Particle-γ-Ray Angular-Correlation Study of ^{57}Ni in the Reaction ^{58}Ni(^{3}He, αγ)^{57}Ni†

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The levels of ^{57}Ni populated in the reaction ^{58}Ni(^{3}He,α)^{57}Ni have been studied using the method of particle–γ-ray angular correlations. The α particles were detected at 0° with respect to the incident beam by a position-sensitive detector located at the focal point of a magnetic spectrometer. Four 7.6×10.2-cm NaI(Tl) crystals were used simultaneously to detect coincident γ rays at angles between 90° and 160°. Using l values known from previous work, the following spin-parity assignments are made for the levels indicated: 0.78 MeV $\frac{5}{2}^-$, 1.11 MeV $\frac{1}{2}^-(\frac{3}{2}^-)$, 2.59 MeV $\frac{7}{2}^-$, 3.24 MeV $\frac{7}{2}^-$, 3.71 MeV $(\geq\frac{3}{2})$, 3.85 MeV $(\frac{3}{2}, \frac{5}{2})$, 4.23 MeV $(\frac{3}{2}, \frac{5}{2}, \frac{7}{2})$, 4.56 MeV $(\leq\frac{7}{2})$, 5.22 MeV $\frac{7}{2}^-$, 5.56 MeV $\frac{3}{2}^+$, 6.00 MeV $\frac{3}{2}^+$. Branching ratios for the decays of these levels are presented, along with mixing rations for the stronger transitions.

I. INTRODUCTION

THE nickel isotopes have been the object of much experimental and theoretical interest in the past few years. Several experiments have been performed to ascertain l values and to investigate the possible j dependence of angular distributions in direct reactions. Calculations based on both quasiparticle approximations and the shell model have been made.[1] The ^{57}Ni nucleus is of particular interest as the ground state can be considered to consist of one neutron outside the doubly closed $f_{7/2}$ shell of ^{56}Ni. Previous experiments have assigned l values to various levels using the ^{58}Ni(^{3}He, α)^{57}Ni reaction,[2–4] the ^{58}Ni(d, t)^{57}Ni reaction[5,6] and the ^{58}Ni(p, d)^{57}Ni reaction.[7,8] In addition, spins of some of these levels have been predicted on the basis of the j dependence of the angular distributions of the outgoing particles in these reactions.[5,9,10]

The present study was undertaken to investigate the properties of levels in ^{57}Ni populated in the ^{58}Ni(^{3}He, α)^{57}Ni reaction by the method of particle γ-ray angular correlations. This method measures the spins of the levels and also yields information about the properties of the decay γ rays which can give further insight into the nature of the levels involved. The angular correlation technique employed here is known as method II of Litherland and Ferguson,[11] in which the population of an excited level formed in a nuclear reaction is restricted to a few magnetic substates by observing the outgoing particles at 0° or 180° with respect to the incoming beam. This imposes constraints on the angular distribution of the deexcitation γ rays emitted in coincidence with these particles. In the case of the ^{58}Ni(^{3}He, α)^{57}Ni reaction only the $M=\pm\frac{1}{2}$ magnetic substates are populated in ^{57}Ni. Further, as the beam is unpolarized, these two substates are equally populated. The alignment of the ^{57}Ni nucleus is thus fixed independent of any assumptions about the reaction mechanism and no unknown populations enter in the subsequent analysis of the γ-ray angular distributions. Consequently, these distributions depend only on the spins of the levels involved and the multipolarities of the radiations connecting them.

II. EXPERIMENTAL PROCEDURE

The experiments were performed using a 15-MeV 200-nA ^{3}He^{++} beam from the University of Pennsylvania Tandem Accelerator. The target was a 500 μg/cm^2 self-supporting nickel foil enriched to 99.9% ^{58}Ni. It was supplied by the Stable Isotopes Division of the Oak Ridge National Laboratory. The experimental arrangement is basically the same as has been described elsewhere[12] with the exception that the present series of experiments were performed using a two-parameter analyzer system rather than the three-parameter system described in Ref. 12. Briefly, the α particles were detected at 0° with respect to the incident beam by a position-sensitive surface barrier detector depleted to a depth of 600 μ placed at the focal point of a double-

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[8] R. Sherr, B. F. Bayman, E. Rost, M. E. Rickey, and C. G. Hoot, Phys. Rev. **139**, B1272 (1965).

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[10] R. Sherr, E. Rost, and M. E. Rickey, Phys. Rev. Letters **12**, 420 (1964).

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[12] R. W. Zurmühle, P. F. Hinrichsen, C. M. Fou, C. R. Gould, and G. P. Anastassiou, Nucl. Instr. Methods **71**, 311 (1969).

focusing magnetic spectrometer. Coincident γ rays were observed using four 7.6×10.2-cm NaI(Tl) crystals placed at angles of 90°, 113°, 136°, and 159° around a specially designed scattering chamber. The coincidence time peak has a full width at half-maximum (FWHM) $\approx$10 nsec and a width at the base of 20 nsec. The coincidence resolving time was set at $2\tau = 25$ nsec to ensure that no events were missed. The position signal from the particle detector and the energy signal from any one of the four γ-ray detectors were stored in 256×256 format on magnetic tape using a TMC two-parameter analyzer and associated buffer tape system. These data were reduced off line on an IBM 7040 computer. The energy range subtended by the detector in the present study was about 1 MeV. Deuterons from the competing (^{3}He, d) reaction have approximately half the energy of the α particles and can be eliminated by energy discrimination. Protons from the competing (^{3}He, p) reaction have a flight time in the spectrometer equal to half that of the α particles and also lose very little energy in the detector. They are, therefore, eliminated both by the fast coincidence requirement and by the subsequent gate on the particle energy. The position spectra are consequently very simple and easily interpreted.

III. ANALYSIS

The theoretical angular distribution of the γ rays is given by Poletti and Warburton[13] in a form very convenient for computation. The angular correlation for the decay of a level of spin a, populated directly in a nuclear reaction, to a level of spin b, is given by

$$W(\Theta) = \sum_k a_k P_k(\cos\Theta) = \sum_k \rho_k(a) F_k(abx) Q_k P_k(\cos\Theta),$$

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 $F_k(abx)$ depend on the spins of the initial and final states and the multipole mixing ratio x. 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 sign convention for the multipole mixing ratio is that of Rose and Brink.[14] In the Rose and Brink convention, the experimental value of the mixing ratio is obtained by fitting the data to formula (11) of Poletti and Warburton[13] with $\sigma = 0$. Both the sign and the magnitude are uniquely determined by this fit regardless of whether the transition is $EL+1$, ML or $ML+1$, EL. No arbitrary changes of sign are subsequently made or implied for natural or unnatural parity mixtures. The expression for the angular correlation is readily extended[13] to the case

[13] A. R. Poletti and E. K. Warburton, Phys. Rev. **137**, B595 (1965).

[14] H. J. Rose and D. M. Brink, Rev. Mod. Phys. **39**, 306 (1967).

TABLE I. Energies of levels in ^{57}Ni measured in the present work using the ^{58}Ni(^{3}He, α)^{57}Ni reaction. These are compared with values from the ^{58}Ni(p, d)^{57}Ni study of Ref. 8. Also shown are l values for these states.

(^{3}He, α)[a] ±0.02 (MeV)	(p, d)[b] ±0.02	l[c]
0.0	0.0	1
0.78	0.78	3
1.11	1.12	1
2.59	2.59	3
3.24	3.23	3
3.37		
3.71	(3.66)[d]	(3)[d]
3 85		
4.23	4.20	(3)[d]
(4.56)[d]	(4.53)[d]	(3)[d]
5.22	5.20	3
5.56	5.57	
6.00	(6.00)[d]	2, 3

[a] Present work.
[b] Reference 8.
[c] References 2–8.
[d] ( ) = multiple peak, or other uncertainty.

where the γ ray observed is the second member of a cascade, the first being unobserved.

The experimental angular correlations were analyzed using a computer program $M2$, written by Church.[15] For spins $\frac{1}{2}$–$\frac{9}{2}$ for the initial state, the program performed a least-squares fit of the data directly to the theoretical correlation formula for different values of $\varphi = \tan^{-1}x$. 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

$$\chi^2 = 1/n \sum_i \{[W(\Theta_i) - Y(\Theta_i)]/\delta Y(\Theta_i)\}^2,$$

where $W(\Theta_i)$ and $Y(\Theta_i)$ are the theoretical and experimental γ-ray yields, respectively, at angle Θ_i, $\delta Y(\Theta_i)$ the experimental error, and n the number of degrees of freedom. The quantity n is equal to the number of experimental points minus the number of unknowns. In the vicinity of the value of φ yielding the minimum value of χ^2, a search is performed using an iterative procedure to find the exact value of φ yielding the best fit. The program could simultaneously fit all the γ rays arising from up to three different branches from the decay of a particular level. A correction for the finite size of the particle detector could be made but in the present work 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 photopeak or the photopeak and first escape peak. In a few cases it was necessary to allow for the contribution

[15] D. J. Church (private communication).

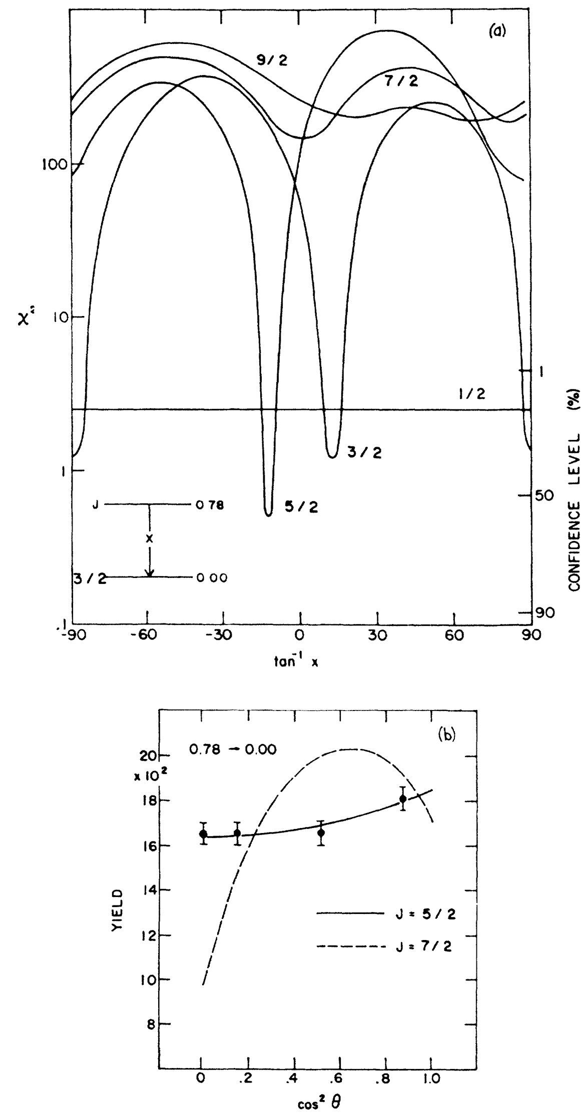


FIG. 1. (a) The χ^2-versus-$\tan^{-1} x$ plots for the 0.78→g.s. transition for spins $\frac{1}{2}$–$\frac{9}{2}$ for the 0.78-MeV level. (b) Experimental angular correlation for this transition and, for spins consistent with $l=3$, the theoretical fits at the minimum values of χ^2 found above.

of higher-energy γ rays. This was done using γ-ray shape curves measured in the experimental configuration with sources yielding γ rays of known energy. For strong low-energy transitions, an exponential background was assumed. The resolution of the crystals varied somewhat and, in general, the experimental errors chosen were about double the statistical errors in order to compensate for the problems arising in the analysis due to this variation.

In addition to the spins and multipole mixing ratios, the present work has yielded information concerning the decay schemes of excited states of ^{57}Ni. The estimates made here for branching ratios used photopeak efficiencies measured in the experimental configuration for the low-energy γ rays and values for higher-energy γ rays obtained by interpolating between tabulated values for 7.6×7.6- and 12.7×10.2-cm crystals.[16]

IV. RESULTS

During the course of the analysis it was considered desirable to remeasure the excitation energies of the levels of ^{57}Ni populated in the (^{3}He, α) reaction. This was done using a surface barrier detector depleted to a depth of 500 μ and placed at an angle of 45° with respect to the beam. This yielded the energy levels shown in Table I. The errors in these energy levels are 20 keV. The agreement with other work, particularly that of Sherr *et al.*[8] is excellent. One new level at 3.37 MeV, which is also seen in the (α-γ) coincidence data, is

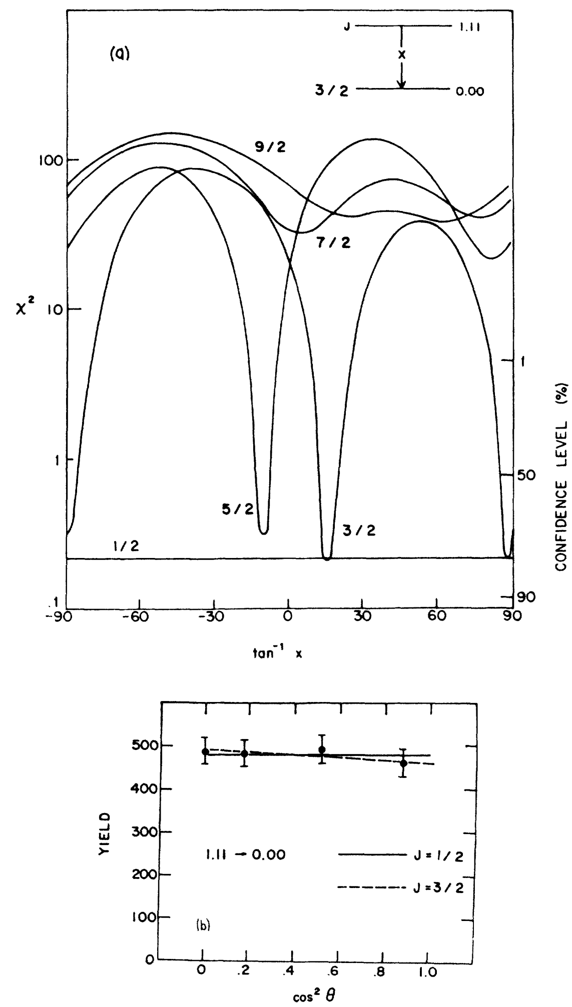


FIG. 2. (a) χ^2 plots for the 1.11→g.s. transition. (b) Experimental correlation and theoretical fits consistent with $l=1$ for the 1.11-MeV level.

[16] L. Jarczyk, H. Knoepfel, J. Lang, R. Müller, and W. Wölfi, Nucl. Instr. Methods 17, 310 (1962).

reported. Also shown are the l values known from other work,[2–8] some of which were utilized in making the present spin assignments.

A. 0.78-MeV Level

The χ^2 plots for this level together with the predicted correlations which are consistent with the known $l=3$ assignment[2] are shown in Fig. 1. (These χ^2 values are normalized. The number of degrees of freedom n equals 3 for the $j=\frac{1}{2}$ fit and 2 for all others.) Although the predicted correlations for $j=\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ are similar, the l value uniquely determines the spin to be $\frac{5}{2}$. This is consistent with the interpretation of this state as the $1f_{5/2}$ single-particle level.[1] The mixing ratio $x=-0.23\pm 0.02$ corresponds to 95% $M1$.

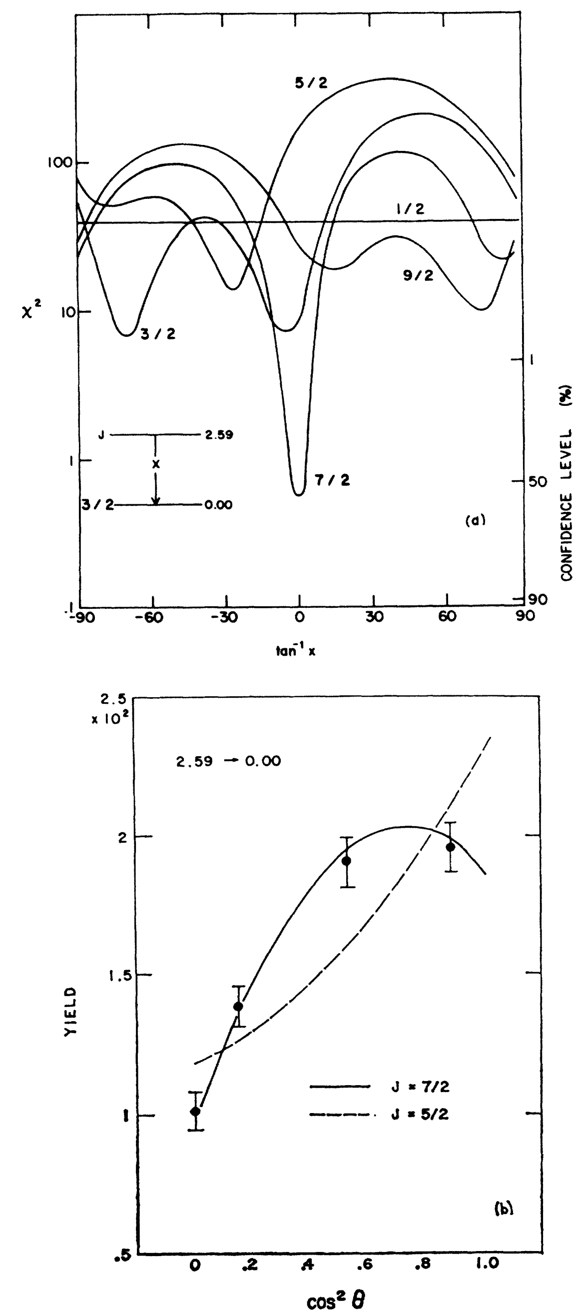


FIG. 3. (a) χ^2 plots for the 2.59→g.s. transition. (b) Experimental correlation and theoretical fits consistent with $l=3$ for the 2.59-MeV level.

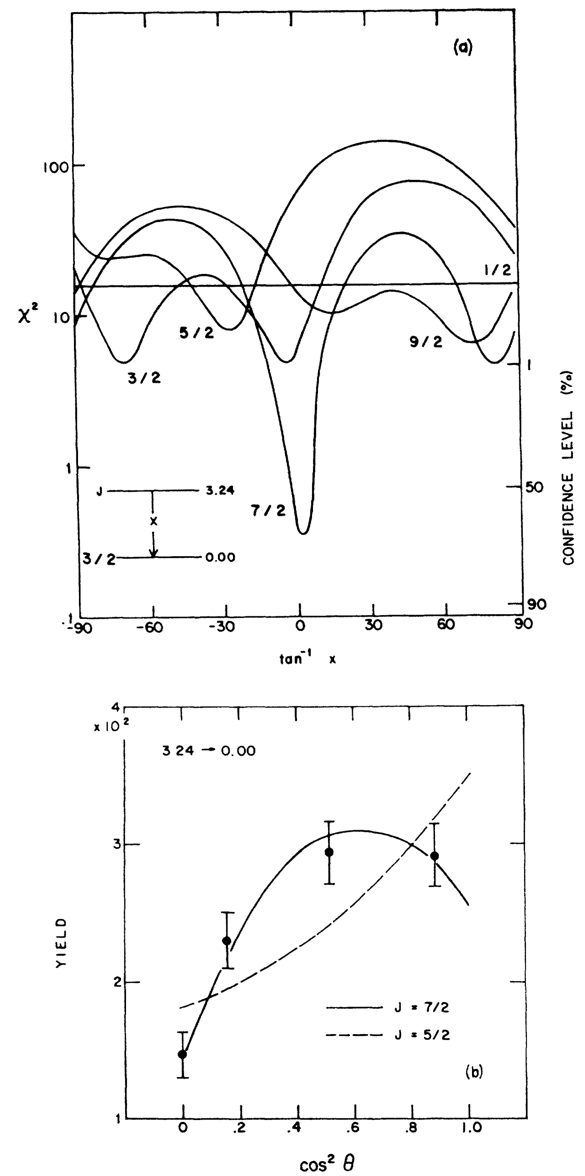


FIG. 4. (a) χ^2 plots for the 3.24→g.s. transition. (b) Experimental correlation and theoretical fits consistent with $l=3$ for the 3.24-MeV level.

B. 1.11-MeV Level

This level is only weakly excited by the (^{3}He, α) reaction but has been assigned[2] $l=1$. The normalized χ^2

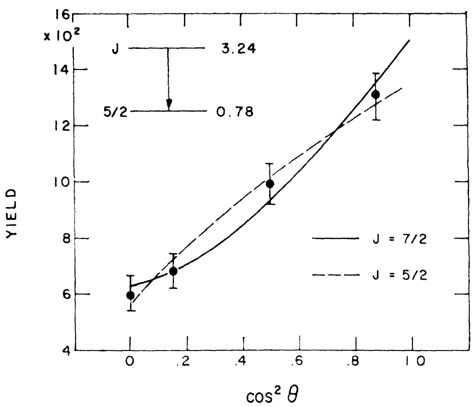


FIG. 5. Experimental correlation and theoretical fits for the 3.24→0.78 transition for spins $\frac{5}{2}$ and $\frac{7}{2}$ for the 3.24-MeV state.

plots and angular correlations consistent with this known l value are shown in Fig. 2. The present experiment does not distinguish between $j=\frac{1}{2}$ and $j=\frac{3}{2}$. The level has been interpreted as the $2p_{1/2}$ single-particle state[1] and, having spin $\frac{1}{2}$, is therefore expected to decay isotropically; our data are consistent with this interpretation. No mixing ratio can be assigned in this case. No branch to the 0.78-MeV state was observed.

C. 2.59-MeV Level

This state is strongly excited in the (^{3}He, α) reaction; the χ^2 plots and the two angular correlations consistent with the known $l=3$ assignment[2] are shown in Fig. 3. The spin is clearly $\frac{7}{2}$ with a mixing ratio $x=-0.02\pm0.03$, corresponding to $\approx100\%$ $E2$. The level is believed to be a $1f_{7/2}$ single-hole state.[1] No branches to either the 0.78- or 1.11-MeV states were observed.

D. 3.24-MeV Level

This state is known[2] to be $l=3$ and is rather weakly excited in the (^{3}He, α) reaction. The level decays 40% to the ground state and 60% to the 0.78-MeV state. The angular correlation of the ground-state transition favors the $j=\frac{7}{2}$ assignment as can be seen from Fig. 4, which shows the χ^2 plots and correlations consistent with the known l value.

To investigate this point further, the 3.24-MeV γ-ray spectrum was subtracted from under the 2.46-MeV γ-ray branch to obtain the number of counts in the 2.46-MeV γ-ray photopeak. The number of counts in the 0.78-MeV γ-ray photopeak was obtained by subtracting an exponential background. The three experimental distributions were then fitted by varying the mixing ratios of the 3.24- and 2.46-MeV γ rays simultaneously while keeping that of the 0.78-MeV γ ray fixed at the value of -0.23 deduced in the analysis of the correlation of the 0.78-MeV state populated directly. The predicted correlations for $j=\frac{5}{2}$, $\frac{7}{2}$ for the branch 3.24→0.78 are very similar (Fig. 5) and are identical for the subsequent 0.78→g.s. transition. The over-all χ^2 value for the best fit for $j=\frac{7}{2}$ is 0.32. This is a factor of 8 better than the χ^2 value of 2.4 for the best fit for $j=\frac{5}{2}$ and thus reinforces the $j=\frac{7}{2}$ assignment for the spin of the 3.24-MeV level. The mixing ratio for the g.s. transition is then $x=0.02\pm0.05$, i.e., $\approx100\%$ $E2$, while that for the branch to the 0.78-MeV level is $x=-0.58\pm0.08$ indicating 75% $M1$, 25% $E2$.

E. 3.37-, 3.71-, 3.85-, 4.23-, 4.56-MeV Levels

These levels were too weakly excited in the present study to allow their spins to be determined. The correlations for the stronger transitions did rule out some spins in certain cases and these are mentioned below. Branching ratios were estimated for the decay modes which could be identified.

No g.s. transition was observed from the 3.37-MeV level. The two γ rays present in the coincidence spectrum are of energies 0.78 and 2.59 MeV and thus a decay to the 0.78-MeV state cannot be distinguished from a decay to the 2.59-MeV state.

For the 3.71-MeV state the two strongest γ rays present are of energies around 2.59 and 1.12 MeV. This indicates a possible transition 3.71→2.59→g.s. but, in the present work is energetically indistinguishable from the decay 3.71→1.11→g.s. The angular distributions are anisotropic for both γ rays and rule out an assignment of $j=\frac{1}{2}$ for the 3.71-MeV state independent of the decay mode. Also, no acceptable fits for any spin of the 3.71-MeV state could be found if the decay was assumed to be solely through the 1.11-MeV state. However, we cannot distinguish a mixture of both decay modes from that of a branch solely through the 2.59-MeV state and therefore do not assign branching ratios separately to these decays. Either the transition to the 2.59-MeV level or a mixture of transitions to both levels takes 70% of the decay strength. There is also a 25% branch through the 0.78-MeV state and a weak branch of $\leq5\%$ to the ground state.

The 3.85-MeV level decays primarily to the ground state. The angular correlation for this γ ray is shown in

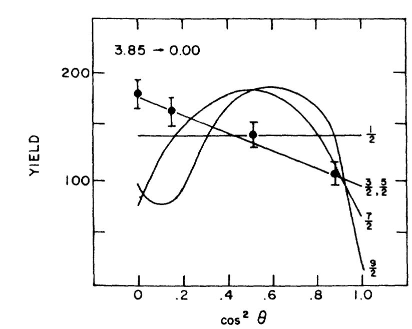


FIG. 6. Experimental correlation and theoretical fits for the 3.85→g.s. transition for spins $\frac{1}{2}$–$\frac{9}{2}$ for the 3.85-MeV state.

Fig. 6. Acceptable fits were found only for $j=\frac{3}{2}$ and $\frac{5}{2}$, both with normalized χ^2 values of 0.15. The χ^2 values for the best fits for $j=\frac{1}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ were 8, 40, and 51, respectively. For $j=\frac{3}{2}$, the mixing ratio is either $x=0.58\pm0.08$ or $x=3.6\pm0.9$. For $j=\frac{5}{2}$, the mixing ratio is -0.01 ± 0.03. The level was assigned $l=3$ in Ref. 4, but the 3.71- and 3.85-MeV states were not resolved there and the $j=\frac{3}{2}$ assignment cannot therefore be ruled out on this basis alone. If the state has positive parity, the mixing ratios for the $j=\frac{3}{2}$ assignment both imply unreasonably large $M2$ admixtures with $E1$, whereas the $j=\frac{5}{2}$ assignment implies pure $E1$. If the state has negative parity, the competing multipolarities for either spin are $M1$, $E2$ and the mixing ratios are all physically reasonable. The level decays 70% to the ground state with weak branches to the 2.59- and 1.11-MeV states of 20 and 10%, respectively.

The 4.23-MeV state decays both to the 2.59- and 0.78-MeV states. The angular correlations for these decays ruled out spins $\frac{1}{2}$ and $\frac{9}{2}$ but did not distinguish between spins $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. The last two spins are consistent with the tentative $l=3$ assignment[3] for this level. The level branches 65% to the 0.78-MeV level and 35% to the 2.59-MeV level. There is also a very weak g.s. transition, but this is estimated to be $\leq 2\%$.

The 4.56-MeV level decays primarily to the ground state but the angular correlation for this transition ruled out only $j=\frac{9}{2}$. The state is estimated to branch 65% to the ground state and 35% to the 0.78-MeV state.

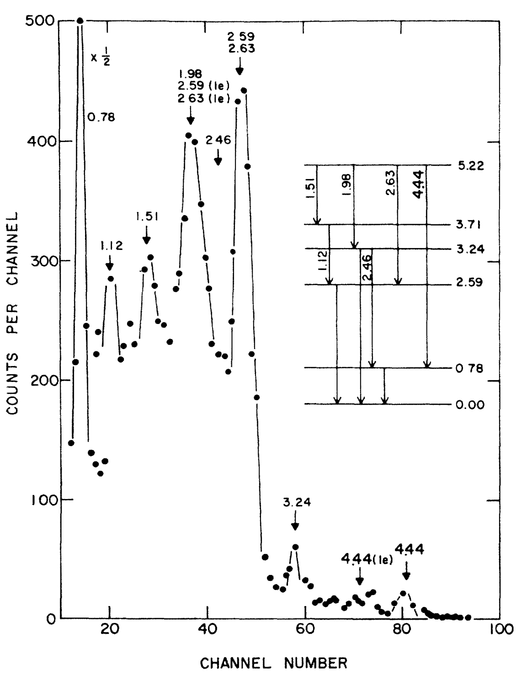


FIG. 7. The γ-ray spectrum obtained at 136° in coincidence with α particles leading to the 5.22-MeV state.

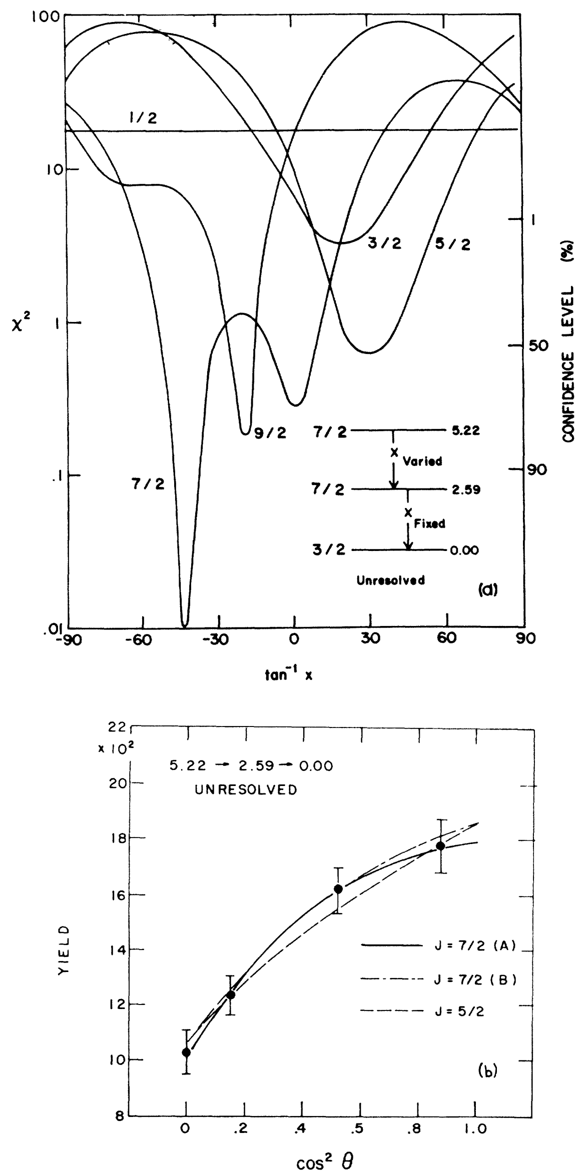


FIG. 8. (a) χ^2 plots in the analysis of the sum of the two unresolved γ rays in the cascade 5.22→2.59→g.s. (b) Experimental correlation and theoretical fits for this sum consistent with $l=3$ for the 5.22-MeV level.

F. 5.22-MeV Level

This level is strongly excited by the (^{3}He, α) reaction and has been assigned[2] $l=3$. It has been identified as the isobaric analog of the ^{57}Co ground state[8]; its spin is, therefore, expected to be $j=\frac{7}{2}$ with an isobaric spin configuration, $|T, T_z\rangle = |\frac{3}{2}, \frac{1}{2}\rangle$. In addition, it is expected to decay to the $T_<$ state with the same spin but isobaric spin configuration $|\frac{1}{2}, \frac{1}{2}\rangle$, via an $M1$ transition.[17] There will, in general, be more than one

[17] S. Maripuu, Nucl. Phys. **A123**, 357 (1969).

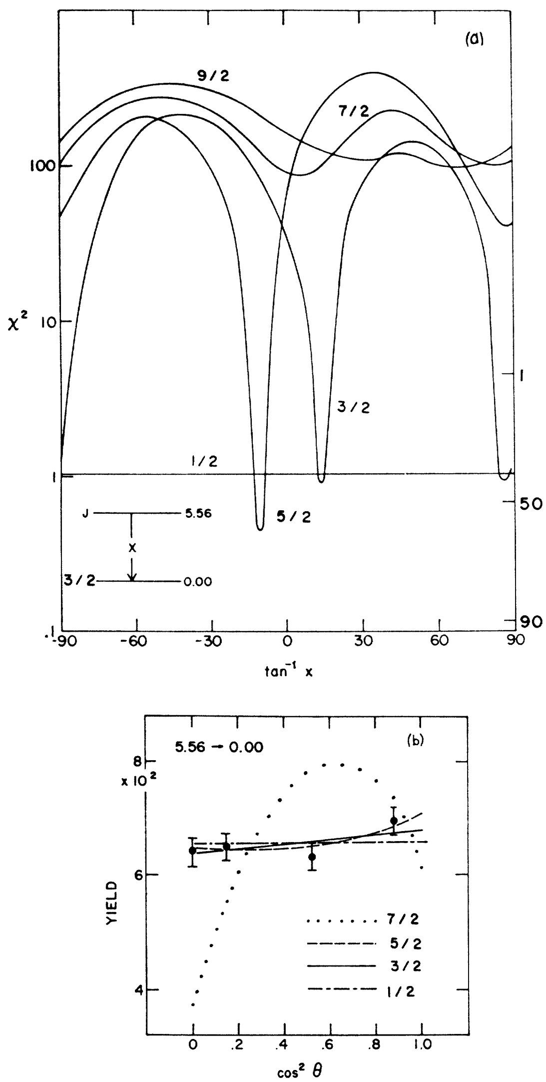


FIG. 9. (a) χ^2 plots for the 5.56→g.s. transition. (b) Experimental correlation and theoretical fits for spins $\frac{1}{2}$–$\frac{7}{2}$ for the 5.56-MeV level.

such $T_<$ state; in ^{57}Ni, this would correspond to a fragmentation of the $f_{7/2}$ neutron pickup strength.

The coincidence γ-ray spectrum is shown in Fig. 7 but is somewhat difficult to interpret. The strongest decay is through the 2.59-MeV state with γ rays of energies 2.63 and 2.59 MeV. These are not resolved but can be analyzed together. The χ^2 distributions and best fits consistent with $l=3$ are shown in Fig. 8. The spins $\frac{5}{2}$ and $\frac{7}{2}$ are not really distinguished although one of the two $\frac{7}{2}$ fits is deceptively good. The $j=\frac{7}{2}$ assignment is supported by the existence of the strong branch through the 2.59-MeV state, since this latter state is identified as the strongest $T_<$ state arising from $f_{7/2}$ neutron pickup. For $j=\frac{7}{2}$, the two possible mixing ratios for the 5.22→2.59 γ ray are $x(A)=-0.95_{-0.26}^{+0.20}$ corresponding to 55% $M1$, 45% $E2$ or $x(B)=0.02\pm0.16$ corresponding to ~100% $M1$. Fit B is consistent with the expected $M1$ nature of the transition but is not here distinguished from fit A.

An identification of the other levels populated in the decay of the 5.22-MeV level should in principle locate the remainder of the $f_{7/2}$ neutron pickup strength. Sherr *et al.*[8] have argued that there should be three such levels altogether on the basis of the fact that only one isobaric analog state is excited in the (p,d) reaction. They have tentatively identified these as the 3.24- and 4.23-MeV states along with the 2.59-MeV state. This hypothesis is supported by the presence of a transition to the 3.24-MeV state, as indicated by the γ ray of energy 3.24 MeV in the spectrum. However, no decay to the 4.23-MeV state is observed. On the other hand, γ rays of energies 1.12 and 1.51 MeV indicate the presence of a weak transition to the 3.71-MeV state.

The presence of the γ ray of energy 4.44 MeV presumably indicates a transition to the 0.78-MeV state directly. Since this state has $j=\frac{5}{2}$, this would be a violation of the isobaric transition rule mentioned above. The level branches 50% to the 2.59-MeV state, 25% to the 3.24-MeV state, 15% to the 3.71-MeV state, and 10% to the 0.78-MeV state. Because of the difficulty in interpreting the spectrum these estimates must be considered only tentative.

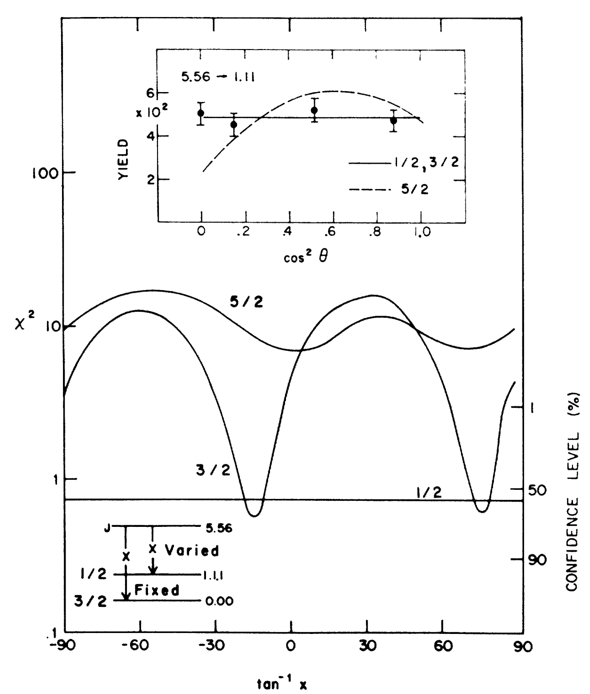


FIG. 10. χ^2 plots and correlation for a simultaneous fit of the 5.56→g.s. and 5.56→1.11 transitions. Only spins which gave acceptable fits to the g.s. transition are considered. Additional evidence for the spin of this state is discussed in the text.

G. 5.56-MeV Level

This level is quite strongly excited in the (^{3}He, α) reaction at 15 MeV. The coincident γ-ray spectrum exhibited a strong g.s. transition. For this γ ray, the χ^2 fits and angular distributions are shown in Fig. 9. Only spins of $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ are acceptable.

The other strong γ rays in the spectrum, at 4.45 and 1.11 MeV were from the cascade 5.56→1.11→g.s. The angular distribution of the photopeak of the 4.45-MeV γ ray was obtained by subtracting the contribution of the 5.56-MeV γ ray from the total spectrum. The shape curve used was extrapolated from the 4.43-MeV γ ray of a Po(Be) neutron source. The angular distribution was then fitted assuming a spin of $\frac{1}{2}$ for the 1.11-MeV state. The results are shown in Fig. 10 along with χ^2 plots corresponding to a simultaneous fit of the 5.56→g.s. and 5.56→1.11 transitions. In these χ^2 fits the mixing ratio of the g.s. transition is fixed at the best-fit value found above, while that of the transition to the 1.11-MeV state is varied. A spin of $\frac{5}{2}$ is ruled out and only $j=\frac{1}{2}$, $\frac{3}{2}$ are acceptable. This contradicts the $l=3$ assignment for this state from the ^{58}Ni(^{3}He, α)^{57}Ni study of Ref. 2. However, it has been noted in this reaction[2,4] that the rather structureless DWBA angular distributions for $l=2$ or 3, although very different from those for $l=0$ or 1, are not easily distinguished from each other. We conclude that $l=2$ or 3 are both possible for this state but not $l=0$ or 1. The $j=\frac{1}{2}$ assignment is therefore ruled out and the spin of this level is $\frac{3}{2}$, arising from $d_{3/2}$ neutron pickup. For this spin, two values of the mixing ratio give equal fits to the data for both the 5.56→g.s. and 5.56→1.11 transitions. For the 5.56→g.s. γ ray, these are $x=0.23\pm0.03$ or $x=\pm$(large) and for the 5.56→1.11 γ ray, $x=-0.27\pm0.06$ or $x=3.7\pm0.8$. For $l=2$ the competing multipolarities are $E1$, $M2$ and the large values of x, corresponding to mostly $M2$, can be excluded on physical grounds. However, the remaining values still imply approximately a 5% $M2$ admixture with $E1$ for both transitions.

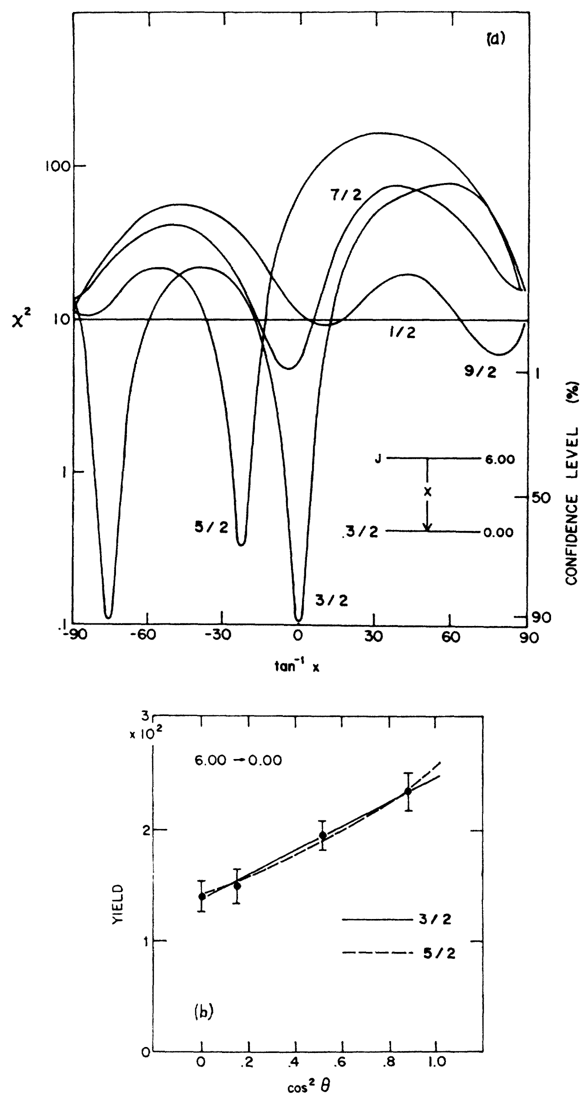


FIG. 11. (a) χ^2 plots for the 6.00→g.s. transition. (b) Experimental correlation and theoretical fits for the spins of the 6.00-MeV level which gave acceptable fits above.

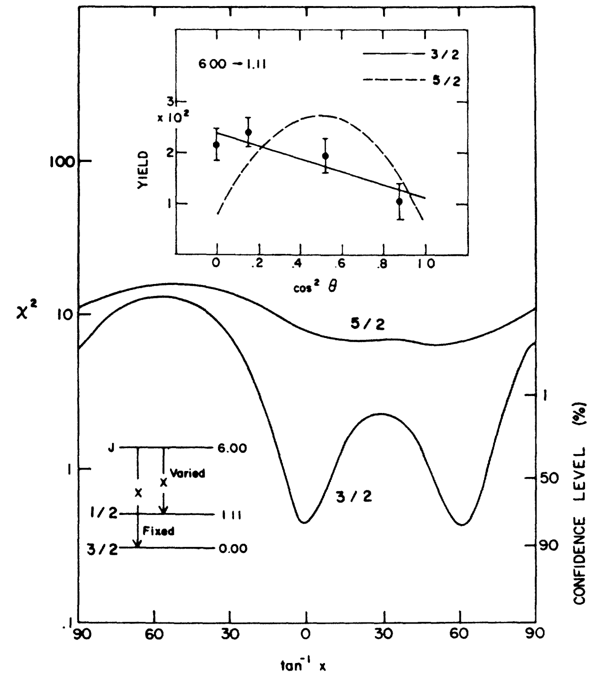


FIG. 12. χ^2 plots and correlation for a simultaneous fit of the 6.00→g.s. and 6.00→1.11 transitions. Only spins which gave acceptable fits to the g.s. transition are considered.

The other decay observed in the 5.56-MeV state γ-ray spectrum was to the 3.85-MeV state. The angular correlation for this γ ray gave acceptable fits for all values of the spin of the 3.85-MeV level except $j=\frac{1}{2}$.

TABLE II. Spins of levels in ^{57}Ni determined in the present work and mixing ratios for the various transitions studied.

Level	J^{π} [a]	Transition	Multipolarities	Mixing ratio[b]
0.78 MeV	$\frac{5}{2}^-$	0.78→g.s.	$E2, M1$	-0.23 ± 0.02
1.11	$\frac{1}{2}^-(\frac{3}{2}^-)$	1.11→g.s.	$E2, M1$	...
2.59	$\frac{7}{2}^-$	2.59→g.s.	$M3, E2$	-0.02 ± 0.03
3.24	$\frac{7}{2}^-$	3.24→g.s.	$M3, E2$	0.02 ± 0.05
		3.24→0.78	$E2, M1$	-0.58 ± 0.08
3.71	$(\geq\frac{3}{2})$			
3.85	$(\frac{3}{2})$	3.85→g.s.	$E2, M1$ or $M2, E1$	0.58 ± 0.08 or 3.6 ± 0.9
	or $(\frac{5}{2})$	3.85→g.s.	$E2, M1$ or $M2, E1$	-0.01 ± 0.03
4.23	$(\frac{3}{2}, \frac{5}{2}, \frac{7}{2})$			
4.56	$(\leq\frac{7}{2})$			
5.22	$\frac{7}{2}^-$	5.22→2.59→g.s.[c]	$E2, M1$	0.02 ± 0.16 or $-0.95^{+0.20}_{-0.26}$
5.56	$\frac{3}{2}^+$	5.56→g.s.	$M2, E1$	0.23 ± 0.03 or ($\pm$ large)
		5.56→1.11	$M2, E1$	-0.27 ± 0.06 or (3.7 ± 0.8)
6.00	$\frac{3}{2}^+$	6.00→g.s.	$M2, E1$	-0.02 ± 0.05 or (-3.6 ± 0.8)
		6.00→1.11	$M2, E1$	-0.03 ± 0.09 or (1.8 ± 0.4)

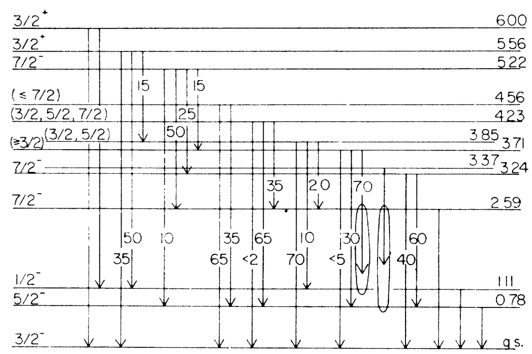
[a] Parity assignments from other work except those for the 5.56- and 6.00-MeV states.
[b] Phase convention of Rose and Brink (Ref. 14). Errors in mixing ratios are calculated by the angular correlation program in accordance with the iterative procedure discussed by P. B. Smith [Can. J. Phys. **42**, 1101 (1964)].
[c] Unresolved. Mixing ratio refers to upper member of cascade.

The 5.56-MeV level is estimated to branch 50% to the 1.11-MeV state, 35% to the ground state and 15% to the 3.85-MeV state.

H. 6.00-MeV Level

This level is weakly excited in the (^{3}He, α) reaction and l values of 2 and 3 were not distinguished in the work of Ref. 2. The coincident γ-ray spectrum resembled closely that of the 5.56-MeV level with strong decays to the ground state and 1.11-MeV state. The χ^2 plots for the g.s. transition are shown in Fig. 11 along with angular distributions for $j=\frac{3}{2}, \frac{5}{2}$, which were the only acceptable fits. The angular distribution of the 4.89-MeV γ ray in the cascade 6.00→1.11→g.s. was obtained by subtracting the contribution of the 6.00-MeV γ ray in the way described in the 5.56-MeV state analysis. The angular distributions for $j=\frac{3}{2}$ and $\frac{5}{2}$ are shown in Fig. 12, along with the two χ^2 plots corresponding to a simultaneous fit of the 6.00→g.s. and 6.00→1.11 transitions. The mixing ratios for the 6.00→g.s. γ ray are fixed in this fit at the values found above while that of the 6.00→1.11 γ ray is varied. The only acceptable fit is for $j=\frac{3}{2}$. Together with the $l=2$ or 3 assignment, this implies that the state is also excited by $d_{3/2}$ neutron pickup. Two mixing ratios are allowed by the data for each transition. For the 6.00→g.s. γ ray these are $x=-0.02\pm0.05$ or $x=-3.6\pm0.8$ and for the 6.00→1.11 γ ray, $x=-0.03\pm0.09$ or $x=1.8\pm0.4$. The competing multipolarities are $E1$, $M2$ and the large values of x, implying mostly $M2$, can again be excluded on physical grounds. The remaining values are consistent with 100% $E1$ for both transitions.

There were indications of γ rays of energies around



^{57}Ni

FIG. 13. Decay scheme, branching ratios, and spins of levels in ^{57}Ni investigated in the present work. The errors in the branching ratios are ±10% for the stronger transitions and ±5% for the weaker transitions (i.e., those with tranching ratios≤20%). As discussed in the text, no branching ratios are assigned to the decays of the 6.00-MeV level. The circles on the decays from the 3.37- and 3.71-MeV levels indicate uncertainties in the identification of the transitions, also as discussed in the text.

3.00, 2.50, and 0.78 MeV in the coincidence spectrum, but the transitions could not be unambiguously identified. However, the two strongest decays were those to the ground state and the 1.11-MeV state; these were of about equal strength.

V. SUMMARY

The spins determined in the present work, together with the mixing ratios for various decays, are shown in Table II. The parity assignments indicated there are from other work except those of the 5.56- and 6.00-MeV levels. As discussed in the text, we have assigned these states positive parity on the basis of our spin measurements and available data in the literature. Some of the parity assignments were used in determining the spins found here; however, for the 2.59-, 3.24-, and 6.00-MeV states, the spins were uniquely determined by the angular correlations. Apart from the 3.85- and 6.00-MeV states, both of which had been assigned $\frac{7}{2}$, there are no disagreements with spin assignments made on the basis of the j dependence of angular distributions in direct reactions.[5,9,10] Our data are consistent with the $\frac{7}{2}^-$ assignments of Ref. 9 for the weak states at 3.71, 4.23, and 4.56 MeV. The decay scheme and estimates for the branching ratios are shown in Fig. 13.

The spins measured for the 0.78- and 2.59-MeV levels are in agreement with the shell-model interpretation of these states as the $f_{5/2}$ single-particle state and $f_{7/2}$ single-hole state. Our measurement for the spin of the 1.11-MeV state did not distinguish $j=\frac{1}{2}, \frac{3}{2}$, but is consistent with the interpretation of this state as the $p_{1/2}$ single-particle level. However, the predominant $M1$ decay mode of the 0.78→g.s. transition indicates the configurations may not be completely pure. The transition is $1f_{5/2}\rightarrow 2p_{3/2}$ and, therefore, violates the $\Delta l=0$ rule for $M1$ transitions.[18] In view of recent calculations[19,20] of effective charges in the f-p shell which indicate the $E2$ transition rate for a single neutron should hardly be retarded, one would then expect appreciable $M1$, $E2$ mixing for this decay. Similar Δl forbidden transitions have been observed among the low-lying levels of the copper isotopes[21] and have been qualitatively explained on the basis of the weak coupling model.[22] This might suggest that the states of ^{57}Ni could be considered as arising from a coupling of the neutron single-particle levels to excited states of ^{56}Ni. The degree of impurity may be very small, of course, since electromagnetic transition rates are known to be sensitive to small admixtures of other configurations.[1]

The decay scheme of the 5.22-MeV state implies the $1f_{7/2}$ single-hole strength is shared primarily between the 2.59- and 3.24-MeV states. The transition to the 3.71-MeV state suggests a possible $j=\frac{7}{2}$ assignment for this level.

The location and decay of the two $d_{3/2}$ states at 5.56 and 6.00 MeV is of interest. We have calculated the spectroscopic factors for these $l=2$ states utilizing the values for $l=3$ given in Ref. 2. These were calculated from their 15-MeV incident beam energy data under the assumption that the binding energy of the picked up neutron was equal to its separation energy. These values were multiplied by the ratio of the theoretical total cross sections for $l=2$ and 3 calculated from the DWBA code JULIE[23] using the parameters of Ref. 2. This yielded spectroscopic factors of 1.2 for the 5.56-MeV and 0.8 for the 6.00-MeV state, giving a sum of 2.0. Assuming both states are $T=\frac{1}{2}$, i.e., are $T_<$ states; the theoretical sum for the spectroscopic factors[8] is expected to be 2.7. This suggests that some of the $T=\frac{1}{2}$ $d_{3/2}$ neutron pickup strength is still missing although most lies in these two states.

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