which can make a large contribution to the excitation probability for the first excited state of ^{53}Cr.

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Lifetimes of Negative-Parity States of ^{49}Sc by the ^{48}Ca$(p, \gamma)^{49}$Sc Reaction*

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The mean lifetimes for 18 γ-ray transitions in ^{49}Sc were determined using the Doppler-shift-attenuation method. Previously unreported γ rays of 1620, 4275, and 6010 keV were observed and placed in a decay scheme. Evidence is presented indicating that the correct spin assignment for the 4493-keV state is $\frac{1}{2}^-$ rather than $\frac{3}{2}^-$. The low-lying negative-parity states of ^{49}Sc are calculated using a simple model in which a single proton in the $2p1f$ shell is coupled to positive-parity core states in ^{48}Ca. The model reproduces most of the single-particle levels quite well. Fair agreement is obtained between calculated and experimentally determined $E2$ and $M1$ transition rates except for the $\frac{5}{2}^-$ to $\frac{7}{2}^-$ transitions.

I. INTRODUCTION

The nucleus ^{49}Sc can be viewed most simply as having a proton outside the doubly-magic-core nucleus ^{48}Ca. The shell model assumes an inert core on the basis of the double-closed shells of ^{48}Ca and predicts a simple single-particle level structure for ^{49}Sc. However, the energy levels and angular momenta from the ^{48}Ca$(^3$He$, d)^{49}$Sc reaction[1] reveal that the simple shell-model approach does not explain the observed fragmentation of the single-particle levels.

Bertsch and Damgaard[2] attempted to describe the structure of ^{49}Sc using single-particle states plus 2p-1h configurations made up of $1f_{7/2}$ neutron hole states, $2p_{3/2}$ neutron states, and $1f_{7/2}$ proton states. They concluded that single-particle states plus 2p-1h configurations did not provide a sufficient basis for a realistic description of ^{49}Sc although there was a qualitative trend away from the simple shell-model behavior.

We have measured the lifetimes of several negative-parity states in ^{49}Sc by the Doppler-shift-attenuation method using the ^{48}Ca$(p,\gamma)^{49}$Sc reaction. The measurements were made at the 1.975-MeV proton resonance using high-resolution Ge(Li) detectors. Experimental procedures and results are given in Secs. II and III.

Federman, Greek, and Osnes[3] have used a simple core-particle interaction model in describing the negative-parity states of ^{41}Ca and ^{41}Sc, with surprisingly good results considering the simplicity of the model. We have done a similar calculation to determine the extent to which such a simple model can describe the low-lying negative-parity states of ^{49}Sc. A brief description of the model and comparison of experimental with calculated results is given in Secs. IV and V.

II. EXPERIMENTAL PROCEDURES

Mean lifetimes were measured by the Doppler-shift-attenuation method using the ^{48}Ca$(p,\gamma)^{49}$Sc reaction. This method has been adequately described in the literature.[4,5] The forward angle in this work was set at 28° and the backward angle at 125° to the proton beam direction.

The 1.975-MeV resonance was selected for lifetime measurements since its decay scheme is probably the best understood.[6] The proton beam was provided by the vertical Van de Graaff at the Los Alamos Scientific Laboratory. The beam was bent through a 90° analyzing magnet and collimated by two carbon apertures. A beam current of about 3-4 μA was provided with a $\frac{1}{4}$-in.-diam beam spot on the target.

The ^{48}Ca target was prepared by evaporating a thickness of 40→60 μg/cm^2 onto a 75-μg/cm^2 carbon backing. The ^{48}Ca was obtained from the Oak Ridge National Laboratories and was 96% isotopically pure. ^{40}Ca composed about 4% of the target and only trace amounts of other elements were present.

The detection and analyzing system consisted of a 20-cm^3 Princeton Gamma-Tech Ge(Li) detector coupled through a Tennelec TC-161 preamplifier, a Canberra model 1416 linear amplifier, and a Tennelec Baseline Restorer TC-611, to a Victoreen ICA-4096D 4096-channel analog-to-digital converter (ADC). The ADC output was sent to a Scientific Data Systems computer model 930 which accumulated the spectra. Magnetic tapes containing the spectra were later analyzed on a CDC-6600 computer to determine peak centroids, areas, and relative intensities. Under beam conditions the system had a resolution of 4 keV at $E_\gamma = 1$ MeV and about 9 keV at $E_\gamma = 5$ MeV.

Detector-to-target distance was 3.5 in. and the active detector volume subtended a 6.5° angle on either side of the center line. The finite dimensions of the detector introduce less than 1% error in the measured γ-ray shifts.

Typical run times were 6 h in the forward position and 6 h in the backward position. No special gain stabilization was used for these runs since calibration spectra before and after each run showed little drift.

An Ortec solid-state Si(Li) detector located at 125° in the backward direction was used to detect the elastic protons scattered from the target. The total counting rate from the γ detector was also monitored. By varying the energy of the proton in 1-keV increments from 1980 to 1970 keV the 1975-

TABLE I. Experimental γ-ray energies, attenuation factors, and mean lifetimes of ^{49}Sc.

γ-ray energy corrected for nuclear recoil (keV)	Attenuation factor $F(\tau)$ (%)	Mean life τ (fsec)
1409.1(0.5)	104.4(17.5)	≤33
1620(1.5)	−76.2(66.7)	≥1000
2228.6(0.5)	3.2(9.2)	(29.9 nsec) [a]
2371.8(0.5)	−4.8(6.1)	(1.4 nsec) [a]
3084.7(0.5)	75.8(11.2)	69^{+42}_{-48}
3808.6(0.5)	87.8(8.6)	30^{+26}_{-21}
4071.9(0.5)	84.7(6.7)	40^{+20}_{-18}
4333.1(0.5)	90.3(8.6)	25^{+25}_{-23}
4341.7(0.5)	100.6(7.5)	≤20
4500.0(0.5)	100.7(7.0)	≤20
4538.6(1.5)	109.1(19.6)	≤27
4577.8(0.5)	96.2(4.7)	≤20
4614.6(0.5)	112.8(15.3)	≤20
4739.4(0.5)	102.1(9.8)	≤20
4833.5(0.5)	97.7(5.2)	≤20
5059.1(0.5)	102.1(4.3)	≤20
5147.7(0.5)	104.1(7.0)	≤20
5376.0(0.5)	88.2(4.9)	30^{+14}_{-13}
6010.3(1.1)	88.1(13.3)	≤70
6415.4(0.5)	88.1(5.4)	31^{+13}_{-14}

[a] Measured by G. Chilosi, R. A. Ricci, and G. B. Vingiani, Phys. Rev. Letters 20, 159 (1968); Phys. Rev. Letters 20, 781E (1968).

keV resonance was located. Approaching the resonance from the high-energy side insured that the 1975-keV level was well located since no major resonance has been detected between 1975 and 2000 keV at 125°.

Contamination in the carbon backing meterial and buildup on the target produced several contaminant γ rays. The most pronounced source came from the $^{19}F(p, \alpha\gamma)^{16}O$ reaction.[7] Fortunately, this γ ray is well known and could be used as a calibration standard at high energies.

After all runs were made and the proton beam shut off, an 8-h run was made to establish the spectrum of beam-induced activities. All that remained was the $^{48}Sc(\beta^-)$ activation. No γ rays could be located which belonged to the $^{49}Sc(\beta^-)$ decay.

The attenuation function $F(\tau)$ was calculated using the approximation procedures of Blaugrund.[8] The specific energy loss due to nuclear and electronic stopping are from the theoretical work of Lindhard, Scharff, and Schiøtt.[9] The numerical integration over Blaugrund's expressions was carried out with the nuclear specific energy loss given by the computer-fitted equation:

$$\left(\frac{d\epsilon}{d\rho}\right)_n = A_0(e^{-ax} - e^{-bx}) + B_0(e^{-cx} - e^{-dx}) \,.$$

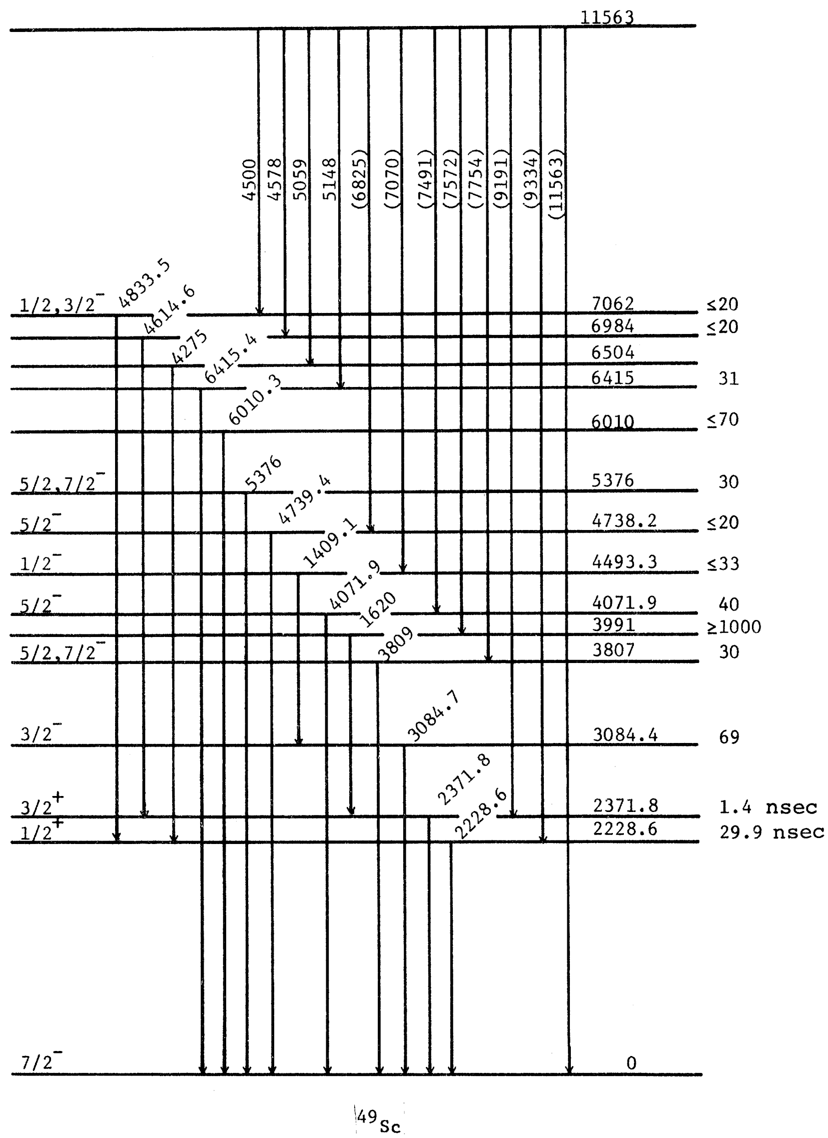

FIG. 1. The ^{49}Sc γ rays observed with energies determined in this experiment are fitted here to the level energies obtained from *Nuclear Data Sheets* (Ref. 12). Mean lives are in fsec if not otherwise stated and energies in keV.

In this expression

$$A_0 = 0.189\,59, \quad a = 0.210\,94, \quad c = 1.029\,04,$$

$$B_0 = 0.746\,46, \quad b = 11.585\,14, \quad d = 2.506\,62\,,$$

and $x \equiv \epsilon^{1/2}$ with ϵ and ρ being the dimensionless energy and length parameters defined by Lindhard, Scharff, and Schiøtt.

Dolan and McDaniels[10] estimate that the uncertainty in the theoretical $F(\tau)$ is approximately 10% for lifetimes longer than 10^{-13} sec, while for shorter lifetimes the uncertainty in $F(\tau)$ is somewhat less than 10%.

III. EXPERIMENTAL RESULTS

Table I presents the measured attenuation factors for 20 γ rays and their corresponding mean lives. The γ-ray energies have been corrected for nuclear recoil. Where possible, the attenuation factors were the result of averaging the observed shifts of the full-energy peaks and their corresponding double-escape peaks. The error shown represents only the uncertainty in peak centroids. It does not include the approximate 10% error inherent in the stopping theory of Lindhard, Scharff, and Schiøtt.[9]

Since the 3084.4-keV state is populated by the decay of the 4493.3-keV state rather than the resonance state, its attenuation factor should in general be corrected. In this case, however, $F(\tau)$ for the 4493.3-keV state is 100% so that this correction results only in an increase of the uncertainty in the lower limit of the mean lifetime of the 3084.4-keV state by an additional 12 fsec.

The γ rays observed in this work agreed well with those of Eichler and Raman.[11] The 1288.4- and 1144.5-keV γ rays were not seen since the resonance-level decay only very weakly populates the 3516.6-keV level. The lower threshold of the ADC prevented the detection of the 143.2-keV γ ray.

Observed in this work are the previously unreported 1620-, 4275-, and 6010-keV γ rays. Because of its energy and appropriate mean life, the 5376-keV γ ray was placed so that it deexcites the 5380-keV level.

The placement of the observed γ rays in the decay scheme is shown in Fig. 1. Only γ rays with relative intensities large enough to clearly distinguish them from background anomalies and source γ rays were considered. The resonance transitions shown in parentheses in Fig. 1 are taken from Vingiani, Chilosi, and Bruynesteyn.[6] The spin and energy assignments for the different levels came from the *Nuclear Data Sheets*.[12]

Seen in this work and by Vingiani, Chilosi, and Bruynesteyn[6] were the 4333.1- and 4341.7-keV γ rays. Neither could be placed in the decay scheme. However, Armstrong and Blair[13,14] report a level at 4.34 MeV which could be deexcited by the observed 4333.1-keV γ ray.

Using the recoil corrected energies of this work, the 1.975-MeV resonance was placed at $11\,563 \pm 3$ keV above the ^{49}Sc ground state. This compares very well with the quoted value[12] of $11\,560 \pm 4$ keV.

The experimentally determined transition rates are given in Table II. Branching ratios of states

TABLE II. Experimental mean lifetimes, multipolarities, transition probabilities, and transition strengths of ^{49}Sc. The $B(E2)$ values are given in units of $e^2\,\mathrm{fm}^4$, $B(M1)$ in μ_0^2, and $B(E1)$ in $e^2\,\mathrm{fm}^2$. Transition strengths are given in Weisskopf units (W.u.). The single-particle transition probabilities are given by $B_{\mathrm{s.p.}}(E2) = 10.652\ e^2\,\mathrm{fm}^4$, $B_{\mathrm{s.p.}}(M1) = 1.790\mu_0^2$, and $B_{\mathrm{s.p.}}(E1) = 0.863\ e^2\,\mathrm{fm}^2$.

Transition (keV)	Energy (keV)	Branching ratio (%)	τ_m (fsec)	Multipolarity	Transition probability	$\lvert M\rvert^2$ (W.u.)
3084.4 → 0	3084.4	99.86	69^{+42}_{-48}	$E2$	$42.5^{+97.1}_{-16.1}$	$3.99^{+9.13}_{-1.51}$
3084.4 → 2228.6	856.1	0.14		$E1$	$(2.03^{+4.65}_{-0.77}) \times 10^{-5}$	$(2.36^{+5.38}_{-0.90}) \times 10^{-5}$
3808.6 → 0	3806.6	100	30^{+26}_{-21}	$M1$	$0.0343^{+0.0800}_{-0.0159}$	$0.0192^{+0.0446}_{-0.0089}$
4071.9 → 0	4071.9	98.87	40^{+20}_{-18}	$M1$	$0.0208^{+0.0170}_{-0.0069}$	$0.0116^{+0.0095}_{-0.0039}$
4071.9 → 3084.4	987.3	1.13		$M1$	$0.0167^{+0.0136}_{-0.0056}$	$0.0093^{+0.0076}_{-0.0031}$
4493.3 → 3084.4	1408.9	100	≤33	$M1$	≥0.6157	≥0.3439
4738.2 → 0	4738.2	100	≤20	$M1$	≥0.0267	≥0.0149
5376 → 0	5376	100	30^{+14}_{-13}	$M1$	$0.0122^{+0.0092}_{-0.0039}$	$0.0068^{+0.0052}_{-0.0022}$
7062 → 2228.6	4833.5	100	≤20	$M1$	≥0.0252	≥0.0141

below 5 MeV were taken from Eichler and Raman[11] and the others were assumed to be 100% to the ground state. For states above 5 MeV spin assignments were chosen for purposes of these calculations to be either $\frac{5}{2}^-$ or $\frac{1}{2}^-$ depending upon the measured l values. The spin assignments for the lower states are those preferred by Eichler and Raman.[11]

The angular correlation results of Eichler and Raman are consistent with either a $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$ spin assignment for the 4493.3-keV level. They measured the directional correlation between the 1408.9- and the 3084.4-keV γ rays. Their data were best fitted by the correlation function $W(\theta) = 1 + A_{22}P_2(\cos\theta)$ with $A_{22} = -0.11 \pm 0.04$. This value is consistent with a dipole-quadrupole transition from a $\frac{1}{2}^-$ to a $\frac{3}{2}^-$ state followed by a quadrupole transition to the $\frac{7}{2}^-$ state if the mixing ratio δ is $-1.8 < \delta < 0.0$ and is consistent for similar transitions with an initial state of $\frac{3}{2}^-$ if $-2.5 < \delta < -0.75$. Our results favor a $\frac{1}{2}^-$ assignment since the $E2$ admixture in the 1409.1-keV transition is probably less than 36%. We found that the reduced transition probability $B(E2)$ for this transition is abnormally large if the $E2$ mixture is 36%. Taking the upper limit of $\tau_m = 33$ fsec, one gets a value of $B(E2)$ equal to 1610 $e^2\,\text{fm}^4$ and a transition strength of $|M|^2 = 151$ W.u. This suggests that $|\delta|$ is probably much less than 0.75. Thus the first spin sequence is the favored.

IV. CORE-PARTICLE MODEL

The Hamiltonian of the core-particle model described by Federman, Greek, and Osnes[3] is written

$$H = H_c + T_p + V(\vec{r}), \quad (1)$$

where H_c is the Hamiltonian of the 48 particles of ^{48}Ca, T_p the kinetic energy of the last particle, and $V(\vec{r})$ the interaction potential between the particle and the core.

The interaction $V(\vec{r})$ was approximated by an average field which is assumed to have the same shape as the nuclear density distribution of the core. This field is spherical when the particle interacts with the core in its ground state; it vibrates about the spherical shape when the particle interacts with the core in its first excited 2^+ state, and has a stable quadrupole deformation of axial symmetry when the particle interacts with the core in its rotational states.

The Hamiltonian of Eq. (1) can be rewritten as

$$H = H_c + H_p + H_{\text{int}}, \quad (2)$$

where

$$H_p \equiv T_p + V(r), \quad (3)$$

and

$$H_{\text{int}} \equiv -\beta r \frac{\partial V}{\partial r}\left(\frac{4\pi}{5}\right)^{1/2}[Y_2(\Omega)Y_2(\omega)] - r\frac{\partial V}{\partial r}\sum_\mu \alpha^*_{2\mu} Y_{2\mu}(\omega). \quad (4)$$

The deformation parameter of the density distribution associated with the rotational band is β, and $\alpha^*_{2\mu}$ is the quadrupole operator of the core. The variables Ω and ω describe the orientation of the nuclear system and the particle to an external fixed frame, respectively.

Eigenvalues of H_c are the experimental levels of ^{48}Ca taken from Tellez, Ballini, Delaunay, and Fouan.[15] The 0^+ ground state and the 2^+ (3.832-MeV) level were believed to be mainly spherical states while the 0^+ (4.286-MeV) level, the 2^+ (4.619-MeV) level, and the level at 5.464 MeV seem to have rotational characteristics. They find simple interpretation in terms of a $K=0$ rotational band with a band head at 4.286 MeV and band constant of $\hbar^2/2\mathscr{I} = 57$ keV.

Support for the hypothesis of this rotational band is provided by the electromagnetic transition rates. The first member of this band has been found to exhibit collective effects[16] as indicated by the rather large transition strength of $|M|^2 = 9.18$ W.u. In addition, Gerace and Green[17] predict that the first 0^+ excited states throughout the even isotopes of calcium contain mainly deformed components.

These five core-contributing states were expressed as admixtures of pure vibrational and ro-

TABLE III. Energy levels (E in MeV) and spectroscopic factors (S in %) for the experimental and calculated levels of ^{49}Sc.

	Exp		Calc	
J^π	E	S	E	S
$\frac{7}{2}^-$	0	93	0	92
	3.81 [a]	7	4.83	3
			3.92	3
$\frac{3}{2}^-$	3.08	68	3.15	63
			4.51	3
	5.68	14	4.72	29
$\frac{5}{2}^-$	3.81 [a]	15		
	4.07	20	4.11	22
	4.73	10	4.57	31
	5.09	35	5.02	35
	5.38	15	5.72	0.1
$\frac{1}{2}^-$	4.49 [b]	70	4.69	62
	5.02	13	5.02	27
	5.82	8		

[a] $l=3$ state placed twice to show agreement with $\frac{7}{2}^-$ calculation.
[b] Previously assigned a spin of $\frac{3}{2}^-$ by Ref. 1.

tational parts. The two admixture coefficients were treated as the only free parameters to fit the observed data. The vibrational constant $\alpha \equiv (\hbar^2/2\omega_2 B_2)^{1/2}$ of the quadrupole operator $\alpha^*_{2\mu}$ and the deformation parameter β were determined from from the admixture constants and the observed transition probabilities[16] connecting the core states.

The unperturbed single-particle energies corresponding to the eigenfunctions of H_p were obtained largely from the observed ^{49}Sc spectra.[1] The energies used were $1f_{7/2}$ (0 MeV), $2p_{3/2}$ (3.54 MeV), $1f_{5/2}$ (4.69 MeV), and $2p_{1/2}$ (4.70 MeV). The $2p_{3/2}$ and $2p_{1/2}$ levels differ from Erskine's[1] values since the 4493-keV level was reassigned a spin of $\frac{1}{2}^-$ consistent with our results and the 5675-keV level was assigned a spin value of $\frac{3}{2}^-$ to compensate for the loss of strength to the $\frac{3}{2}^-$ states.

The radial wave functions corresponding to the single-particle levels were obtained numerically by using the computer program code LINDA.[18] The parameters of this program are defined by Chwieroth.[19]

V. COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES

The best set of admixture constants was determined by fitting the energies and spectroscopic factors to the corresponding measured values. The most reasonable values found give a 69% spherical contribution to the 0^+ ground state of ^{48}Ca and an 86% vibrational contribution to the 2^+ (3.832-MeV) state. This then fixed the vibrational-rotational parameters $\alpha = 0.073$ and $\beta = 0.091$.

Spectroscopic factors, energy levels, and spins generated by this model are compared with experimental values in Fig. 2 and Table III. All energy levels generated by the model below 6 MeV are shown. Calculated and observed reduced transition rates are compared in Table IV.

The $\frac{7}{2}^-$ ground state of ^{49}Sc has a single-particle strength near 100% and our calculated value of 92% agrees well with this. Also calculated are a second and third state at 3.92 and 4.83 MeV, respectively. The lower of these two values corresponds nicely with the 3.81-MeV observed value if Erskine's measured spectroscopic factor is adjusted for a $\frac{7}{2}^-$ state. Assuming a $\frac{7}{2}^-$ spin assignment gives a 7% spectroscopic factor for the 3.81-MeV state and a 93% value for the ground state. These values agree much better with theory. The calculated and measured transition rate between the 3.81-MeV and ground state agree quite well, too.

The calculated energies and spectroscopic factors of the three $\frac{5}{2}^-$ states above 3.81 MeV compare fairly well with their experimental values. However, a comparison of the $\frac{5}{2}^-$ transition rates for all except the 4071.9 → 3084.4-keV transition points to a severe weakness in the model. The calculated rates are generally much too large for these transitions. A $\frac{5}{2}^-$ state at 5.72 MeV with a spectroscopic factor of 0.1% is also generated by the model, but it is doubtful that it is the 5.38-MeV state. Besides the very poor agreement of spectroscopic factors the calculated transition probability, $B(M1) = 0.0001\ \mu_0^2$, is much too low. The 5.09-MeV level was not populated in our work; thus no com-

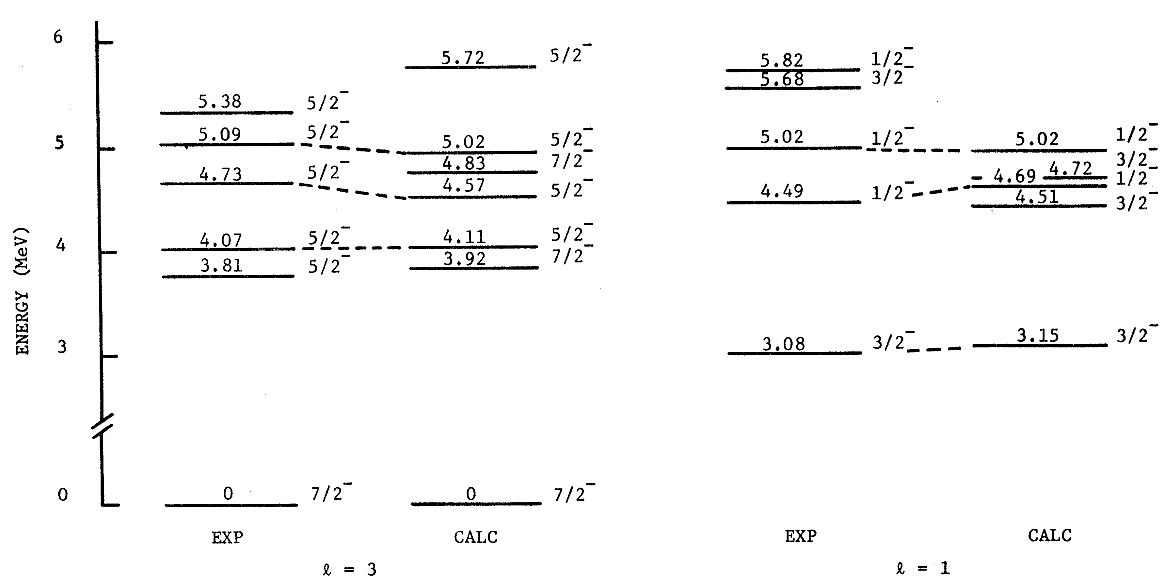

FIG. 2. Experimental and calculated spectra of negative-parity states in ^{49}Sc.

TABLE IV. Calculated and observed reduced transition rates of ^{49}Sc.

Transition Spin	Transition Energy	$B(E2)$ e^2 fm^4 Calculated	$B(E2)$ e^2 fm^4 Experimental
$(\frac{3}{2}^-)_1 \rightarrow (\frac{7}{2}^-)_1$	$3084.4 \rightarrow 0$	96	42^{+97}_{-16}
$(\frac{3}{2}^-)_2 \rightarrow (\frac{7}{2}^-)_1$	$4510 \rightarrow 0$	30	
$(\frac{3}{2}^-)_3 \rightarrow (\frac{7}{2}^-)_1$	$5675 \rightarrow 0$	0.7	

Transition Spin	Transition Energy	$B(M1)$ μ_0^2 Calculated	$B(M1)$ μ_0^2 Experimental
$(\frac{1}{2}^-)_1 \rightarrow (\frac{3}{2}^-)_1$	$4493.3 \rightarrow 3084.4$	0.45	≥ 0.62
$(\frac{5}{2}^-)_1 \rightarrow (\frac{3}{2}^-)_1$	$4071.9 \rightarrow 3084.4$	0.05	$0.02^{+0.02}_{-0.01}$
$(\frac{5}{2}^-)_1 \rightarrow (\frac{7}{2}^-)_1$	$4071.9 \rightarrow 0$	0.85	$0.02^{+0.02}_{-0.01}$
$(\frac{5}{2}^-)_2 \rightarrow (\frac{7}{2}^-)_1$	$4738.2 \rightarrow 0$	1.00	≥ 0.03
$(\frac{5}{2}^-)_3 \rightarrow (\frac{7}{2}^-)_1$	$5090 \rightarrow 0$	0.69	
$(\frac{5}{2}^-)_4 \rightarrow (\frac{7}{2}^-)_1$	$5376 \rightarrow 0$	0.0001	$0.012^{+0.009}_{-0.004}$
$(\frac{7}{2}^-)_2 \rightarrow (\frac{7}{2}^-)_1$	$3807^{a} \rightarrow 0$	0.01	$0.03^{+0.08}_{-0.02}$

[a] This transition assumes a $\frac{7}{2}^-$ assignment for the 3807-keV level.

parison could be made.

The calculated energy and spectroscopic factor for the lowest $\frac{3}{2}^-$ state are well produced by the model as is the transition rate. The effective proton charge used was $1.2e$. This transition rate is decreased to 54 e^2fm^4, in much better agreement with experiment, if an effective charge of $1.0e$ for the proton is used. A calculated state at 4.51 MeV with a small spectroscopic factor and the experimentally determined state at 5.68 MeV with a spectroscopic factor of 14% are not seen.

The energies and spectroscopic factors for the 4.49- and 5.02-MeV $\frac{1}{2}^-$ states are reproduced well as is the transition rate for the 4493 → 3084-keV transition. The 5.02- and 5.82-MeV states were not excited in this reaction.

The reason for the failure of the model to accurately predict most of the transition rates for those transitions involving $\frac{5}{2}^-$ states is difficult to assess. A recent study[20] of proton elastic scattering from ^{48}Ca suggests that the 4.619-MeV level is probably an $L=4^+$ state and is therefore not the 2^+ member of the rotational band which we assumed, in which case our choice of basis functions is not satisfactory. On the other hand, the relatively good fit of the remaining transition rates, and of most of the energy levels and spectroscopic factors indicates that the bases functions used are satisfactory, but that some of the admixture coefficients are incorrect.

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