PHYSICAL REVIEW C VOLUME 4, NUMBER 2 AUGUST 1971

Study of ^{49}Cr Using the ^{50}Cr(^{3}He, α)^{49}Cr Reaction and ^{50}Cr(^{3}He, $\alpha\gamma$)^{49}Cr Angular Correlations*

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(Received 9 March 1971)

Energy levels in ^{49}Cr have been studied using the ^{50}Cr(^{3}He,α)^{49}Cr reaction. Angular distributions of α particles were measured and compared with distorted-wave Born-approximation calculations to determine l values. α-γ angular correlations were also measured. The following spin-parity assignments are consistent with our results for the levels indicated: 0.27 MeV $\frac{7}{2}^-$, 1.07 MeV ($\frac{5}{2}^-$,$\frac{9}{2}^-$), 1.57 MeV ($\frac{5}{2}^-$,$\frac{7}{2}^-$,$\frac{11}{2}^-$), 1.71 MeV ($\frac{1}{2}^-$,$\frac{3}{2}^-$), 1.74 MeV $\frac{3}{2}^-$, 1.98 MeV $\frac{3}{2}^+$, 2.43 MeV $\frac{5}{2}^-$, 2.58 MeV $\frac{1}{2}^+$, 2.61 MeV $\frac{3}{2}^-$, 3.24 MeV $\frac{5}{2}^-$, 3.51 MeV ($\frac{5}{2}^-$,$\frac{7}{2}^-$), 3.93 MeV $\frac{1}{2}^-$, 4.76 MeV $\frac{7}{2}^-$, 5.57 MeV $\frac{3}{2}^+$, 6.43 MeV $\frac{1}{2}^+$, 6.47 MeV $\frac{1}{2}^+$, 6.76 MeV $\frac{1}{2}^+$. Branching ratios for the decays of these levels were measured. Multipole mixing ratios were extracted from the correlation data.

I. INTRODUCTION

While most studies of nuclei in the $f_{7/2}$ shell have been concentrated near the closed shells ^{40}Ca and ^{48}Ca, there has been a growing interest in nuclei which lie in the middle of the $f_{7/2}$ shell. For nuclei in this region the main question is whether the shell model can adequately describe spectroscopic properties which depend upon the coupling of many extracore nucleons. The shell-model calculations of McCullen, Bayman, and Zamick[1] have been successful in predicting the energy levels, spins, and parities of nuclei near the closed shells in which only a few "active" nucleons are considered in the calculations. Even in this region, however, refinements of the shell-model calculations are needed, both in the direction of including a larger configuration basis and towards the inclusion of collective effects. Such extended shell-model calculations are very difficult for nuclei in the middle of the $f_{7/2}$ shell because of the large number of active nucleons involved. However, spectroscopic properties for nuclei in this region have been calculated using both pure ($f_{7/2}$) shell-model configurations[2] and a collective-model approach.[3] It is of interest to see how well these calculations compare with the experimental data.

The greatest hindrance to a complete picture of nuclei in this region is the lack of detailed spectroscopic information. For many odd-A nuclei only the energies of excited levels are known. It is desirable to measure the spins, parities, and lifetimes of the excited levels and their electromagnetic transition properties. Since nuclear models make definite predictions for such γ-ray transition rates, the measurement of these quantities serves as a sensitive test of the nuclear wave functions connected by the γ-ray transitions.

The present study of ^{49}Cr was undertaken to obtain detailed spectroscopic information for a nucleus in the $f_{7/2}$ shell far from any shell closure. With 24 protons and 25 neutrons ^{49}Cr is in the middle of the $f_{7/2}$ shell. One might perhaps expect a collective description of the level properties to prove useful here. While both shell-model[2] and collective-model[3] calculations have been carried out for ^{49}Cr, there has been no detailed experimental study of the spins and decay modes of excited levels.

This lack of experimental data is due, in part, to the relative inaccessibility of the ^{49}Cr nucleus. The only single-nucleon transfer possible is the neutron-pickup reaction from ^{50}Cr. Whitten and McIntyre have studied low-lying levels in ^{49}Cr using the (p, d) reaction[4] and, more recently, David *et al.* employed the (^{3}He, α) reaction[5] to measure the angular distribution of α particles for excited levels up to 7 MeV.

In the present study we measured particle-γ angular correlations in the ^{50}Cr(^{3}He, $\alpha\gamma$)^{49}Cr reaction to determine spins of excited levels and to study their electromagnetic decay properties. The technique used here is known as Method II of Litherland and Ferguson.[6] In this method the population of excited levels is restricted to a small number of magnetic sublevels by observing the outgoing particles at 0 or 180° with respect to the beam direction. Constraints are thus imposed on the angular distribution of the coincident γ radiation which often allows one to determine the spin of the excited levels and the multipolarity of the decay γ radiation. For the zero-spin target ^{50}Cr, the (^{3}He, α) reaction only populates magnetic states with $m=\pm\frac{1}{2}$. Further, since the beam is unpolarized the $m=\pm\frac{1}{2}$ substates are equally populated. One thus selects an aligned ensemble of ^{49}Cr nuclei in which there are no unknown population parameters. No assumptions are made concerning the reaction mechanism, and the γ-ray angular distribution depends only upon the spins of the nuclear levels involved and on the multipole order and mixing ratio of the γ radiation.

Experiments were also conducted to determine the angular distribution of the α particles for the low-lying levels in ^{49}Cr using the $^{50}Cr(^{3}He, \alpha)^{49}Cr$ reaction. These experiments were undertaken to resolve inconsistencies between some of the results of the angular-correlation measurements and published work[5] concerning the $^{50}Cr(^{3}He, \alpha)$-^{49}Cr reaction. The results of the present work are in disagreement with those of Ref. 5 for a number of the more weakly excited states (see below). For the strong states the present work is in agreement with Ref. 5, and in some cases we have used their l-value assignments in conjunction with the angular-correlation experiments to fix the spin assignments of excited levels.

II. EXPERIMENTAL PROCEDURE

The angular-correlation experiments were conducted using a 15-MeV $^{3}He^{++}$ beam from the University of Pennsylvania tandem accelerator. The self-supporting targets were prepared from ^{50}Cr isotopically enriched to 95.6%. The basic experimental arrangement has been described elsewhere.[7] Briefly, the α particles were detected at 0° with respect to the incident beam by a position-sensitive surface-barrier detector placed at the focal point of a double-focussing magnetic spectrometer. Coincident γ rays were observed using four 7.6× 10.2-cm NaI(Tl) crystals placed at angles 90, 113, 136, and 159° with respect to the incident beam. The data was stored event by event in multiparameter mode on magnetic tape by a PDP9-ND3300 computer analyzer system. Subject to certain timing and energy conditions the three parameters digitized and stored were: the position signal from the position-sensitive detector, the energy signal from any one of the γ-ray detectors, and the time difference between the two signals. Furthermore, every event was labeled according to which γ-ray detector observed the signal.

Angular distributions of the α particles from the $^{50}Cr(^{3}He, \alpha)^{49}Cr$ reaction were measured using the University of Pennsylvania multiangle magnetic spectrograph. A 18-MeV $^{3}He^{++}$ beam was used to bombard self-supporting targets of thickness 50 $\mu g/cm^2$. Exposures were taken at 23 angles from $3\frac{3}{4}$ to 90° in intervals of $3\frac{3}{4}$°. The energy resolution was 25 keV.

III. ANALYSIS

The theoretical angular distribution of the γ rays is given by Poletti and Warburton[8] in a form very convenient for computation. For the decay from a level of spin a, populated directly in a nuclear reaction, to a level of spin b,

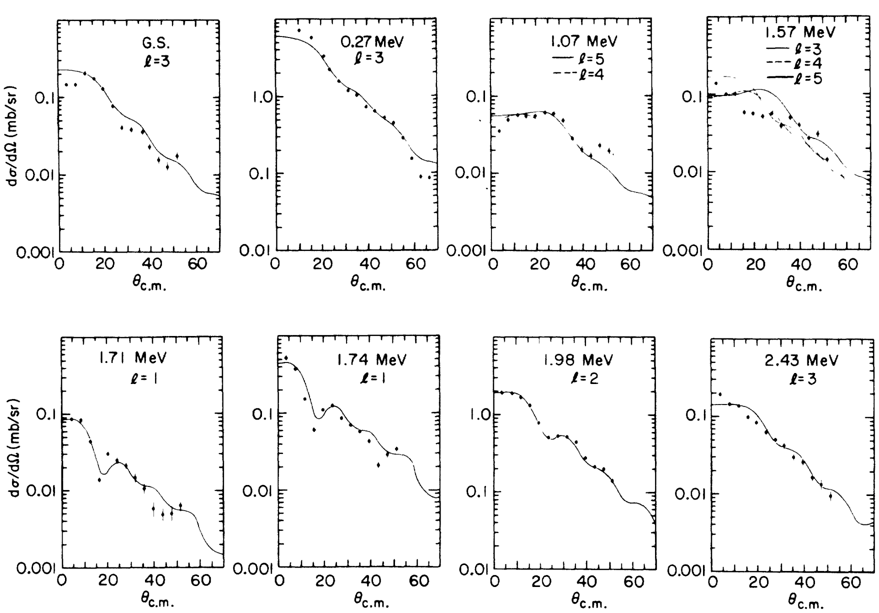

FIG. 1. Angular distributions of α particles measured in the present work for the ground and first seven excited states of ^{49}Cr.

$$W(\theta) = \sum_k a_k P_k(\cos\theta) = \sum_k \rho_k(a) F_k(ab\delta) P_k(\cos\theta)\,, \qquad (1)$$

where the sum goes over even values of $k \leq 2a$. The $\rho_k(a)$ are constructed from statistical tensors and describe the alignment of the initial state. The $F_k(ab\delta)$ depend on the spins of the initial and final states and on the multipole mixing ratio δ. The phase convention used is that defined by Rose and Brink.[9] The Q_k are finite-geometry attenuation coefficients and the $P_k(\cos\theta)$ are Legendre polynomials. In the present work only the two lowest allowed multipolarities are considered. The expression for the angular correlation is readily extended to the case where the γ ray observed is the second member of a cascade, the first being unobserved.[8]

The experimental angular correlations were analyzed using a computer program M2.[10] First, a spin is assumed for the initial state. The program then performs a least-squares fit of the data directly to the theoretical correlation formula [Eq. (1)] for different values of $\phi = \tan^{-1}\delta$; typically ϕ is varied between −90 and +90° in 10° steps. For each value of ϕ, the program calculates the usual normalized quantity χ^2, defined by

$$\chi^2 = \frac{1}{n} \sum_i \left[\frac{W(\theta_i) - Y(\theta_i)}{\delta Y(\theta_i)}\right]^2\,, \qquad (2)$$

where $W(\theta_i)$ and $Y(\theta_i)$ are the theoretical and experimental γ-ray yields, respectively, at angles θ_i; $\delta Y(\theta_i)$ is the experimental error; and n is the number of degrees of freedom. The quantity n is equal to the number of experimental points minus the number of unknown. In the vicinity of the value of ϕ yielding a minimum value of χ^2, a search is performed using an iterative procedure to find the precise value of ϕ yielding the best fit. This procedure also yields the error in the mixing ratio, as described by Smith.[11] A correction for the finite size of the particle detector could be made, but because of the small effective entrance half angles (1.75 and 3.5°, respectively, in the vertical and horizontal planes), this was considered negligible. For most of the transitions studied in the present work, the number of counts in the peaks of interest could be straightforwardly obtained by summing the number of counts in the photopeak. In some cases it was necessary to allow for the contribution of higher-energy γ rays. This was done using shape curves measured in the experimental configuration with radioactive

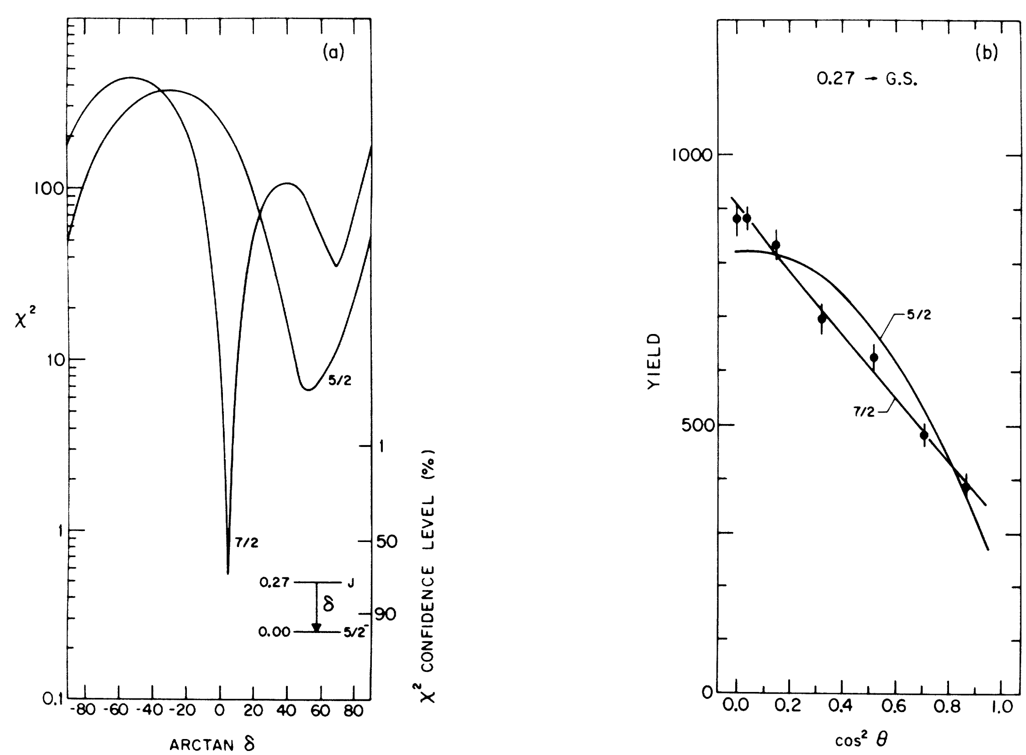

FIG. 2. (a) χ^2 plot for the 0.27 MeV→g.s. transition for spins consistent with $l_n = 3$. (b) Experimental angular correlation for the 0.27→g.s. transition along with the best fits for $J = \frac{5}{2}, \frac{7}{2}$.

sources or from nuclear reactions yielding γ rays of known energy.

In addition to the spins and multipole mixing ratios, the present work has yielded information concerning the decay schemes of excited states in ^{49}Cr. The estimates used here for these branching ratios used photopeak efficiencies obtained by interpolating between tabulated[12] values for 7.6 $\times$ 7.6-cm and 12.6$\times$ 10.2-cm crystals.

The angular distributions of the α particles from the ^{50}Cr(^{3}He, α)^{49}Cr reaction were compared with the zero-range distorted-wave predictions using the code DWUCK.[13] The optical-model parameters were taken from Ref. 5.

IV. RESULTS

Angular distributions of the α particles for the first seven excited states in the ^{49}Cr nucleus were determined from the multiangle spectrograph experiments. For the higher excited states the correlation results draw upon the l assignments of Ref. 5.

A. Ground State

The angular distribution of α particles leading to the ground state of ^{49}Cr is shown in Fig. 1. The ground-state spin is known from β decay[14, 15] to be $\frac{5}{2}$. The $l = 3$ distribution is consistent with this assignment.

B. 0.27-MeV Level

The first excited state at 0.27 MeV is very strongly excited by the (^{3}He, α) reaction. The large spectroscopic factor for this state[5] identifies it as the expected $\frac{7}{2}^-$ level. The $l = 3$ angular distribution of α particles is also shown in Fig. 1. All but the three most forward angles on this distribution were measured using the multigap spectrograph. In order to obtain good statistics on the weakly excited states, it was necessary to overexpose the forward angles of the 0.27-MeV level. Thus, a separate experiment using solid-state detectors in a scattering chamber was conducted to extend the α distribution to 10° in the lab. Figure 2 shows the correlation results for the two spins, $\frac{5}{2}$ and $\frac{7}{2}$, consistent with the $l = 3$ assignment. Spin $\frac{5}{2}$ implies a χ^2 above the 1% confidence limit[16] and can thus be eliminated. The best-fit value for the mixing ratio for the spin $\frac{7}{2}$ is $\delta(E2/M1) = 0.105 \pm 0.013$.

C. 1.07-MeV Level

The second excited state at 1.07 MeV is very weakly excited. The angular distribution of α par-

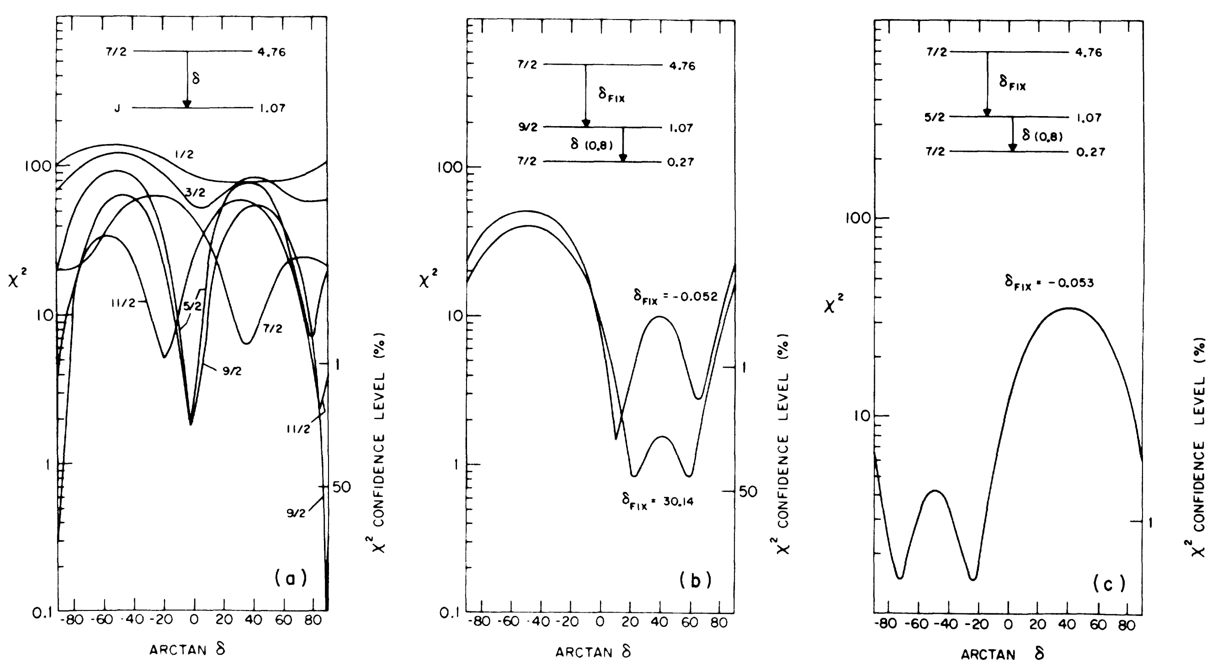

FIG. 3. (a) χ^2 plot for the 4.76→1.07-MeV transition as a function of the spin of the 1.07-MeV level. (b) χ^2 plot for the 1.07→0.27-MeV transition assuming the 1.07-MeV level has spin $\frac{9}{2}$. (c) χ^2 plot for the 1.07→0.27-MeV transition assuming the 1.07-MeV level has spin $\frac{5}{2}$.

ticles is shown in Fig. 1. This angular distribution is in disagreement with that measured by David *et al.*, who assign $l=0$ to this level.[5] In fact our distribution could not be fitted with any distorted-wave Born-approximation (DWBA) prediction for angular momentum transfers $l \leq 3$. Trying higher l values, we found that an $l=5$ distorted-wave prediction gives a reasonable fit to the data. However, $l=5$ pickup implies some $1h$ admixture in the ground-state wave function of ^{50}Cr. Such an admixture is very unlikely. An $l=5$ pickup is more likely to proceed by a two step (inelastic scattering in the entrance or exit channel) or through a compound nuclear reaction. Our angular distribution is suggestive of some sort of direct mechanism and the fact that it does not resemble any distribution with $l=0$, 1, 2, or 3 suggests that the state has no simple configuration or has $l \geq 4$. In the subsequent discussion below we make no restrictions on the l value for this level.

The low cross section for this state prohibits a correlation measurement. However, the isobaric analog of the ^{49}V ground-state decays to this level and makes a correlation study possible. The analog state at 4.76 MeV has spin and parity $\frac{7}{2}^-$ (see below). No γ ray of 1.07 MeV is observed in the spectrum; thus there is no ground-state transition from the second excited level. The correlation results are obtained from the 4.76 → 1.07-MeV transition. For these results it was necessary to strip the 4.49-MeV γ ray resulting from the 4.76 → 0.27-MeV transition. In the stripping procedure a shape curve measured in the experimental geometry using the ^{12}C(α, α') reaction was used. This reaction strongly excites the first excited state of ^{12}C and provides a single γ ray at 4.43 MeV.

The correlation results for the 4.76 → 1.07-MeV transition are shown in Fig. 3. The spins which fall below the 1% confidence limit are $\frac{5}{2}$, $\frac{9}{2}$, and $\frac{11}{2}$. For spin $\frac{11}{2}$, the multipole mixing ratio is 9.4 which is unreasonable, since it implies an 80% $M3$ admixture. This argument rests on the assumption that the 1.07-MeV level has negative parity. If positive parity is assumed for the 1.07-MeV level, spin $\frac{11}{2}$ is again unlikely, since in the decay of the 4.76-MeV level below it would imply an $M2$ transition (4.76 → 1.07) competing strongly with an $M1$ transition (4.76 → 0.27). The second minimum in the χ^2 plot for spin $\frac{11}{2}$ falls above the 1% confidence limit and, assuming negative parity, also corresponds to an unreasonably high $M3$ admixture. Thus, spin $\frac{11}{2}$ can be eliminated. For spin $\frac{9}{2}$ there are two acceptable minima, $\delta = -0.05$

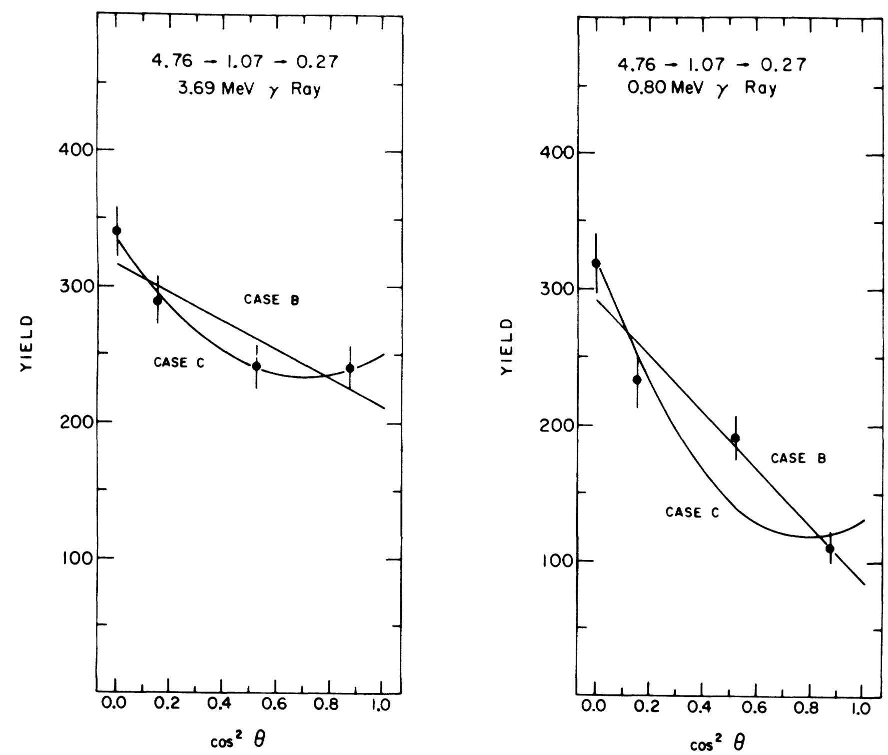

FIG. 4. Experimental angular correlations for the 3.69- and 0.80-MeV γ rays along with the best fits for cases B and C, as discussed in the text.

± 0.04 and $30.1^{+\infty}_{-14.7}$. Spin $\frac{5}{2}$ has one acceptable minimum, $\delta = -0.05 \pm 0.03$.

The analysis of the correlation for the 0.8-MeV γ ray ($1.07 \to 0.27$) does not narrow down the spin assignment any further but does restrict the value of the mixing ratio of this transition, which in turn allows the elimination of $\frac{3}{2}$ and $\frac{9}{2}$ as possible spins for the 1.57-MeV level (see below). We fixed the spin of the 1.07-MeV level first at $\frac{9}{2}$ and then at $\frac{5}{2}$. The results are also shown in Fig. 3. Only the mixing ratio $\delta(0.8)$ from the $1.07 \to 0.27$-MeV transition was varied. The 3.69- and 0.8-MeV γ rays were fitted simultaneously with $\delta(3.69)$ fixed at the values determined from analysis of the 3.69-MeV angular correlation alone. Thus, there are eight data points with two unknown normalizations and one unknown mixing ratio. The χ^2 plots are normalized to five degrees of freedom. The six possible values determined for $\delta(0.8)$ are listed in Table I. The γ-ray angular distributions from the 3.69- and 0.8-MeV transitions are shown in Fig. 4. The data are fitted using, as examples, case B (the worst fit) and case C (the best fit).

D. 1.57-MeV Level

The angular distribution of α particles leading to the third excited level at 1.57 MeV is shown in Fig. 1. This distribution could not be fitted with any DWBA predictions. This level decays 65% to the 1.07-MeV level and 35% to the 0.27-MeV level. The χ^2 plot for the 1.30-MeV transition to the 0.27-MeV level is shown in Fig. 5. Only spin $J = \frac{1}{2}$ can be eliminated from these results. The angular correlation for the 0.80-MeV transition from the 1.07-MeV level was obtained by stripping the 1.3-MeV γ ray using shape curves from a ^{22}Na (1.274 MeV) source. The 0.50-MeV correlation data was obtained by subtracting a constant background from each spectrum. These three γ rays (1.3, 0.8, and 0.5 MeV) were analyzed simultaneously with the mixing ratio of the 0.8-MeV transition restricted to the six values (cases A–F) determined previously. The mixing ratio of the 1.3-MeV γ ray was fixed at values corresponding to minima in χ^2 as shown in Fig. 5, while the mixing ratio of the 0.5-MeV γ ray was varied. The results are shown in Table II. The only acceptable spins for the 1.57-MeV level are $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{11}{2}$. As an example, the results of one of these fits in which the mixing ratio of the 0.80-MeV γ ray was fixed at $\delta(0.80) = 0.19$ (case A) are shown in Fig. 6. The best-fit value of the mixing ratio for the 0.5-MeV transition for the different cases varied from $-5.9 \leq \delta \leq 1.6$. David *et al.*[5] have made a tentative $l = 1$ assignment to this level which would imply a spin of $\frac{3}{2}$ or $\frac{1}{2}$. Our α-particle angular distribution is in disagreement with their measurements and our correlation results eliminate both spin $\frac{3}{2}$ and spin $\frac{1}{2}$.

TABLE I. Table of acceptable values for the mixing ratio of the 0.8-MeV γ ray assuming the 1.07-MeV state has spin $\frac{5}{2}$ and $\frac{9}{2}$. The 1% confidence limit is $\chi^2 = 3.02$.

Case	Spin of 1.07-MeV level	$\delta(3.69)$	$\delta(0.8)$	χ^2
A	$\frac{9}{2}$	−0.05	0.19 ± 0.04	1.49
B	$\frac{9}{2}$	−0.05	$2.19^{+0.28}_{-0.23}$	2.73
C	$\frac{9}{2}$	30.14	$0.41^{+0.11}_{-0.10}$	0.83
D	$\frac{9}{2}$	30.14	$1.60^{+0.36}_{-0.27}$	0.85
E	$\frac{5}{2}$	−0.05	$-0.43^{+0.07}_{-0.08}$	1.48
F	$\frac{5}{2}$	−0.05	$-3.40^{+0.64}_{-0.98}$	1.45

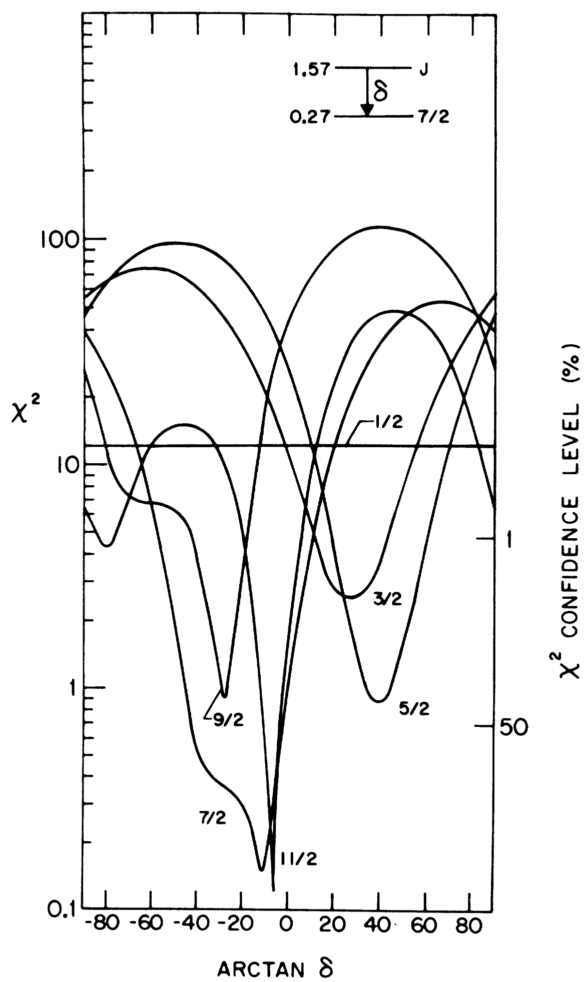

FIG. 5. χ^2 plot for the $1.57 \to 0.27$-MeV transition.

E. 1.71-MeV Level

This level has not been previously reported. It is the more weakly excited member of the 1.71-1.74-MeV doublet. A portion of an α-particle spectrum containing this doublet at a lab angle of $11\frac{1}{4}°$ is shown in Fig. 7. The angular distribution of α particles from this level is shown in Fig. 1 along with the $l=1$ DWBA prediction. The correlation results consistent with the $l=1$ assignment are are shown in Fig. 8. Both spins $\frac{3}{2}$ and $\frac{1}{2}$ are acceptable fits. Assuming a spin of $\frac{3}{2}$ the two best-fit values of the mixing ratio are $\delta = 0.08 \pm 0.13$ and $\delta = 3.2^{+2.6}_{-1.1}$. This level decays only to the ground state.

F. 1.74-MeV Level

Figure 1 shows the angular distribution of α particles leading to this level. The $l=1$ assignment is in agreement with the results of Ref. 5. The χ^2 plot and angular correlation for the ground-state transition are shown in Fig. 9. Both spins $\frac{1}{2}$ and $\frac{3}{2}$ give acceptable fits to the data. This level branches 66% to the ground state and 34% to the first excited state. The observation of a branch to the $\frac{7}{2}^-$ first excited state eliminates spin $\frac{1}{2}$ for this state, since this would imply an $M3$ γ ray competing with an $E2$ decay to the ground state. For spin $\frac{3}{2}$ there are two minima in the χ^2 plot corresponding to $\delta = -0.03 \pm 0.07$ and $\delta = 5.28^{+4.07}_{-1.64}$. The first value corresponds to a pure $M1$ transition while the second implies 96% $E2$.

G. 1.98-MeV Level

The angular distribution of the 1.98-MeV level is shown in Fig. 1. The $l=2$ assignment is in agreement with that of Ref. 5. The correlation results for the 1.98-MeV → g.s. transition are shown in Fig. 10. These results eliminate spin $\frac{5}{2}$. The χ^2 plot for $J=\frac{3}{2}$ has two minima corresponding to $\delta = -31.8^{+12.7}_{-82.7}$ and $\delta = -0.25 \pm 0.02$. The larger value of δ corresponds to a pure $M2$ transition and is very unlikely on physical grounds. This level decays 80% to the ground state. There are also γ rays observed at 1.74 and 0.27 MeV. These γ rays are consistent with a decay to at least the 1.74 member of the 1.71-1.74-MeV doublet. (A decay to the 1.71-MeV level cannot be ruled out.)

H. 2.43-MeV Level

This level has an $l=3$ angular distribution (Fig. 1) which is in disagreement with the $l=2$ assignment of David *et al.*[5] This level decays 40% to the ground state, 17% to the first excited level, and 43% to the 1.98-MeV level. The large branching to the $\frac{3}{2}^+$ level at 1.98 MeV favors the $\frac{5}{2}^-$ assignment. Confirmation of this spin assignment is obtained from the angular correlation of the 0.45-MeV γ ray to the 1.98-MeV level. These results are shown in Fig. 11. Spin $\frac{7}{2}$ is clearly eliminated. The mixing ratio for spin $\frac{5}{2}$ is $\delta(M2/E1) = -0.22 \pm 0.05$ which corresponds to a 5% $M2$ admixture.

I. 2.58- and 2.61-MeV Levels

The γ-ray angular distribution for the 2.58-MeV level is isotropic. These results are consistent with the $l=0$ assignment of David *et al.*[5] This level decays 100% to the 1.74-MeV level.

The 2.61-MeV level is known to have an $l=1$ α distribution.[5] The correlation results for the 2.61

TABLE II. Summary of results for the 1.57-MeV state, as discussed in the text. The 1% confidence limit is $\chi^2 = 2.51$.

Case	Spin of 1.57-MeV level	$\delta(1.3)$	$\delta(0.8)$	$\delta(0.5)$	χ^2
A	$\frac{5}{2}$	0.84	0.19	-0.63 ± 0.06	3.10
A	$\frac{7}{2}$	−0.19	0.19	-0.24 ± 0.04	1.33
A	$\frac{9}{2}$	−0.52	0.19	$1.43^{+0.09}_{-0.16}$	4.72
A	$\frac{11}{2}$	−0.11	0.19	0.12 ± 0.03	1.30
B	$\frac{5}{2}$	0.84	2.19	$-0.66^{+0.06}_{-0.07}$	2.50
B	$\frac{7}{2}$	−0.19	2.19	$-5.91^{+1.04}_{-1.56}$	2.48
B	$\frac{9}{2}$	−0.52	2.19	$1.56^{+0.25}_{-0.20}$	4.64
B	$\frac{11}{2}$	−0.11	2.19	0.12 ± 0.03	4.56
C	$\frac{5}{2}$	0.84	0.41	$-0.67^{+0.06}_{-0.07}$	1.51
C	$\frac{7}{2}$	−0.19	0.41	$-5.95^{+1.02}_{-1.53}$	1.98
C	$\frac{9}{2}$	−0.52	0.41	$1.59^{+0.29}_{-0.23}$	4.11
C	$\frac{11}{2}$	−0.11	0.41	0.12 ± 0.03	4.70
D	$\frac{5}{2}$	0.84	1.60	-0.69 ± 0.06	1.72
D	$\frac{7}{2}$	−0.19	1.60	$-5.98^{+1.02}_{-1.52}$	1.97
D	$\frac{9}{2}$	−0.52	1.60	$1.63^{+0.30}_{-0.24}$	4.33
D	$\frac{11}{2}$	−0.11	1.60	0.12 ± 0.03	5.48
E	$\frac{3}{2}$	0.52	−0.43	-0.35 ± 0.05	3.63
E	$\frac{5}{2}$	0.84	−0.43	0.92 ± 0.09	7.06
E	$\frac{7}{2}$	−0.19	−0.43	0.10 ± 0.03	1.29
E	$\frac{9}{2}$	−0.52	−0.43	0.45 ± 0.05	21.06
F	$\frac{3}{2}$	0.52	−3.40	-0.35 ± 0.05	3.50
F	$\frac{5}{2}$	0.84	−3.40	$0.92^{+0.09}_{-0.08}$	6.71
F	$\frac{7}{2}$	−0.19	−3.40	0.10 ± 0.03	1.52
F	$\frac{9}{2}$	−0.52	−3.40	0.49 ± 0.06	21.12

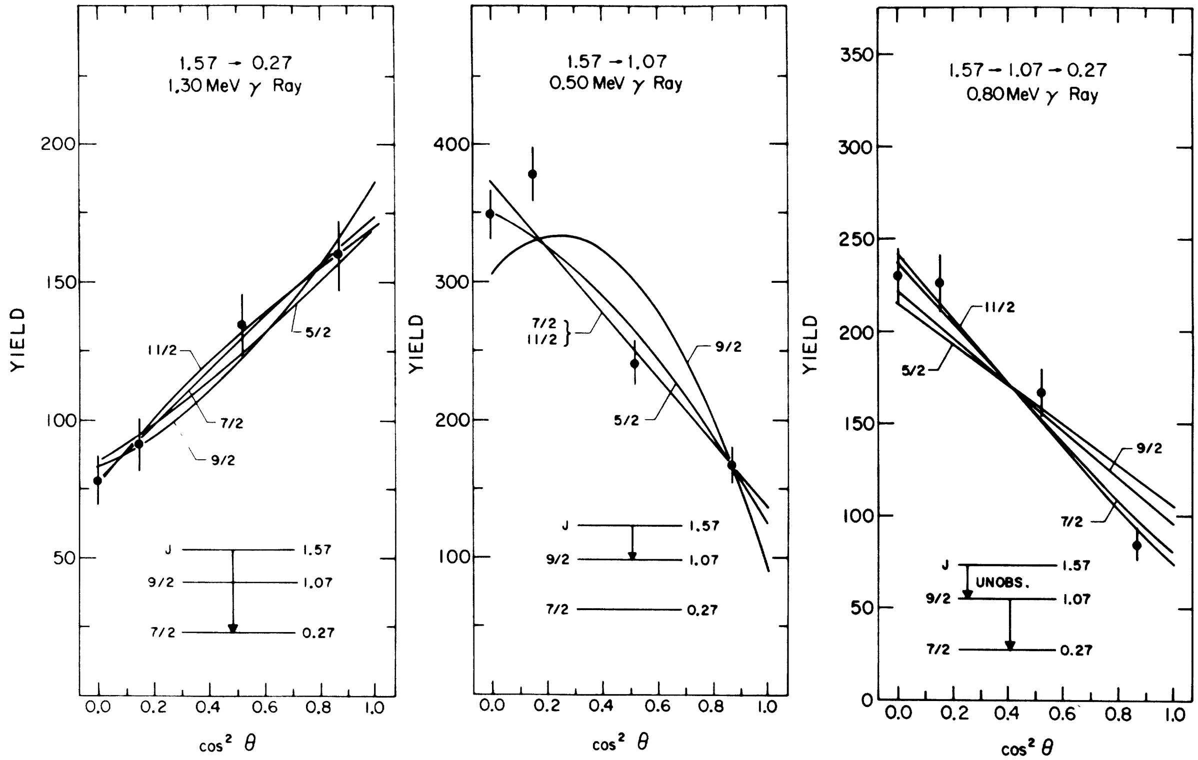

FIG. 6. Experimental angular correlations for the 1.30-, 0.80-, and 0.50-MeV γ rays from the 1.57-MeV state along with the theoretical correlations resulting from case A, Table II.

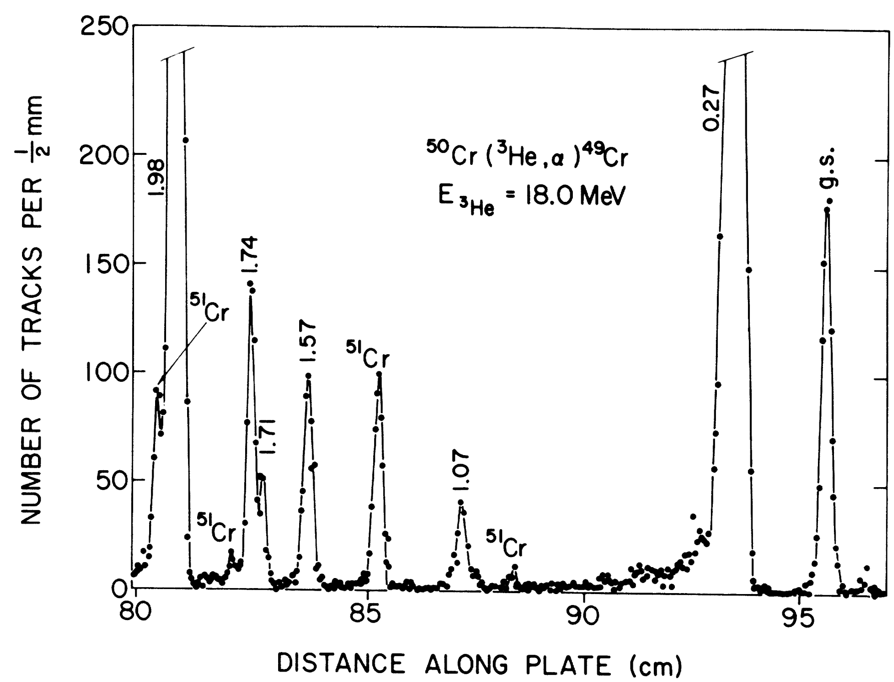

FIG. 7. α-particle spectrum measured at $\theta_{lab} = 11\frac{1}{4}°$ showing the 1.71-1.74-MeV doublet.

$\rightarrow$ 0.27-MeV γ-ray transition are shown in Fig. 12. Both spins $\frac{3}{2}$ and $\frac{1}{2}$ give acceptable fits. This level branches 28% to the ground state, 54% to the first excited state, and 18% to the 1.71-1.74 MeV doublet. The strong branch to the $\frac{7}{2}^-$ first excited state eliminates spin $\frac{1}{2}$ for the 2.61-MeV state; this would be an $M3$ γ ray with a lifetime considerably greater than our coincidence resolving time. The mixing ratio for spin $\frac{3}{2}$ has two minima in the χ^2 plot corresponding to $\delta = -0.12 \pm 0.08$ and $\delta = 1.87^{+0.45}_{-0.33}$. The larger value of δ corresponds to an unreasonably large $M3$ admixture, and can be rejected on physical grounds. Also shown in Fig. 12 is the γ-ray angular distribution obtained by summing the γ-ray spectrum at each angle between 0.40 and 2.80 MeV. The distribution is anisotropic which confirms the rejection of spin $\frac{1}{2}$ for this level.

J. 3.24-, 3.51-, and 3.93-MeV Levels

These three levels are moderately excited in the (^{3}He, α) reaction but the lower efficiency of the NaI crystals for high-energy γ rays makes the decay schemes difficult to determine. The γ spectra from the four NaI(Tl) crystals were thus added together to obtain better statistics.

The 3.24-MeV level decays 51% to the first excited level, 38% to the 1.98-MeV level, and 11% to the ground state. The spectrum also reveals a weak γ ray at 0.81 MeV which is consistent with a transition to the 2.43-MeV level. However, not all the γ rays associated with the 2.43-MeV level are visible in the sum spectrum. Particularly the 2.43-MeV γ ray appears obscured in the Compton background of the 2.97-MeV γ ray which results from the 3.24 $\rightarrow$ 0.27-MeV transition. The 1.26-MeV γ ray from the 3.24 $\rightarrow$ 1.98 transition was used in the correlation analysis. The $l = 3$ assignment to this level implies a spin of $\frac{5}{2}$ or $\frac{7}{2}$. The correlation results for the two choices are shown in Fig. 13. Spin $\frac{7}{2}$ can be excluded. The two minima in the χ^2 plot for spin $\frac{5}{2}$ correspond to $\delta = -0.17 \pm 0.06$ and $\delta = 7.26^{+5.65}_{-2.24}$. The larger value of δ would imply an almost pure $M2$ transition and is physically very unlikely.

The 3.51-MeV level decays, with about equal strength, to the ground state and the 1.07-MeV level. There is possibly a weak transition to the 0.27-MeV level. The $l = 3$ assignment implies spins of $\frac{5}{2}$ or $\frac{7}{2}$. The correlation results for the ground-state transition are shown in Fig. 14. The

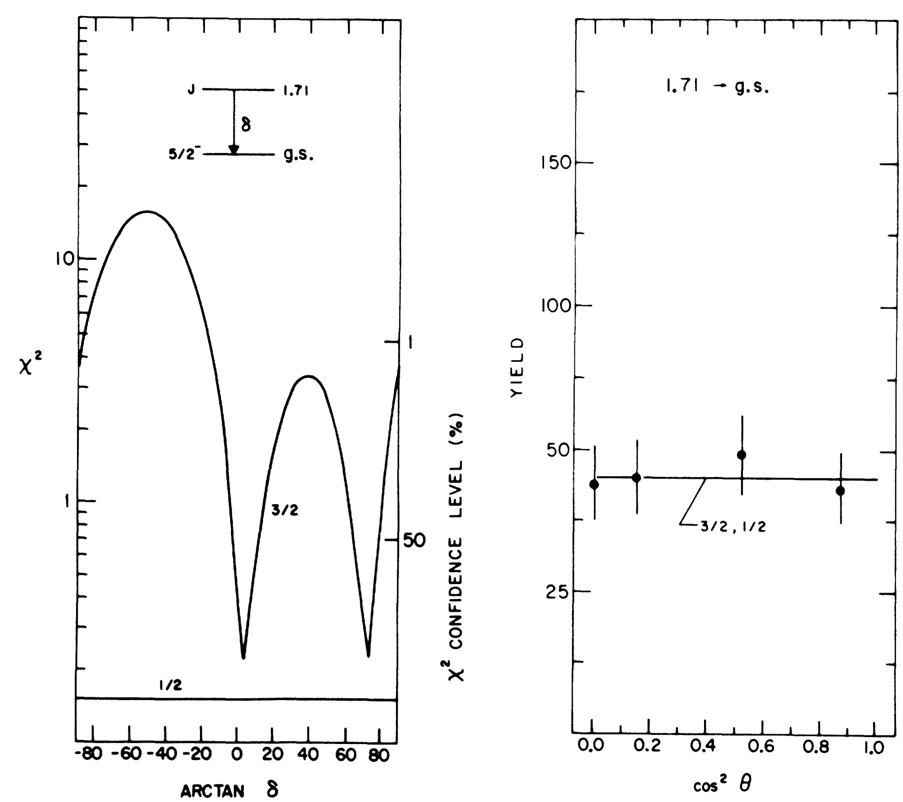

FIG. 8. χ^2 plot and experimental angular correlation for the 1.71-MeV $\rightarrow$ g.s. transition. Also shown are the theoretical angular correlations corresponding to the best fit for $J = \frac{1}{2}, \frac{3}{2}$.

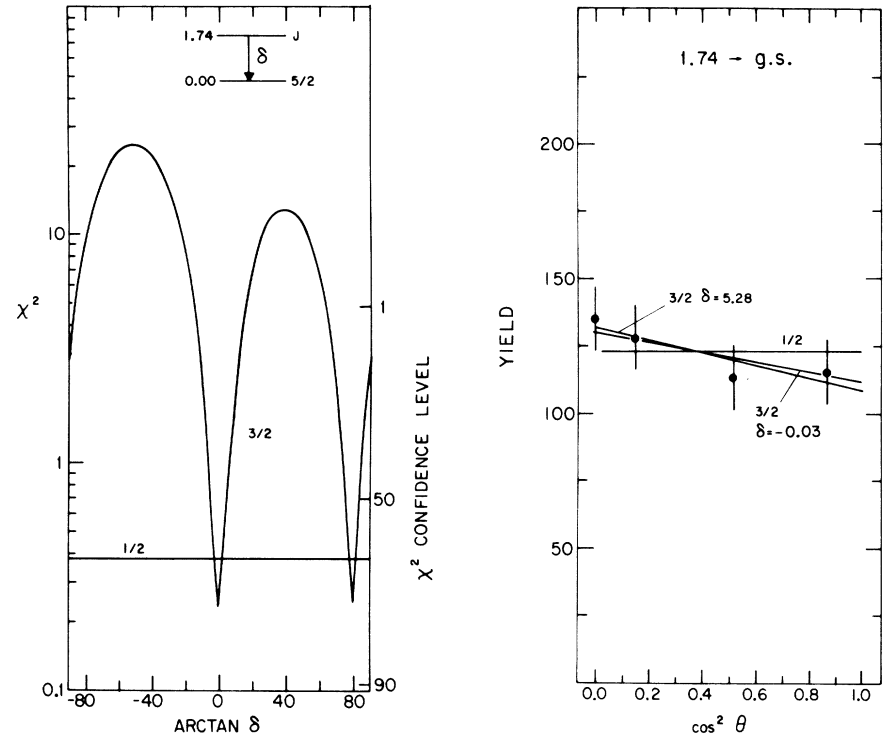

FIG. 9. χ^2 plot and experimental angular correlation for the 1.74-MeV→g.s. transition. Also shown are the theoretical correlations consistent with $l_n = 1$.

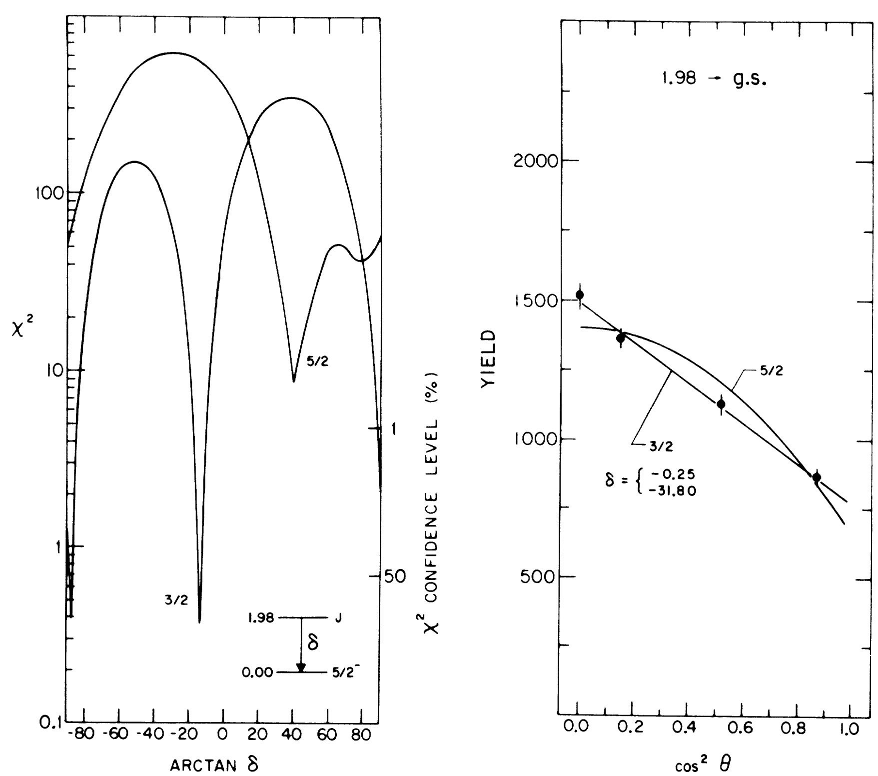

FIG. 10. χ^2 plot and experimental angular correlations for the 1.98-MeV→g.s. transition. The theoretical correlations giving the best fit for $J = \frac{3}{2}$ and $J = \frac{5}{2}$ are also shown.

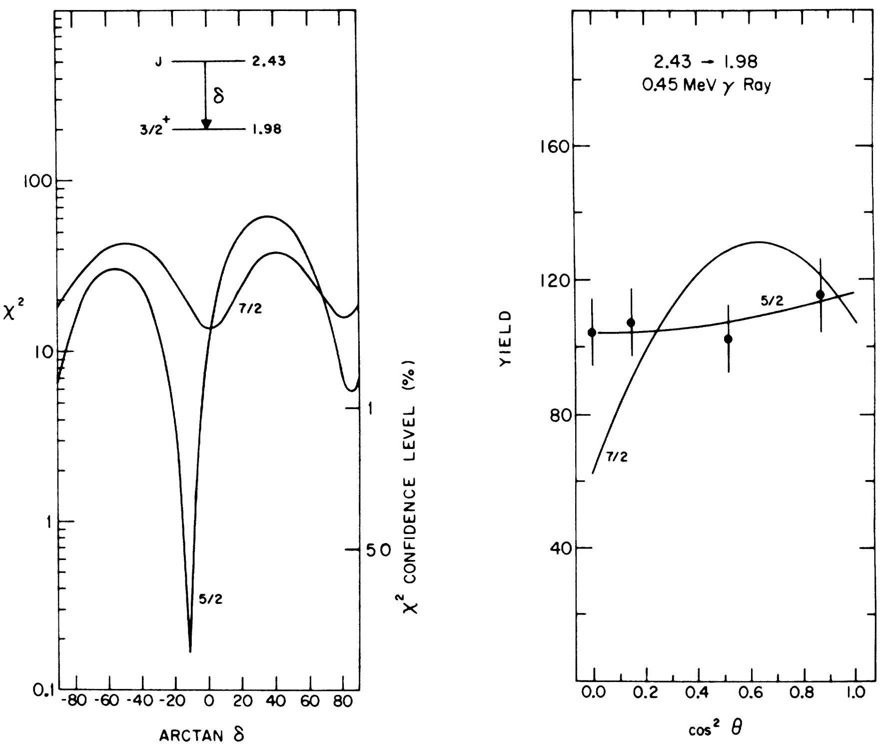

FIG. 11. χ^2 plot and experimental angular correlation for the 2.43→1.98-MeV transition, along with the theoretical predictions consistent with $l_n = 3$.

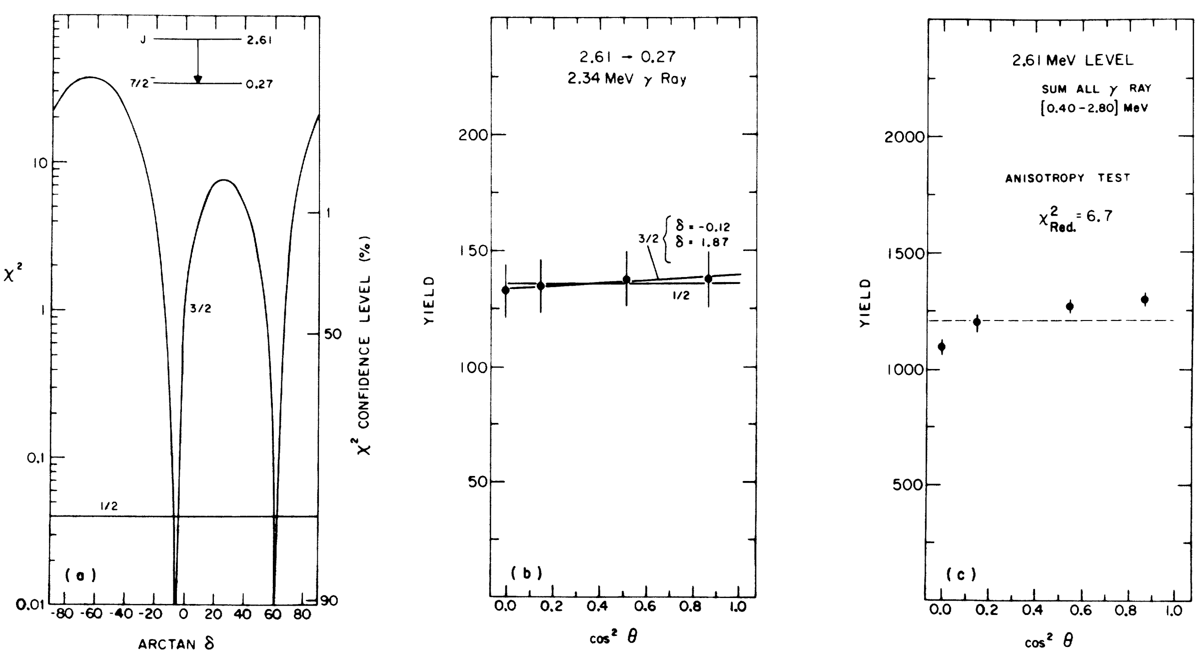

FIG. 12. (a) χ^2 plot for the 2.61→0.27-MeV transition. (b) Experimental angular distribution of the 2.34-MeV γ ray and theoretical predictions for $J = \frac{1}{2}, \frac{3}{2}$. (c) Angular distribution of all γ rays between 0.4 and 2.80 MeV, showing that an unacceptable fit is obtained for $J = \frac{1}{2}$.

data can be fitted with either spin. The mixing ratio for the best fit for spin $\frac{5}{2}$ is $\delta = 0.08 \pm 0.08$ and for spin $\frac{7}{2}$ is $\delta = -0.38 \pm 0.06$.

The level at 3.93 MeV has been assigned[5] $l = 1$. The angular distribution of γ rays is isotropic as shown in Fig. 15. These results are consistent with a spin of $\frac{1}{2}$ for this level. Spin $\frac{3}{2}$ is not strictly eliminated. However, since γ-ray angular distributions over various energy ranges involving more than one γ ray all yield isotropic distributions, spin $\frac{3}{2}$ is rather unlikely. The dominant decay mode is the $E1$ transition to the 1.98-MeV level. Possibly there are weak transitions to the 1.71-1.74-MeV doublet and the 2.58-2.61-MeV doublet. The present data do not permit more detailed analysis of the decay scheme.

K. 4.76-MeV Level

This level has been identified[5] as the isobaric analog of the ^{49}V ground state, with spin and parity $\frac{7}{2}^-$. The correlation results for the transition to the 0.27-MeV level are shown in Fig. 16.

The present data are consistent with spin $\frac{7}{2}$, but do not eliminate spin $\frac{5}{2}$, the other possibility for $l = 3$. Assuming spin and parity $\frac{7}{2}^-$, there are two allowed values for the $E2/M1$ mixing ratio, $\delta = 0.052 \pm 0.09$ and $\delta = -1.19^{+0.23}_{-0.29}$.

In Fig. 16 the experimental angular correlation is shown together with the theoretical correlations corresponding to (a) spin $\frac{7}{2}$, $\delta = 0.052$ (solid curve) and (b) spin $\frac{7}{2}$, $\delta = -1.19$ (dashed curve). The best fit for spin $\frac{5}{2}$ is almost identical to the solid curve. This is an analog → antianalog transition, and one would expect[17,18] a pure $M1$ transition here. The value $\delta = 0.052$ is consistent with such an interpretation, but the present data do not distinguish between this fit and the one obtained with $\delta = -1.19$. This state branches 64% to the first excited state, 30% to the 1.07-MeV level, and 6% to the ground state.

The fact that this level branches strongly to the second excited state is very interesting in itself. The transition to the first excited state is probably fast because this state is the antianalog state of the 4.76-MeV level. Consequently there also must be a good overlap between the 4.76-MeV level and the 1.07-MeV level in order to produce a 30% branch. On the other hand the cross section for the direct excitation of the 1.07-MeV level is very small. These facts are much easier to reconcile if the 1.07-MeV level will eventually turn out to be a $\frac{9}{2}^-$ state and not a $\frac{5}{2}^-$ state.

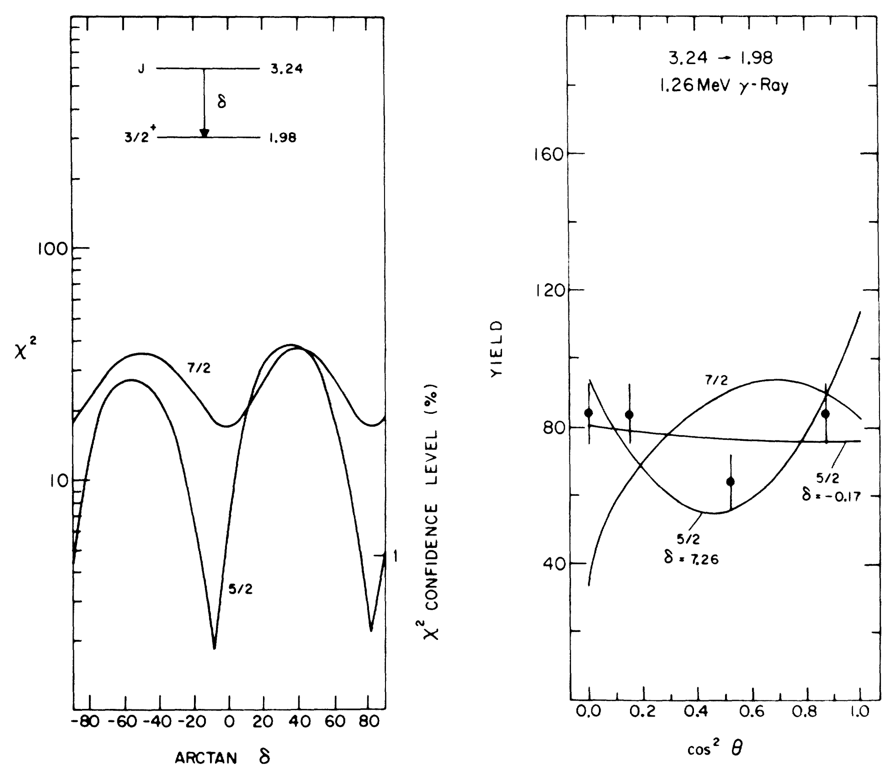

FIG. 13. χ^2 plot and experimental angular correlation for the 3.24→1.98-MeV transition. Also shown are the best fits for $J = \frac{5}{2}, \frac{7}{2}$.

L. 5.57-MeV State

The state at 5.57 MeV is believed to be the isobaric analog of the 0.75-MeV $\frac{3}{2}^{+}$ state in ^{49}V.[5] This assignment was made on the basis of: (a) the excellent fit of the (^{3}He, α) angular distribution by an $l=2$ DWBA prediction; and (b) the approximate equality of the spectroscopic factor measured in the (^{3}He, α) reaction leading to the 5.57-MeV state in ^{49}Cr and spectroscopic factor measured in the (t, α) reaction[19] leading to the 0.75-MeV state in ^{49}V. The decay of this state is complex, and a complete decay scheme could not be constructed. However, transitions were identified to the ground state, the 1.98-MeV state, and the 2.43-MeV state. The ratio of intensities for these decays were approximately 1: 2: 1, normalizing to the ground-state branch. These decays account for most of the strength.

The angular correlation for the 3.59-MeV γ ray leading to the 1.98-MeV state can be fitted with either spin $\frac{3}{2}$ or $\frac{5}{2}$; the χ^2 plot is shown in Fig. 17. Assuming the spin is $\frac{3}{2}$, the allowed values for the $E2/M1$ mixing ratio are $\delta = 0.014 \pm 0.068$ and $\delta = -4.10^{+0.90}_{-0.71}$. Also shown in Fig. 17 is the best fit for $J=\frac{3}{2}$ and $\frac{5}{2}$. The 1.98-MeV state is presumably the $T_{<}$ $\frac{3}{2}^{+}$ state (antianalog state) and one would expect a pure $M1$ transition here. This is consistent with the present data. It is interesting to note that the $M1$ decay to the antianalog state competes favorably with the $E1$ decay to the ground state, despite the fact that for a $d_{3/2}$ state the analog → antianalog $M1$ transition is not predicted[18] to be enhanced.

M. States Above 6 MeV

The doublet at 6.43 and 6.47 MeV is very interesting. This region of excitation is where the isobaric analog of the $\frac{1}{2}^{+}$ state at 1.65 MeV in ^{49}V should occur.[5] Two strong states are observed in the (^{3}He, α) study of Ref. 5. The 6.47-MeV state is assigned $l=0$; the 6.43 MeV is tentatively assigned $l=0$. The angular distribution of γ rays from each of these states is isotropic, which is consistent with spin and parity $\frac{1}{2}^{+}$. The decay schemes of the two levels are similar. The 6.43-MeV state decays 15% to the 1.71-1.74-MeV doublet, 47% to the 2.58-2.61-MeV doublet, and 38% to the 3.93-MeV state. The 6.47-MeV state decays 41% to the 1.71-1.74-MeV doublet, 42% to the 2.58-2.61-MeV doublet, and 17% to the 3.93-MeV state. The decays to the 1.71-, 1.74-, and 3.93-MeV states are probably $E1$, and account for about half the total strength in both cases. The decay to the 2.58-MeV $\frac{1}{2}^{+}$ state would be the decay to the $T_{<}$

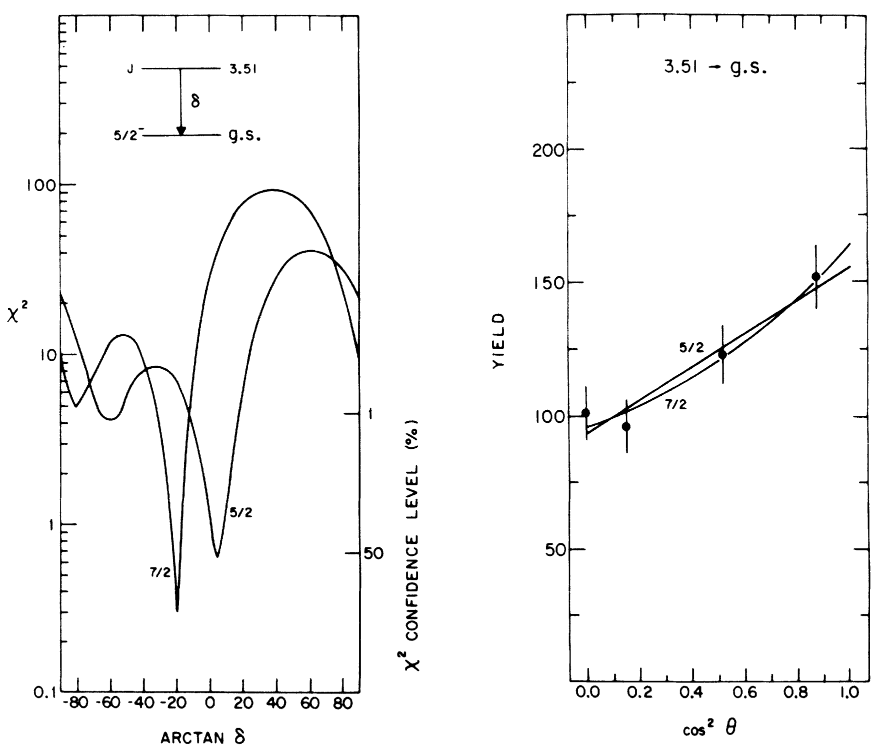

FIG. 14. χ^2 plot and experimental angular correlation for the 3.51-MeV → g.s. transition. Also shown are the best fits for $J=\frac{5}{2}, \frac{7}{2}$.

TABLE III. Summary of results of the present work.

E_x (MeV)	J^{π}	γ transition	Mixing ratio	Multipolarity	l [a]	l [b]
g.s.	$\frac{5}{2}^-$				3	3
0.27	$\frac{7}{2}^-$	0.27→g.s.	0.105 ± 0.013	$E2/M1$	3	3
1.07	$(\frac{9}{2}^-)$	4.76→1.07	$\{-0.05\pm0.04$ $30.14^{+\infty}_{-14.67}$	$E2/M1$		0
	or					
	$(\frac{5}{2}^-)$	4.76→1.07	-0.05 ± 0.03	$E2/M1$		
1.57	$(\frac{5}{2}^-)$, $(\frac{7}{2}^-)$, or $(\frac{11}{2}^-)$ [c]				...	(1)
1.71	$(\frac{1}{2}^-)$,	1.71→g.s.	Undetermined		1	
	or					
	$(\frac{3}{2}^-)$	1.71→g.s.	$\{0.08\pm0.13$ $3.2^{+2.6}_{-1.1}$	$E2/M1$	1	
1.74	$\frac{3}{2}^-$	1.74→g.s.	$\{-0.03\pm0.07$ $5.28^{+4.07}_{-1.64}$	$E2/M1$	1	1
1.98	$\frac{3}{2}^+$	1.98→g.s.	$\{-0.25\pm0.02$ $-31.8^{+12.7}_{-82.8}$	$M2/E1$	2	2
2.43	$\frac{5}{2}^-$	2.43→1.98	-0.22 ± 0.05	$M2/E1$	3	(2)
2.58	$\frac{1}{2}^+$		Undetermined			0
2.61	$\frac{3}{2}^-$	2.61→0.27	$\{-0.12\pm0.08$ $1.87^{+0.45}_{-0.33}$	$M3/E2$		1
3.24	$\frac{5}{2}^-$	3.24→1.98	$\{-0.17\pm0.06$ $7.26^{+5.65}_{-2.24}$	$M2/E1$		3
3.51	$(\frac{5}{2}^-)$	3.51→g.s.	0.08 ± 0.08	$E2/M1$		3
	or					
	$(\frac{7}{2}^-)$	3.51→g.s.	-0.38 ± 0.06	$E2/M1$		3
3.93	$\frac{1}{2}^-$		Undetermined			(1)
4.76	$\frac{7}{2}^-$	4.76→0.27	$\{0.052\pm0.09$ $-1.19^{+0.23}_{-0.29}$	$E2/M1$		3
5.57	$\frac{3}{2}^+$	5.57→1.98	$\{0.014\pm0.068$ $-4.10^{+0.90}_{-0.71}$	$E2/M1$		2
6.43	$\frac{1}{2}^+$		Undetermined			(0)
6.47	$\frac{1}{2}^+$		Undetermined			0
6.76	$\frac{1}{2}^+$		Undetermined			0

[a] Present work. [b] Reference 5. [c] See Table II.

antianalog state, but is indistinguishable here from an $E1$ decay to the neighboring 2.61-MeV $\frac{3}{2}^-$ state. It would be interesting to have a high-resolution measurement here to resolve the ambiguity.

The 6.76-MeV state has been assigned $l=0$ and identified as the isobaric analog of the 2.00-MeV state in ^{49}V.[5] The angular distribution of γ rays from this state is isotropic, which is consistent with spin and parity $\frac{1}{2}^+$. This state is somewhat weaker in the (^{3}He, α) reaction than the 6.43- and 6.47-MeV states, and a complete decay scheme could not be constructed. Decays to the 1.71-1.74-MeV doublet and the 3.93-MeV state were identified.

N. Summary of Results

A summary of the results is shown in Table III. The excitation energies of the various levels are listed together with the spins as determined in this study. Parentheses are used to indicate uncertain assignments. The γ-ray transitions studied are shown together with the multipole mixing ratios and multipolarities involved. The phase convention used for defining the multipole mixing ratio is that of Rose and Brink.[9] Except for the 1.07- and 1.57-MeV levels the spins investigated for each state were limited to $J=l\pm\frac{1}{2}$. For the 2.43-MeV level the $l=3$ assignment, determined in this study, was used instead of the tentative $l=2$ assignment of Ref. 5. For the 1.07- and 1.57-MeV states a complete list of the multipole mixing ratios for the various members of the γ-ray cascades has been given in Tables I and II. For the 1.07- and 1.57-MeV levels the l assignments as measured by David *et al.*[5] are inconsistent with the present angular-correlation results. In particular the $l=0$ assignment to the 1.07-MeV level implies $J=\frac{1}{2}$, which would result in an isotropic distribution of γ rays. However, the experimental γ-ray distribution is anisotropic (see Fig. 4).

Despite the good agreement between the $l=5$ DWBA prediction and the angular distribution of the 1.07-MeV level, no l assignment to this level is is made here. Neutron pickup with $l=5$ would imply the presence of some $1h$ strength in the ground-state wave function of ^{50}Cr. Such an admixture is quite unlikely and the neutron pickup probably proceeds by a compound nuclear or two-step process. Our results do not determine the parity of the 1.07- or 1.57-MeV levels; the multipolarities listed in Table III are based on the assumption of negative parity for these two levels. This assumption appears justified because the positive-parity states at 1.98 and 2.58 MeV are probably $d_{3/2}$ and $s_{1/2}$ hole states and have the simple neutron configurations $(d_{3/2}{}^{-1}f_{7/2}{}^6)_{3/2}$ and $(s_{1/2}{}^{-1}f_{7/2}{}^6)_{1/2}$. It is unlikely that more complex recouplings of nucleons could produce positive-parity states lower in energy than the 1.98-MeV level.

The disagreement with the work of Ref. 5 is not simply a matter of assigning different l values to similar experimental angular distributions. It is the experimental distributions of the α particles which differ, particularly for the 1.07-MeV level. For the more strongly excited states however, our measured α-particle angular distributions closely agree with those of Ref. 5. Therefore, we have used their l assignments for all levels above 2.43 MeV.

Figure 18 shows the decay scheme and branching ratios for the various levels studied. The errors in the branching ratios are ±10% for the

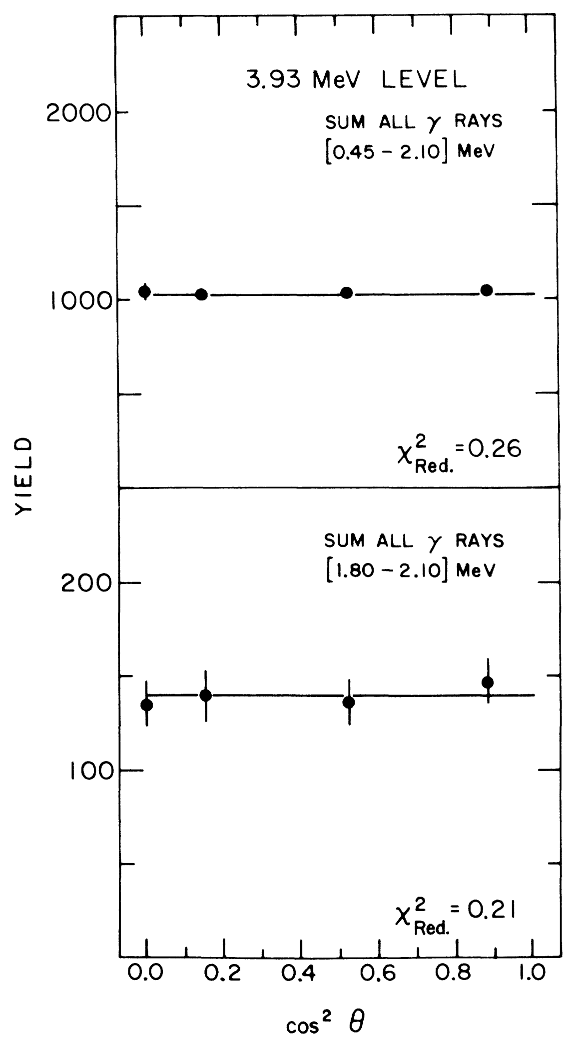

FIG. 15. Experimental angular correlation for different portions of the γ spectrum resulting from the 3.93-MeV level.

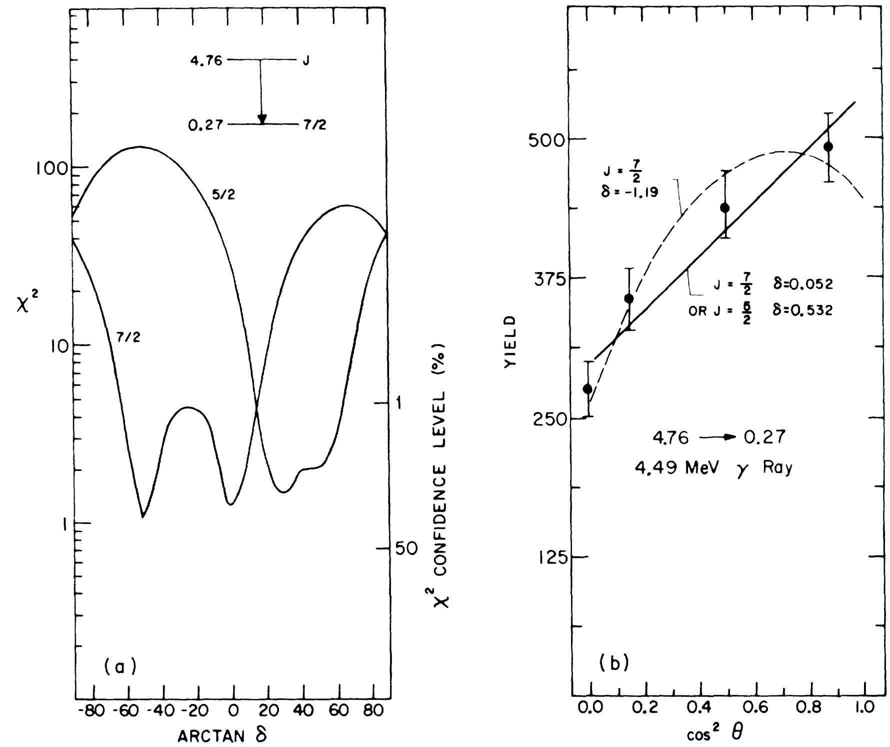

FIG. 16. (a), (b) χ^2 plot and experimental angular correlation for the 4.76→ 0.27-MeV transition. Also shown are the best fits consistent with $l_n = 3$.

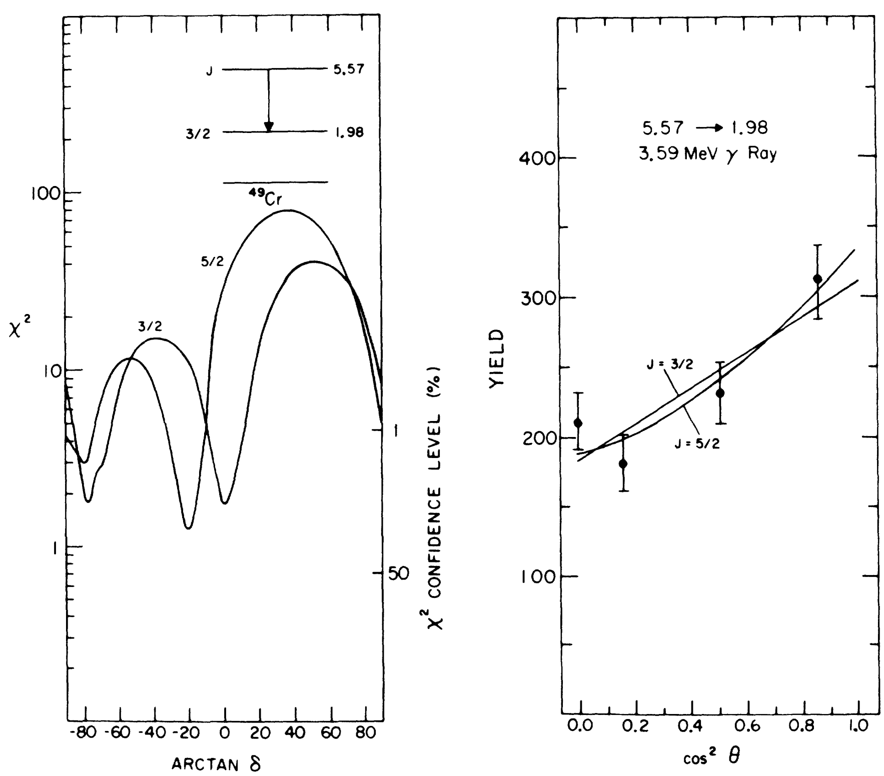

FIG. 17. χ^2 plot and experimental angular correlation for the 5.57→ 1.98-MeV transition. Also shown are the best fits for $J = \frac{3}{2}, \frac{5}{2}$.

strong transitions and ±5% for the weak transitions (≤20%).

V. COMPARISON WITH THEORY

A. Shell Model

A theoretical calculation of the energy levels and spins of the ^{49}Cr nucleus has been done by Ginocchio[2] using the spherical shell model. In these calculations, pure $(f_{7/2})^n$ configurations are coupled using the experimental level structure of ^{42}Ca, ^{42}Sc, and ^{50}Ti to derive the two-body matrix elements. Figure 19 shows the experimental level scheme together with the predictions of the shell model. The shell model correctly predicts the $\frac{5}{2}^-$ ground state. The shell model predicts the $\frac{7}{2}^-$ level (the first excited state) to be at 0.170 MeV which is in fair agreement with the experimental value of 0.27 MeV. This $\frac{7}{2}^-$ level is expected to be very strongly excited in a neutron-pickup reaction, having a simple configuration $[^{40}\mathrm{Ca}+(\pi f_{7/2}{}^4)(\nu f_{7/2}{}^5)^{7/2}]^{7/2}$. Apart from these two levels there is little agreement between the shell model and the observed levels. Eleven negative-parity states below 3 MeV are predicted, six of which have spin $J \leqslant \frac{7}{2}$ and should be excited with $l=1$ or 3 in neutron pickup. Experimentally one observes eight negative-parity states and six states with $l=1$ or 3. While the $\frac{11}{2}$ state predicted at 1.49 MeV may correspond to the observed level at 1.57 MeV, the $\frac{9}{2}$ prediction is 770 keV higher than the observed level at 1.07 MeV. It is not expected, however, that the direct neutron-pickup reaction populates the high-spin states since it is unlikely that the ^{50}Cr ground-state wave function contains any $h_{9/2}$ or $h_{11/2}$ components. It is therefore possible that some high-spin states have not been identified yet.

Detailed comparison of the low-spin states (i.e., $J \leqslant \frac{7}{2}$) with the shell-model calculations shows a number of discrepancies. The model predicts a spin $\frac{5}{2}$ state at 2.82 MeV and a spin $\frac{3}{2}$ state at 2.86 MeV. The closest corresponding levels observed are those at 2.43 MeV ($J^\pi = \frac{5}{2}^-$) and 2.61 MeV ($J^\pi = \frac{3}{2}^-$). The $\frac{7}{2}^-$ state predicted at 2.70 MeV is not observed. The $\frac{3}{2}^-$ state at 1.44 MeV may correspond to the observed level at 1.71 or 1.74 MeV. However, this correspondence would represent a reversal of the usual systematics of the depression of the observed $\frac{3}{2}^-$ level relative to the predicted $\frac{3}{2}^-$ level.[1]

To summarize, the shell-model predictions are in relatively poor agreement with the observed levels in ^{49}Cr. While some of the high-spin states may easily be missed in the (^{3}He, α) reaction, the predicted low-spin states are not in good agree-

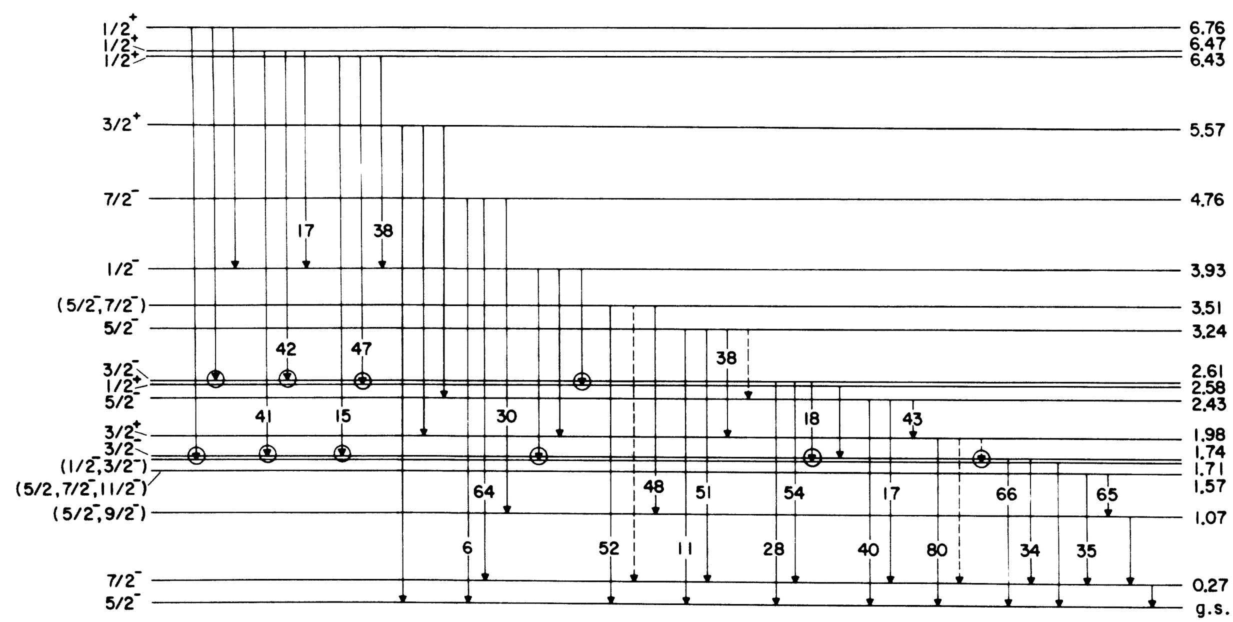

FIG. 18. Decay scheme of ^{49}Cr, showing spins and branching ratios measured in the present work, along with previously known spins. Spin assignments in parentheses are tentative. Dashed lines indicate uncertain transitions. A circle at the end of an arrow indicates a transition to either or both members of the circled final states. The errors in the branching ratios are ±10% for the strong transitions and ±5% for the weak transitions (≤20%).

ment with experiment. It would be desirable to include the larger configuration space of the entire $1f$-$2p$ shell in the calculations.

B. Strong-Coupling Model

Malik and Scholz have calculated the level structure of ^{49}Cr using the strong-coupling model.[3] Basic to these calculations is the Bohr and Mottelson[20] collective model with a Coriolis coupling between rotational bands. In the odd-even nuclei, the last odd nucleon is considered to be coupled to a deformed symmetric core. The odd nucleon occupies Nilsson single-particle orbitals within the $N=3$ oscillator shell ($1f$-$2p$ shell). The diagonalization of the Coriolis coupling term ($\vec{I}\cdot\vec{j}$) yields the energy eigenvalues as a function of the deformation parameter β. The energy levels and spins shown in Fig. 19 are calculated using $\beta=0.25$.[21] For the positive-parity states arising from the $N=2$ oscillator shell, only the relative spacing of the levels is calculated and the lowest $\frac{3}{2}^+$ state is "normalized" to correspond to the observed $\frac{3}{2}^+$ state at 1.98 MeV. (The positive-parity states are shown as dashed lines for clarity.)

The strong-coupling model correctly predicts spin $\frac{5}{2}$ for the ground state and spin $\frac{7}{2}$ for the first excited state. Below 3-MeV excitation the model predicts too high a level density, both for positive- and negative-parity states. Perhaps the most significant difference between this model and the shell-model calculation is the prediction of a state at 0.90 MeV with $J^{\pi}=\frac{9}{2}^-$. This level probably corresponds to the observed level at 1.07 MeV. Further the predicted $\frac{11}{2}^-$ level falls close to the observed 1.57-MeV state. It is extremely interesting that the first three excited levels in ^{49}Cr may well be members of a rotational band having spins $\frac{7}{2}$, $\frac{9}{2}$, and $\frac{11}{2}$. Such rotational bands have generally not been identified in the $f_{7/2}$ region. While our data do not unambiguously determine the $\frac{9}{2}$, $\frac{11}{2}$ spin sequence, our results are at least consistent with such an assignment. One does, however,

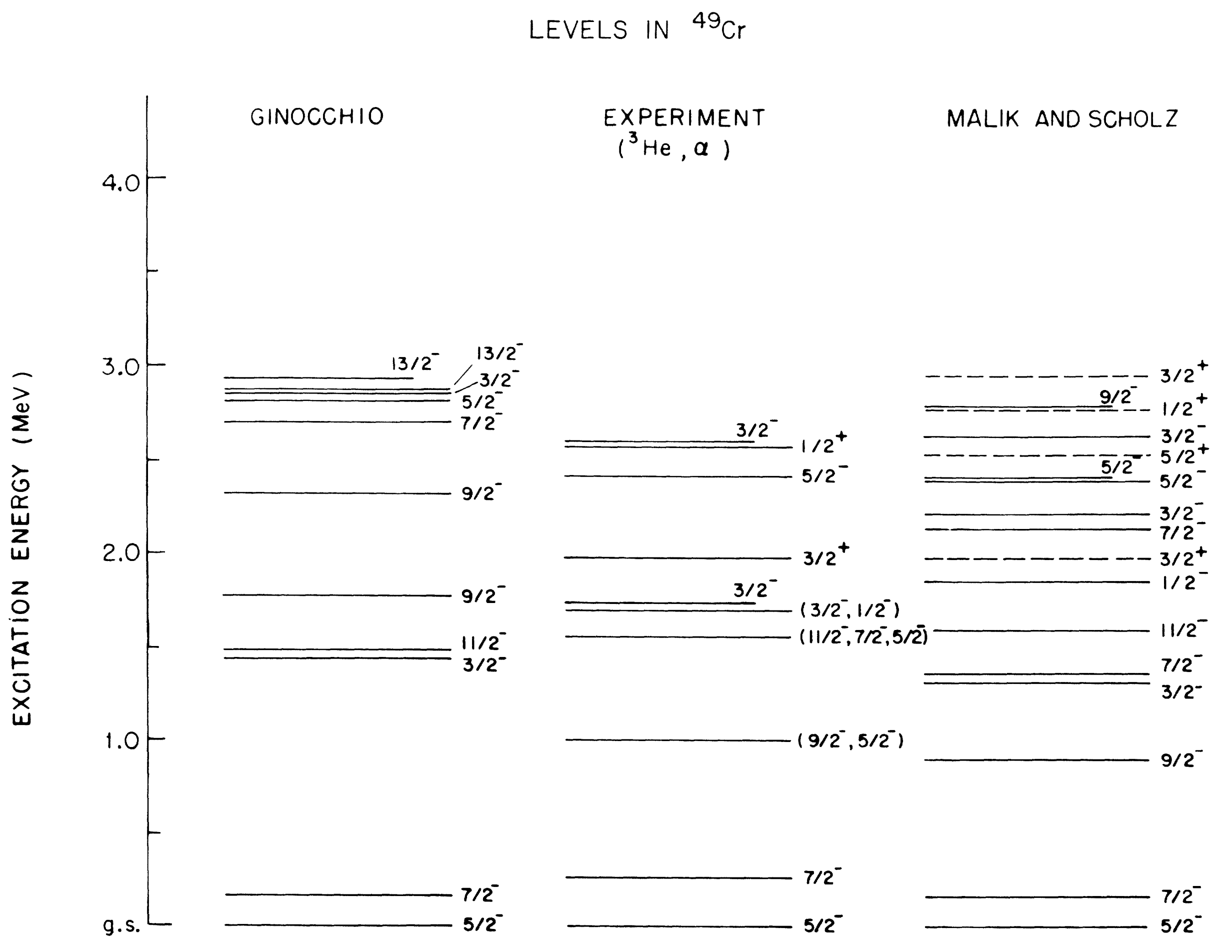

FIG. 19. Comparison of the results of the present investigation with the shell model (Ginocchio), and the Coriolis-coupling model (Malik and Scholz).

have difficulty in trying to match lower-spin states ($J \leq \frac{9}{2}$) predicted by the strong-coupling model to the observed levels. The predicted $\frac{7}{2}^-$ state at 1.37 MeV is not observed (unless the 1.57-MeV level has spin $\frac{7}{2}$, in which case the spin $\frac{11}{2}$ state is not observed). The model does not predict the doublet at 1.71-1.74 MeV. The $\frac{5}{2}^-$ level at 2.43 MeV and the $\frac{3}{2}^-$ level at 2.61 MeV do correspond to strong-coupling model states at 2.41 (or 2.40 MeV) and 2.64 MeV, respectively. However, the level density is rather high at these excitation energies, and not much significance should be attached to this correspondence.

The strong-coupling model meets with partial success in predicting the level structure of ^{49}Cr. Our experimental results for the 1.07- and 1.57-MeV levels are consistent with the $\frac{9}{2}$, $\frac{11}{2}$ spin sequence predicted from the model calculations. However, the incomplete correspondence for the low-lying levels and the prediction of too many levels in the region of 2–3-MeV excitation are serious drawbacks of the strong-coupling-model calculations.

It would be extremely useful to know the lifetimes of excited states in ^{49}Cr. Most likely some of the ambiguities regarding the spin assignments could be resolved. The multipole mixing ratios and branching ratios could then be used to determine the absolute value of the reduced matrix elements. A knowledge of these matrix elements would supply a further test for the various models.

Also the neutron-pickup reaction is rather selective and does not excite some of the states in ^{49}Cr, particularly high-spin states. Other reaction studies such as multinucleon transfers will have to be performed to locate these levels. Generally speaking, further detailed studies of nuclei in the middle of the $f_{7/2}$ shell are needed to uncover the nuclear systematics.

ACKNOWLEDGMENTS

The authors are indebted to Dr. D. J. Church and Dr. P. D. Kunz for the use of the programs M2 and DWUCK, respectively. They also wish to express their gratitude to Dr. W. Scholz for many useful discussions in connection with the strong-coupling-model calculations.

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*Work supported by the National Science Foundation.

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