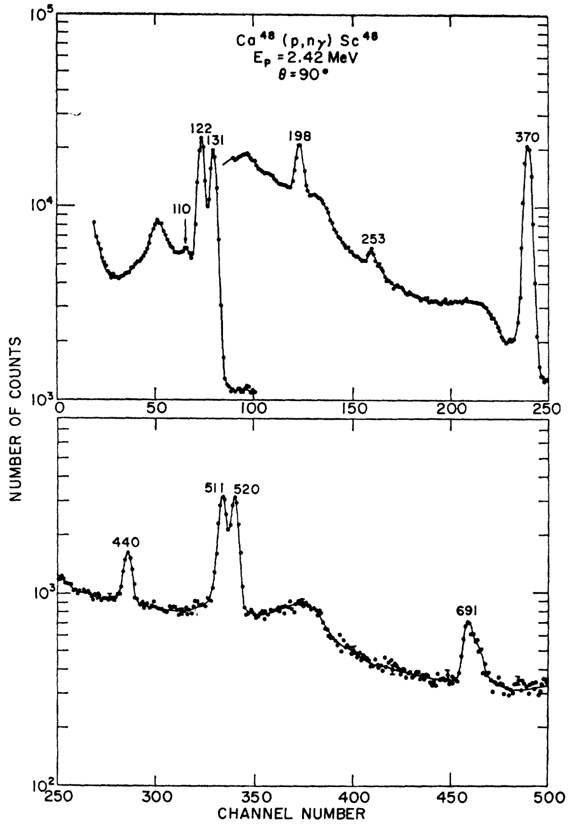

FIG. 2. A gamma-ray spectrum recorded with a lithium-drifted germanium gamma-ray detector. The line at 691 keV is broadened by nuclear recoil following inelastic neutron scattering in the detector (see Table I, footnote a). Other lines are discussed in the text and listed in Table I. The data are not normalized at channel 100.

(4) −1678, (5) −1942, (6) −2130, (7) −2414, (8) −2077, (9) −2725, (10) −2807, and (1) −3039 keV. Each value is estimated to be uncertain by ±20 keV. Agreement with the work of Elwyn *et al.*[1] is good, but there are some discrepancies between our work and that of Ferguson and Paul,[2] as summarized in Fig. 6.

III. GAMMA-RAY MEASUREMENTS

Gamma rays emitted by the decay of the excited states of Sc^{48} were observed with a lithium-drifted germanium gamma-ray detector which had a sensitive volume of about 3.5 cm^3. It was mounted in a cryostat of a type described elsewhere.[13] The targets used had isotopic enrichments of Ca^{48} ranging up to 98% and were prepared by vacuum evaporation of $CaCO_3$ onto thick backings of gold and carbon and by pressing the $CaCO_3$ powder on a niobium backing. Most of the work was done with a thick carbon backing. Background was estimated from runs with targets of normal calcium, plain carbon, and gold. Gamma rays which are assigned to $p+Ca^{48}$ interactions must come from the $Ca^{48}(p,n)Sc^{48}$ reaction which is, neglecting the capture reaction, the only energetically allowed reaction for this range of incident-proton energies. Typical spectra obtained are shown in Fig. 2 for the gamma-ray energy region of 0 to 720 keV and in Fig. 3 for the energy region from 650 to 2500 keV. Other spectra were taken at proton energies from 1.2 to 3.6 MeV to provide information on the position of the excited states of Sc^{48} from which the gamma rays are emitted. Table I is a listing of the prominent lines observed in the gamma-ray spectra. Gamma-ray energies were found by comparison with standard sources and by using a precision pulser calibration method.[14] By observation at 90° to the proton beam, Doppler-shift effects were minimized and, in any case, the maximum Doppler shift expected in this experiment is less than 1 keV. Estimated uncertainties in the gamma-ray energy determinations are, in general, ±2 keV or less.

The two gamma rays at 122 and 131 keV are of particular interest. Figure 4 shows an expanded view of this region, as well as a Co^{57} calibration spectrum. The energy of the lower member of the doublet is in reasonable agreement with the energy separation of the two lowest states seen in the neutron work. In agreement with past suggestions,[3,4] it seemed likely that the 131-keV gamma ray represents a previously unseen cascade transition to the ground state. To show that this is indeed the case, a coincidence measurement was first made to prove that the 122- and 131-keV lines are in prompt coincidence. The measurements were made with a 2-in.×2-in. NaI crystal and the ger-

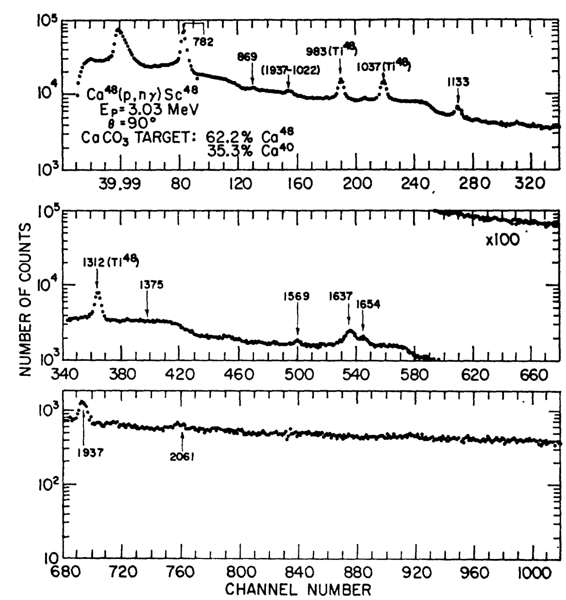

FIG. 3. Higher energy region of the gamma-ray spectrum. Line energies are given in keV.

[13] C. Chasman and R. A. Ristinen, Nucl. Instr. Methods **34**, 250 (1965).

[14] D. E. Alburger, C. Chasman, K. W. Jones, and R. A. Ristinen, Phys. Rev. **136**, B913 (1964).

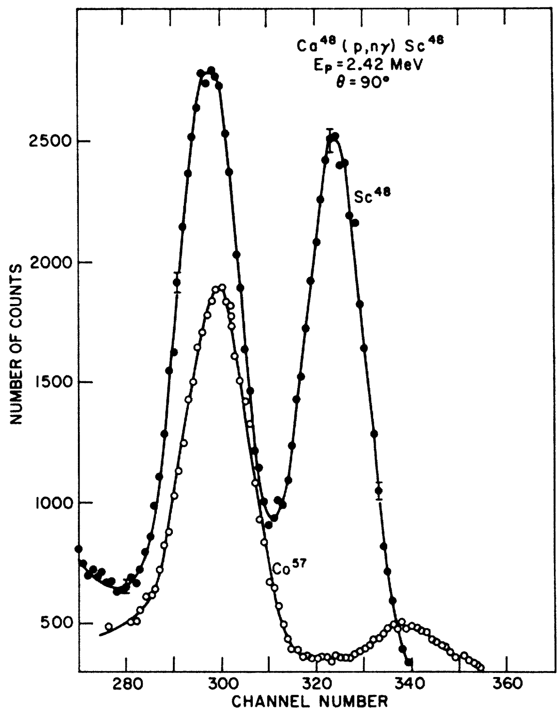

FIG. 4. An expanded view of the 122–131-keV doublet with a superimposed Co^{57} spectrum.

manium gamma-ray detector. The NaI counter could not, of course, resolve the doublet, but adequate separation was achieved by setting a gating window on the high side and then on the low side on the line. When this was done, it was found from inspection of the coincidence spectra from the germanium gamma-ray detector that the 122-keV peak was enhanced relative to the 131-keV peak when the NaI gate was on the high side of the line and that the 131-keV peak was enhanced when the gate was on the low side. Results of these measurements are shown in Fig. 5. Further, a spectrum taken at 1.2-MeV proton energy showed only the 122–131-keV doublet, with no higher energy gamma rays being produced. We conclude from this, and the observed intensities, that the two lines are in direct cascade. The energy of the 122-keV line is in good agreement with the energy spacing between lines 1 and 2 seen in the present neutron work. Therefore, the 131-keV gamma ray must represent a transition to the ground state of Sc^{48} which is not evident in the neutron spectrum. The Q value for the $Ca^{48}(p,n_0)Sc^{48}$ reaction is then found to be -529 ± 10 keV by combining the 131-keV gamma-ray energy with the neutron-measurement Q value of -660 ± 10 keV,[15] for what is now considered the first excited state of Sc^{48}. The 1961 Nuclidic Mass Table of König, Mattauch, and Wapstra[16] determines the mass of Ca^{48} through the Q value of the $Ca^{48}(p,n_0)Sc^{48}$ reaction taken as -660 ± 10 keV. Revising their value in accordance with the new Q value gives a value of $-44\,240\pm14$ keV for the Ca^{48} mass excess.

Further coincidence work showed that the 122–131-keV doublet was in prompt coincidence ($2\tau\approx10^{-7}$ sec) with the 370, 520, and 782-keV lines and that the 520- and 782-keV lines were not in mutual coincidence. Coincidences with higher energy lines were not observed, presumably because of the low counting rates for the higher energy gamma rays.

IV. RESULTS AND DISCUSSION

The placing of the gamma-ray transitions in the level scheme shown in Fig. 6 is straightforward. Levels deduced from the neutron work and the gamma-ray work are displayed separately, along with the results of Elwyn *et al.*[1] and Ferguson and Paul.[2] Agreement between the three neutron experiments is fairly good. Ferguson and Paul find levels at 714 and 851 keV which we do not find in either our neutron or gamma-ray work, while we find levels at 1592 and 2077 keV in the neutron spectrum with which we cannot definitely find associated gamma rays and which are not observed by Ferguson *et al.*

A search was made for an isomeric state in Sc^{48} by means of pulsed beam techniques, but no evidence for the gamma-ray decay of such a state with a half-life between 10 and 250 nsec was found.

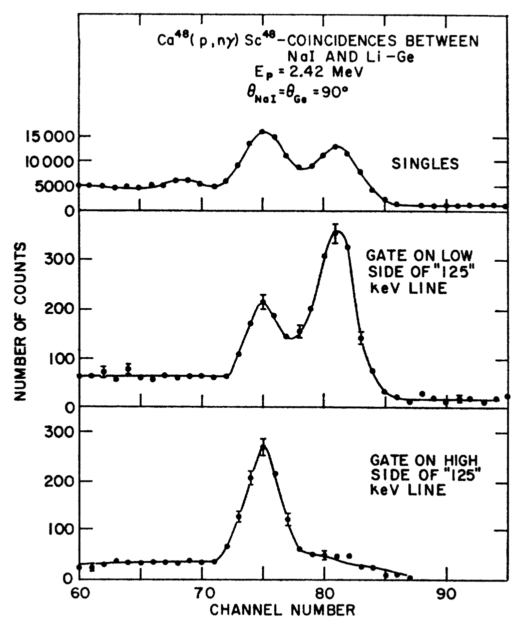

FIG. 5. Coincidence spectra recorded in the germanium gamma-ray detector with the gating window set on the low and high sides of the composite 122–131-keV peak in a NaI(Tl) scintillation counter.

[15] C. M. P. Johnson (private communication), quoted by L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nucl. Phys. 31, 1 (1962).

[16] L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nucl. Phys. 31, 18 (1962).

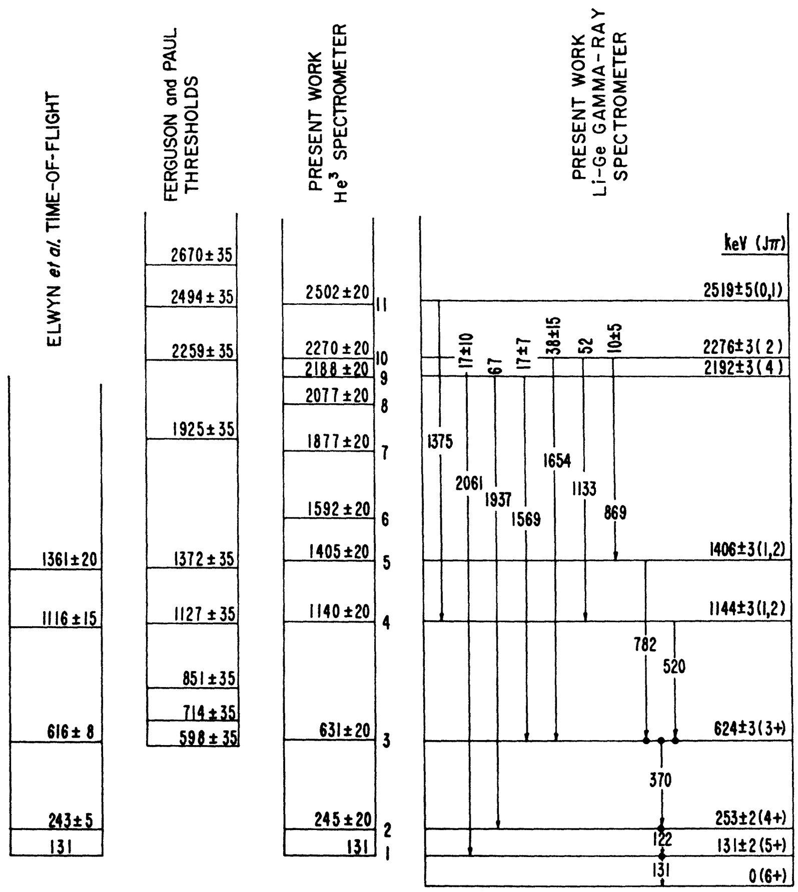

FIG. 6. Energy levels of Sc^{48} from neutron- and gamma-ray spectroscopy. The energy levels determined by previous investigators are shifted to correspond to a Q value of -529 keV for the $Ca^{48}(p,n_0)Sc^{48}$ reaction. The number near each level in the present neutron work relates the level to a peak in Fig. 1. Gamma-ray branching ratios are indicated at the 2192- and 2276-keV levels. Experimentally determined coincidence relationships are indicated by dots.

There does not appear to be good evidence for crossover transitions following the decay of states lower in energy than 1406 keV. Lines were observed at 253 keV and 492 keV, but, because of gamma-ray summing in the detector, only an upper limit of 3% can be placed on the crossover transition intensity for these two energies, relative to the cascade intensity.

From the coincidence and pulsed-beam measurement it is concluded that, with the possible exception of a very low-energy (<30 keV) first excited state which could have been missed, the half-lives of the states at lower than 1-MeV excitation must be less than 10^{-8} sec. Even if $E2$ speeds are considered to be enhanced by a factor of 100, a single-particle interpretation of the transition rates[17] requires that the 122- and 131-keV transitions be of predominantly dipole multipolarity. However, the 370-keV transition can be either a mixed magnetic-dipole–electric-quadrupole or a pure electric-quadrupole transition.

If the previously measured[6,7] $J=6$ assignment to the ground state is correct, the 131-keV level must then have $J=5$, 6, or 7. The lowest spin $J=5$ is favored by the neutron data in light of the fact that the reaction does appreciably populate the 131-keV level, but not the ground state. If the $J=5$ interpretation is correct, then the dipole character of the 122-keV gamma ray leads to a $J=4$, 5 or 6 assignment for the 253-keV level. In this case, the $J=4$ choice is most probable because a spin of 5 or 6 would lead, again assuming single-particle transition speeds, to a 253-keV dipole transition of greater intensity than the 122-keV transition, whereas the gamma-ray data put an upper limit of 3% on a 253-keV transition relative to the 122-keV transition. If the foregoing conclusions are correct, spins of 2 and 6 for the 624-keV level are consistent with a pure quadrupole character for the 370-keV transition. However, the $J=6$ assignment is unlikely because of the absence of crossover transitions to the ground and first excited states and because the state has a relatively large neutron-production cross section (Fig. 1). If the 370-keV transition has a dipole component, only a spin of 3 is consistent with the observed decay to the 253-keV $J=4$ state. Thus, the 624-keV state is found to have a spin of either 2 or 3, depending upon the multipolarity admixture of the 370-keV transition. The levels at 1144 and 1406 keV most probably have spin of 2 or less because they decay only to the 624-keV $J=2,3$ state. Three branches of gamma-ray decay are associated with the depopulation of the 2192-keV level. The intensity

[17] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

TABLE I. Table of prominent lines observed in gamma-ray spectra. The neutron-produced lines are from the detector and holder,[a] and the Na^{23} was a contaminant in the target backing. All errors in the energies are those determined by this work.

Energy (keV)	Origin	Energy (keV)	Origin
110 ± 2[b]	$F^{19}(n,n'\gamma)F^{19}$	691 ± 3[b]	$Ge^{72}(n,n'e^-)Ge^{72}$
122 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$	782 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$
131 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$	869 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$
175 ± 5[d]	$Sc^{48}\rightarrow Ti^{48}$	983 ± 2[b]	$Sc^{48}\rightarrow Ti^{48}$
198 ± 2[b]	$F^{19}(n,n'\gamma)F^{19}$	1037 ± 2[b]	$Sc^{48}\rightarrow Ti^{48}$
252 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$ sum	1133 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$
370 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$ sum	1312 ± 2[b]	$Sc^{48}\rightarrow Ti^{48}$
440 ± 2[b]	$Na^{23}(p,p'\gamma)Na^{23}$	1375 ± 4[c]	$Ca^{48}(p,n\gamma)Sc^{48}$
492 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$ sum	1569 ± 3[c]	$Ca^{48}(p,n\gamma)Sc^{48}$
511	Annihilation radiation	1637 ± 5[b]	$Na^{23}(p,p'\gamma)Na^{23}$
520 ± 2[c]	$Ca^{48}(p,n\gamma)Sc^{48}$	1654 ± 3[c]	$Ca^{48}(p,n\gamma)Sc^{48}$
600 ± 3[b]	$Ge^{74}(n,n'\gamma)Ge^{74}$	1937 ± 4[c]	$Ca^{48}(p,n\gamma)Sc^{48}$
		2061 ± 4[c]	$Ca^{48}(p,n\gamma)Sc^{48}$

[a] A discussion of the effects of fast neutrons on a lithium-drifted germanium gamma-ray detector is given by C. Chasman, K. W. Jones, and R. A. Ristinen, Nucl. Instr. Methods (to be published).
[b] Lines tabulated in *Nuclear Data Sheets*, edited by K. Way *et al.* (National Academy of Sciences–National Research Council, Washington, D. C.) NRC 61-2.
[c] Lines identified by this work.
[d] M. Hillman, Phys. Rev. **129**, 2227 (1963).

ratios of these three transitions are consistent with single-particle speeds only if all three are dipole. These branching ratios are indicated in Fig. 6. Since two of the three gamma rays go to states of $J=5$ and 4 at 131 and 253 keV, respectively, the third, which populates the 624-keV level, can only go to a state having a spin of 3, 4, 5, or 6. In consideration of the previous restriction to $J=2$ or 3 for the 624-keV state, we now have unique assignments of $J=3$ for the 624-keV state and $J=4$ for the 2192-keV level. The gamma-ray decay of the state at 2276 keV leads to the 624-keV $J=3$ level and to both the 1144- and 1406-keV $J=\leq 2$ levels. Again, in a situation similar to that seen in the decay of the 2192-keV level, the three gamma-ray branches are in an intensity ratio which is only compatible with all three being predominantly dipole. The dipole transition to the 624-keV $J=3$ level requires a spin of 2, 3, or 4 for the parent 2276-keV state. But the absence of a prominent branch to the 253-keV $J=4$ state and the presence of transitions to the 1144- and 1406-keV $J\leq 2$ levels lead to a preferred spin of 2 for the 2276-keV level and require $J=1$ or 2 for the 1144- and 1406-keV levels. The level at 2519 keV seen in the neutron spectrum is confirmed by a single gamma-ray branch only at the highest incident-proton energies. Possibly, this is a $J=0$ or 1 state because a single mode of decay to a $J=1$, 2 state is observed with no higher energy crossover transition to higher spin states.

The foregoing statements concerning level spins are at best plausibility arguments based largely on a single-particle estimate of electromagnetic transition rates. If some of the transitions are either enhanced or inhibited to an exceptional degree, the related conclusions may be in error.

A correspondence between the neutron spectrum (Fig. 1) and the spins shown in the level scheme is obvious. Peaks 3, 4, and 5 are conspicuously strong in the neutron spectrum and it is just those associated levels at 624, 1144, and 1406 keV which have been assigned the lower spin values. Low spin states are expected to be preferentially populated because of greater nuclear penetrabilities for protons and neutrons of low angular momenta.

The five lowest levels exactly correspond in sequence of spin assignments to the calculated spectrum of McCullen *et al.*[9] Hence, judging from the general success of these calculations when applied to neighboring nuclei, these five levels probably occur within the $1f_{7/2}$ configuration. Excitation energies are generally in agreement within about 250 keV, which is the degree of reliability claimed for the theory. It is not clear which of the two levels at 1144 and 1406 keV is to be associated with this coupling scheme, but the lower of the two more nearly agrees in energy with the calculations cited above. These two states may represent another example of the frequent proximity noted by McCullen *et al.* in $1f_{7/2}$ shell nuclei of two states of the same spin and parity, one of which is an example of pure $1f_{7/2}$ character, and the other a product of configurational admixtures. The calculations also predict a spin-7 state at ≈ 1.3 MeV, but the present work would not be expected to reveal a state of high spin at such an energy, and none was seen. If these five lower levels are all formed by the coupling of a $1f_{7/2}$ proton and a $1f_{7/2}$ neutron hole outside of closed shells, as suggested by the agreement with McCullen *et al.*, their parity must be positive, requiring that the 131-, 122-, 370, and 520-keV transitions be $M1$ and $E2$. Parity assignments to the levels at 1406, 2192, 2276, and 2519 keV are ambiguous even though some gamma-ray branches connect these levels to lower states of presumably known spin and parity. In these cases the competing speeds of $E1$ and $M1$ transitions are such that no firm arguments can be made on the basis of gamma-ray branching ratios. No obvious association can be made between the proton hole states of 0.77, 1.40, and 2.10 MeV reported by Yntema and Satchler[8] and the levels observed in this work, although the two levels at 1406 and 2192 keV could be negative-parity $d_{3/2}$ and $s_{1/2}$ hole states, respectively. A negative-parity $d_{3/2}$ hole-state assignment seems implausible for the energy levels observed nearest 770 keV.

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