GAMMA-RAY BRANCHING FROM THE Ca^{49} GROUND-STATE ANALOG IN Sc^{49} †

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Gamma rays from the reaction $Ca^{48}(p,\gamma)Sc^{49}$ have been observed at proton energies corresponding to formation of the Ca^{49} ground-state analog. Gamma-ray intensities have been measured and anomalous behavior is observed.

The $T=\frac{9}{2}$ isobaric analog states in Sc^{49*}, corresponding to the $J^\pi=\frac{3}{2}^-$ ground state of Ca^{49}, have recently been identified by study of the cross sections for the elastic scattering of protons[1] by Ca^{48}, and the reactions $Ca^{48}(p,n\gamma)Sc^{48}$ and $Ca^{48}(p,\gamma)Sc^{49}$.[2,3] Relatively few experiments have been concerned with the electromagnetic decay of analog states although the transition rates from such states should be valuable in determining their structure. The decay of the analog states in Sc^{49*} is perhaps of particular interest because the position of the low-lying shell-model states in Sc^{49} is known[4] from analysis of $Ca^{48}(He^3,d)Sc^{49}$ angular distributions and also because the strength of the $\frac{3}{2}^-$ analog state is shared between at least two close-lying states. We report here the results of a high-resolution study of the reaction $Ca^{48}(p,\gamma)Sc^{49}$ at proton energies corresponding to the two states in Sc^{49*} which carry the major portion of the $\frac{3}{2}^-$ analog-state strength.

The analog state of interest in Sc^{49*} is formed at an excitation energy of 11.6 MeV. The Q value for the reaction $Ca^{48}(p,n_0)Sc^{48}$ is –0.530 MeV; and it has been estimated by El-Nadi et al.[2] from their study of the reaction $Ca^{48}(p,n\gamma)Sc^{48}$ that the level density of the $T=\frac{7}{2}$ states in Sc^{49*} at about 11.6-MeV excitation is approximately 65 MeV^{-1}, which perhaps should be taken as a lower limit since the energy resolution used was about 5 keV. The average level width appears to be less than 5 keV for the energy region around the analog states (Ref. 3 and Fig. 1). It is thus quite reasonable to expect that the analog state should be spread over several states as has been found experimentally.[2,3] Whether there is further fine structure such as is observed by Keyworth et al.[5] for analog states in K^{41} cannot be answered from the existing data. In the case considered here, Sc^{49} with a single proton outside closed shells is much less complex than the case of K^{41} and it might be that the actual splitting is not as complex.

The Ca^{48} target was prepared by evaporation of $Ca^{48}CO_3$ (96.5%) onto a thick Pt backing. The positions of the analog states were determined by measuring the excitation curve for the 0.37-MeV gamma ray produced in the reaction $Ca^{48}(p,n\gamma)Sc^{48}$, which is a good measure of the total (p,n) reaction cross section, as well as by measuring the yields for capture gamma rays with energies greater than 2.6 and 5.5 MeV. The over-all energy resolution including beam energy spread and target thickness was about 1 to 2 keV. The results are shown in Fig. 1. Two strong states were observed at E_p(lab) = 1.968 and 1.977 MeV which could be identified with the states seen in elastic scattering by Jones et al.[1] Two other states were also observed at E_p(lab) = 1.963 and 1.985 MeV. They were considerably weaker than the first two states and were not identified in the elastic scattering experiment. These results are in agreement with the data of Ricci, Chilosi, and Vigiani.[3] It is reasonable to assume, however, that they might also carry some of the analog-state strength. The energy resolution and size of step used in the excitation curve in the present experiment and that of Ricci, Chilosi, and Vigiani would average over any fine structure, such as that observed by Keyworth et al.[5] [We note that the energy scale for the present work is 10-12 keV lower than that of Jones et al. (Ref. 1); and that the uncertainty in our calibration is about ±10 keV.] Measurements of gamma-ray decay spectra were made on the two strong states and backgrounds were estimated from runs on close-by minima in the cross section. Short runs were also made on the two weak resonances.

Gamma rays emitted by the target were detected with a 30-cm^3 coaxial Ge(Li) gamma-ray detector with a resolution of 15 keV at 6 MeV and 22 keV at 11 MeV. A direct measurement of the energy dependence of the efficiency of the detector was not made, but it was assumed that measurements by Broude, Litherland, Smulders, and Alexander[6] on a 25-cm^3 coaxial detector could be applied. The spectra

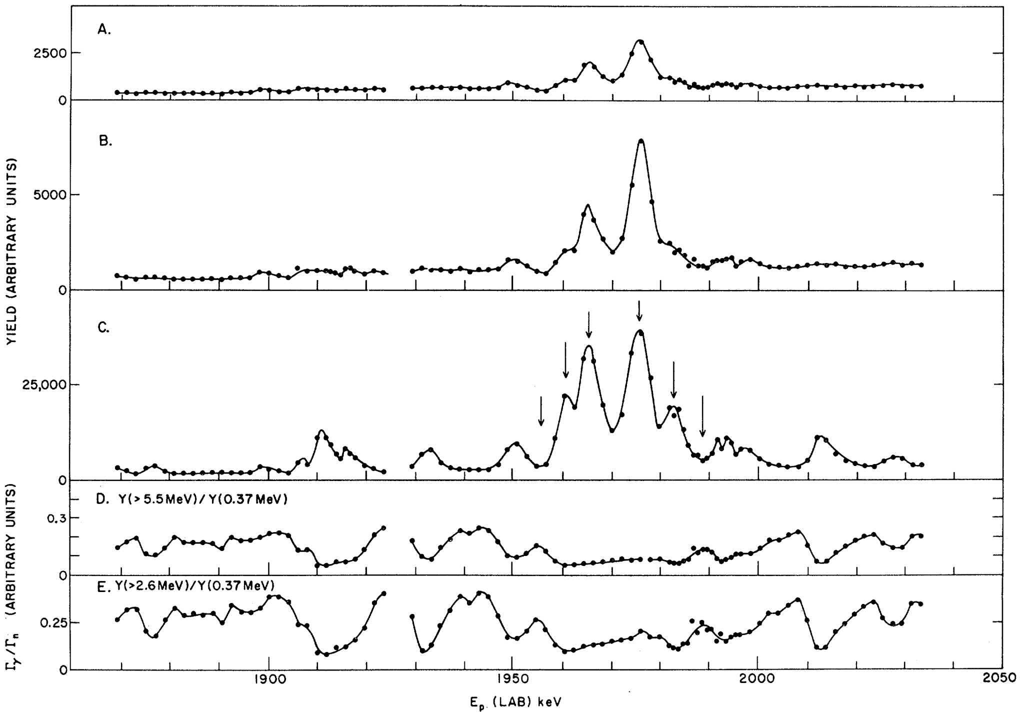

FIG. 1. Excitation curve taken with a 7.6-cm× 7.6-cm NaI(Tl) gamma-ray detector at 90° to the incident beam. (a), (b) The yield of capture gamma rays with energies greater than 5.5 and 2.6 MeV, respectively. (c) The yield of the 0.37-MeV gamma ray from the reaction $Ca^{48}(p,n\gamma)Sc^{48}$. Since most of the cross section for the (p,n) reaction is to excited states in Sc^{48} which cascade to the ground state by the transition which emits the 0.37-MeV gamma ray this curve is a good representation of the total cross section for the reaction $Ca^{48}(p,n)Sc^{48}$. (d), (e) The ratio of the capture gamma rays to the 0.37-MeV gamma rays. If it is assumed that both reactions proceed strictly through compound nucleus formation this ratio should be roughly proportional to Γ_γ/Γ_n where Γ_γ is the total width for gamma-ray emission. The statistical uncertainties are approximately the size of the points. Capture gamma-ray spectra were taken with a Ge(Li) gamma-ray detector at the points marked with arrows in (c). Linear scales are used for the ordinates of all parts of the drawing.

were displayed in a 4096-channel pulse-height analyzer with digital stabilization of the analog-digital converter. The energy dispersion was about 2.9 keV/channel, which allowed positive identification of several of the capture gamma rays by the energy shift between the spectra taken at E_p(lab) = 1968 and 1977 keV. The energy calibration of the counter was made in terms of lines from well-known low-lying states[4,7] in Sc^{49} and O^{16} and was extrapolated to higher energies by means of an auxiliary calibration with a precision pulser. The uncertainty in the calibration should be less than 20 keV at 10 MeV and less than 10 keV at energies below 5 MeV. Gamma-ray widths, Γ_γ, for the lines observed were found by comparing the yield of capture gammas to the yield of 0.37-MeV gammas from the reaction $Ca^{48}(p,n\gamma)Sc^{48}$. The yield of the 0.37-MeV gamma is approximately proportional to the total (p,n) cross section since most of the reaction cross section proceeds to high states in Sc^{48} which cascade to the lower states by emission of an 0.37-MeV gamma ray.[2,8] Since the neutron widths of the two states are known from the analysis of Jones et al.[1] the gamma-ray width can be calculated from the relationship

$$\Gamma_\gamma = \Gamma_n \times \frac{\text{yield of capture gammas}}{\text{yield of 0.37-MeV gammas}} \times \frac{\epsilon_{0.37}}{\epsilon_{\text{capt}}},$$

where the counter efficiency is given by ϵ. The uncertainties in the values of the counter efficiency and neutron widths are relatively large, and the values of the gamma widths extracted are probably only accurate to within a factor of 2 or 3.

Portions of the 4096-channel spectra obtained at E_p(lab) = 1.968 and 1.977 MeV are shown in Fig. 2 and a numerical summary of the results

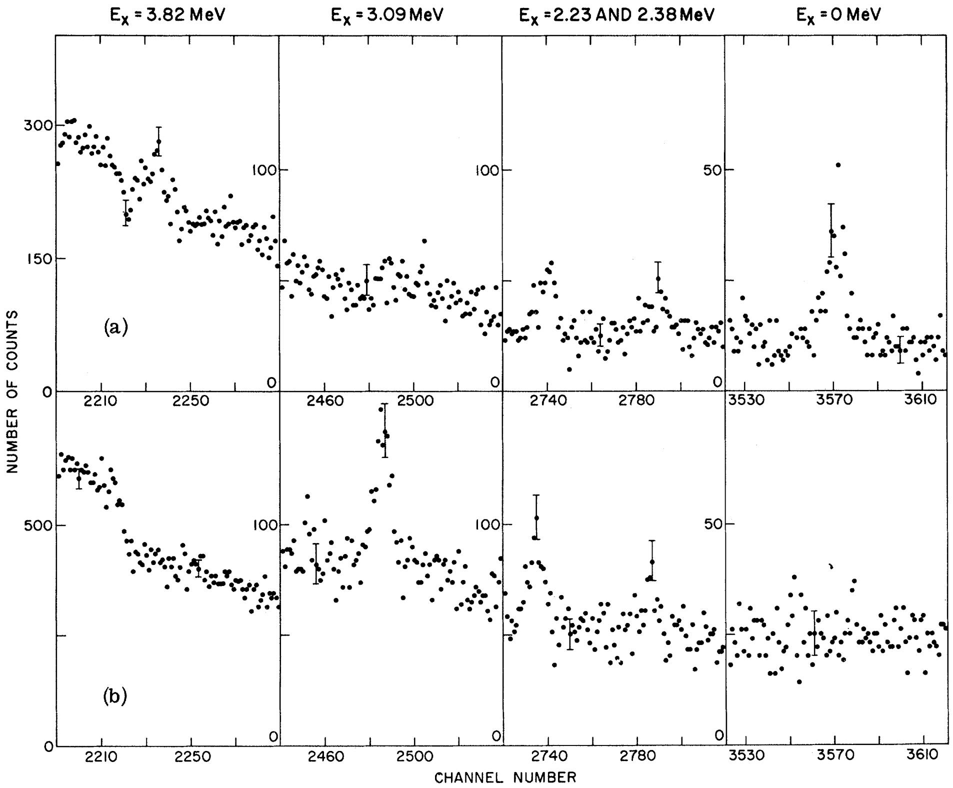

FIG. 2. Selected portions of pulse-height distributions obtained with a Ge(Li) gamma-ray detector. (a) Selected lines obtained at a proton bombarding energy of 1.977 MeV; (b) the same pulse-height regions for a bombarding energy of 1.968 Mev. These two energies correspond to compound states which have a large proton width and which are the analogs of the Ca^{49} ground state. The energies of the final state in Sc^{49} for the gamma transition are given at the top of the figure. The energy dispersion is about 2.9 keV/channel and the energy range covered by the entire 4096-channel spectrum was about 0-12 MeV. Sample statistical uncertainties are shown in the figures. Peaks shown are the two-escape peaks in all cases.

is given in Table I. It can be seen that the gamma-ray de-excitation to low-lying states in Sc^{49} is strikingly different in the two cases. This behavior of the gamma-ray branching from the two analog states is quite surprising. If it is assumed that the structure of the two states is dominated by the strength of the Ca^{49} ground-state analog and that the structure of the normal isospin states with which the analog state is mixing are very complex, then the observed branching ratios from the analog states to low-lying single-particle states should be quite similar. Such a behavior has indeed been observed by Erné, Veltman, and Wintermans[9] for a somewhat similar situation in $Cl^{37}+p$ where the analog of the 5^- first excited state of Cl^{38} is apparently split by about 4 keV and the branching ratios for decay from the two states are quite similar. In the present case it is necessary to provide some mechanism which can produce a cancellation of the $E2$ strength to the ground state and the $M1$ strength to the 3819-keV state for the $E_p(\text{lab}) = 1.968$-MeV resonance and of the $M1$ strength to the 3092-keV ($T=\frac{7}{2}$, $J^\pi=\frac{3}{2}^-$) state for the $E_p(\text{lab}) = 1.977$-MeV resonance. One possibility is that the $T=\frac{7}{2}$ state (or states) with which the analog state is mixing is of comparatively simple character such as three-particle, two-hole, for example, and has relatively large matrix elements for decays to the single-particle states. Thus it is able to produce large interference effects with the analog states. That this is consistent with at least the magnitude of the total gamma-ray width for neighboring $T=\frac{7}{2}$ states may be seen from the following argument.

The yield of high-energy gamma rays [Figs. 1(a) and 1(b)] is proportional to $\Gamma_p\Gamma_\gamma$ and the yield of 0.37-MeV gammas is proportional to $\Gamma_p\Gamma_n$. In both cases the identical resonance denominator will appear. Hence the ratio of these yields gives the ratio Γ_γ/Γ_n and it can be seen in Fig. 1 that this ratio is consistent to about a factor of 2 on all resonances. Since

Table I. Transitions from analogs of the Ca^{49} ground state in Sc^{49} to low-lying excited states in Sc^{49}.

Sc^{49} final-state[a] excitation energy (keV)	l[a]	J^π [a]	S'[a]	Assumed multipolarity of gamma transition	Γ_w [b] (eV)	E_p(lab) = 1.968 MeV		E_p(lab) = 1.977 MeV	
						Γ_γ (eV)	Γ_γ/Γ_w	Γ_γ (eV)	Γ_γ/Γ_w
0.0	3	$(7/2^-)$	1.0	$E2$	1.8	≤ 0.7	≤ 0.4	3.5	1.9
2233.0	(2)	$(3/2^+)$	0.05	$E1$	745.0	1.1	0.002	0.9	0.001
2382.0	(0)	$(1/2^+)$	0.005	$E1$	710.0	2.1	0.003	1.2	0.002
3092.0	1	$(3/2^-)$	0.68	$M1$	12.9	2.7	0.2	≤ 0.5	≤ 0.04
3819.0	3	$(5/2^-)$	0.15	$M1$	9.8	≤ 0.4	≤ 0.04	2.8	0.3
3923.0[c]	...					...		...	
4004.0[c]	...					...		...	
4080.0	3	$(5/2^-)$	0.20	$M1$	8.9	3.9	0.4	3.0	0.3

[a] Ref. 4. The values under S' are spectroscopic factors which have been corrected for a small J dependence of cross sections computed by the code used in the analysis of the data.

[b] The values for the Weisskopf estimates Γ_w given above were calculated from the tables given by D. H. Wilkinson in Nuclear Spectroscopy, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Pt. B. More detailed calculations by D. Kurath (private communication) indicate that the $E2$ width is ≈ 0.6 to 0.9 eV and that the widths for the $M1$ transitions are about 0.1 to 0.46 Weisskopf units.

[c] The transitions to these states were not observed because the energy region in which they fall was obscured by the presence of Doppler-broadened lines from the reaction $F^{19}(p, \alpha\gamma)O^{16}$ produced in fluorine which was present as a target contaminant.

the elastic proton scattering experiment of Jones et al.[1] shows that Γ_p is appreciable only at the analog resonances and even there it is only 25% of Γ_n, it follows that $\Gamma_n \approx \Gamma$. The widths of the peaks observed in the excitation curve for the (p,n) reaction[2] and Fig. 1(c) show that Γ is constant to within a factor of 2 or 3 for bombarding energies from 1.87 to 2.03 MeV. Therefore, Γ_γ for the $T=\frac{7}{2}$ states in this region are roughly equal to the value of Γ_γ for the two $T=\frac{9}{2}$ analog states and are therefore consistent with the observed interference. (This argument should not depend strongly on whether the widths observed are for single levels or for several partially resolved levels.) Measurement of the various partial gamma-ray widths for the transitions from the $T=\frac{7}{2}$ states considered here, for example, the widths for the ground-state transition, would be interesting and are required before any definite conclusions can be drawn although even if they are small an accidental degeneracy of the analog state with a single simple $T=\frac{7}{2}$ state could still be possible.

We, of course, do not rule out the possibility of other explanations, but, to our knowledge, such differences in gamma branching have not been previously observed for analog states in this mass region, and it should be of interest to determine whether the differences arise from a fortuitous interference such as we have discussed, or whether it is a more general occurrence stemming from the splitting of the analog states.

We are indebted to Dr. D. Kurath for furnishing us with the single-particle transition widths quoted in Table I. We are grateful to Dr. A. Z. Schwarzschild, Dr. S. Kahana, Dr. B. Margolis, Dr. L. L. Lee, and Dr. J. P. Schiffer for several very helpful conversations and criticisms and to Dr. T. K. Alexander and Dr. F. C. Erné for communicating their results prior to publication.

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MAGNETIC MOMENT OF THE FIRST EXCITED STATE OF ^{114}Cd†

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The magnetic moment of the first 2^+ state at 558.5 keV in ^{114}Cd has been measured to be $|\mu_2| = 0.88 \pm 0.12\ \mu_N$ by the perturbed gamma-gamma angular correlation technique utilizing the internal hyperfine field in an Fe lattice.

The nucleus ^{114}Cd has played a significant role in nuclear physics as it has long been thought to exhibit every feature of a quadrupole-type vibrational spectrum.[1] However, the recent experimental determination[2] of the static quadrupole moment Q_2 of the 558.5-keV first excited 2^+ state of ^{114}Cd has shown a large value which is quite incompatible with that expected from a simple harmonic-quadrupole vibration of a spherical nucleus. The average experimental value $Q_2^{\rm expt} = -0.50 \pm 0.25$ b can be obtained if ^{114}Cd is assumed to be a rotational nucleus; however, other spectroscopic properties of at least the low-lying states are well described as the characteristic quadrupole vibrations of a spherical nucleus. Tamura and Udagawa[3] have recently shown that reasonable models of vibrational nuclei can be constructed which can explain the large observed Q_2. In their phenomenological model (model A), where the first 2^+ state is assumed to be an orthogonal linear combination of one-phonon and two-phonon harmonic vibrational 2^+ states, they predict $|Q_2| = 0.58$ b, the sign depending on the details of the mixing interaction. On the other hand, in their microscopic model (model B) they predict $Q_2 = -0.511$ b for $e_{\rm eff} = 1$. Thus both models seem to explain the large Q_2 while retaining the vibrational character of the nucleus. However, the predictions of these two models for the magnetic moment, μ_2, of this state are widely different. Model A predicts $\mu_2^{(A)} = 0.86\ \mu_N$, whereas model B predicts $\mu_2^{(B)} = 2.38\ \mu_N$. Thus a measurement of μ_2 can decide which of the two models is more appropriate in explaining most of the low-lying nuclear properties of the ^{114}Cd nucleus.

The present note describes our experimental results on the determination of the g factor of the 558.5-keV 2^+ state utilizing the integral–reversed-field method of the perturbed gamma-gamma angular correlation technique.[4] The mean life of this state is known to be $\tau = (1.32 \pm 0.09) \times 10^{-11}$ sec from the measured $B(E2)$ values following Coulomb excitation.[5] In order to measure the g factor of such a short-lived state, we employed the large hyperfine magnetic field available at the site of the Cd nuclei when they are introduced in very dilute form into an Fe lattice.[6] The known field $H_{\rm int}$ at Cd in Fe lattice is $|H| = 348 \pm 10$ kG. The activity utilized in this experiment is the 49-day ^{114m}In, which decays by electron capture[7] (branching ratio of 3.5% of the total activity) to the 1278-keV state which in turn decays to the ground state of ^{114}Cd via the (722-558.5)-keV gamma-gamma cascade. The angular correlation coefficients for this cascade have been measured by Steffen[8] to be $A_2 = 0.099 \pm 0.005$, $A_4 = 0.01 \pm 0.07$ and also by Kawamura[9] to be $A_2 = 0.091 \pm 0.006$, $A_4 = 0.030 \pm 0.009$; thus this cascade is believed to be $4^+(E2)2^+(E2)0^+$.

Indium metal, enriched to 96.4% in ^{113}In as obtained from Oak Ridge National Laboratory, was irradiated for 7 days at a flux of 2×10^{14} n/cm^2 sec to produce the ^{114m}In activity. 0.15 mg of active In was sealed in vacuum in an Fe container (purity 99.999%) weighing 1 g and was then melted in an induction furnance employing a levitating Ag boat. The molten alloy (about 0.015% In by weight) was rapidly cooled to room temperature and later was coined into a cylinder of 5-mm diameter and 6-mm height. Two such sources were prepared (source 1 and source 2). After an initial measurement