Study of Low-Lying States in ^{46}Ti, ^{48}Ti, and ^{54}Fe†

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Several excited states in the nuclei ^{46}Ti, ^{48}Ti, and ^{54}Fe were studied by means of triple angular-correlation measurements. The excited states were produced by proton inelastic scattering, and γ-γ angular correlations were measured on the cascade from the state being studied, through the first excited state. The 2.01-, 2.61-, and 2.96-MeV states in ^{46}Ti were studied at a proton bombarding energy of 5.00 MeV. The experimental results for the 2.01-MeV state were consistent with a previous $J=4$ assignment. The results yielded a $J=0$ assignment to the 2.61-MeV state. The results for the 2.96-MeV state indicate either $J=2$ or $J=3$, with $J=2$ strongly favored. The mixing ratio for the transition from the 2.96-MeV state to the 0.89-MeV state is $\delta=(-1.07\pm0.15)$ for $J=2$, or $\delta=(+0.26\pm0.05)$ for $J=3$. The 3.00-MeV state in ^{48}Ti was studied at a bombarding energy of 4.75-MeV. The experimental results yielded a $J=0$ assignment to the 3.00-MeV state. The 2.56-MeV state in ^{54}Fe was studied at a bombarding energy of 5.15 MeV. The results yielded a spin assignment of $J=0$ to the 2.56-MeV state.

I. INTRODUCTION

In recent years there has been considerable theoretical interest in the nuclear $1f_{7/2}$ shell. A number of attempts have been made to explain the properties of nuclei in this region of the periodic table within the framework of the j-j coupling shell model. In particular McCullen, Bayman, and Zamick[1] have performed a detailed investigation of nuclei in the $1f_{7/2}$ shell, using a model based on pure $(1f_{7/2})^n$ configuration wave functions. While these workers were able to explain many of the observed properties of nuclei in the $1f_{7/2}$ shell, there were frequent and often quite serious discrepancies between the predictions of their model and the observed properties of excited states. Most noticeable was the systematic occurrence of many more low-lying excited states (less than 4 MeV excitation) than predicted by their model. Recent calculations[2–4] which include configuration mixing have yielded better agreement, but so far only a few nuclei have been considered. On the other hand a number of investigations[5–8] have been made within the framework of the collective model. Again detailed calculations are available for only a few nuclei, but the preliminary results seem quite promising.

Nuclei in the $1f_{7/2}$ shell have been the subject of a number of experimental investigations, but much spectroscopic information is still needed. Of prime importance are the positions and properties of low-lying excited states. Quite recently a number of even-even nuclei in the $1f_{7/2}$ shell were found to possess low-lying spin-0 states. It is now clear that spin-0 excited states are a systematic feature of nuclei in this region and, as will be discussed in more detail later, ten of the eleven stable even-even nuclei in the $1f_{7/2}$ shell definitely possess such states. The identification of low-lying spin-0 excited states in the $1f_{7/2}$ shell is of some interest since these states cannot be described by the pure-configuration shell model.

The present work[9] was undertaken in order to identify low-lying spin-0 states in ^{46}Ti, ^{48}Ti, and ^{54}Fe, using angular-correlation measurements. The experimental method was that of γ-γ angular correlation measurements on a cascade from an excited state produced by a nuclear reaction. Proton inelastic scattering was used in these experiments to produce the state being studied, with the outgoing proton beam unobserved. The excited state produced in this way is, in general, aligned with respect to the incident beam direction. In order to interpret an angular correlation from an aligned state, it is necessary to know the relative populations of the magnetic substates (which will be called population parameters in the following). The values of the population parameters can, in principle, be calculated, but this would require a detailed knowledge of the nuclear reaction used to produce the aligned state. Such information is often unavailable and, in addition, this approach would also make the results of the experiment dependent upon the validity of a particular reaction model. The method used in the present work was to treat the population parameters as unknowns, to be determined during the analysis of the correlation measurements. The methods of analysis used in this work will be described in the next section. The procedure of treating the population parameters as unknowns in the analysis was first suggested by Warburton and Rose,[10] and this method is described in some detail by Lither-

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[1] J. D. McCullen, F. B. Bayman, and L. Zamick, Phys. Rev. **134**, B515 (1964).
[2] B. J. Raz and M. Soga, Phys. Rev. Letters **15**, 924 (1965).
[3] T. Engeland and E. Osnes, Phys. Letters **20**, 424 (1966).
[4] P. Federman and I. Talmi, Phys. Letters **22**, 469 (1966).
[5] R. D. Lawson, Phys. Rev. **124**, 1500 (1961).
[6] R. D. Lawson and B. Zeidman, Phys. Rev. **128**, 821 (1962).
[7] G. F. Bertsch, Nucl. Phys. **79**, 209 (1966).
[8] W. J. Gerace and A. M. Green (to be published).
[9] Preliminary reports on this work were presented at American Physical Society meetings: D. J. Church, R. N. Horoshko, and G. E. Mitchell, Bull. Am. Phys. Soc. **11**, 406 (1966); **12**, 110 (1967).
[10] E. K. Warburton and H. J. Rose, Phys. Rev. **109**, 1190 (1958).

land and Ferguson,[11] and Ferguson.[12] Broude and Gove[13] have given a detailed account of the application of this method.

II. METHOD OF ANALYSIS

The analysis of γ-γ angular correlations with the initial state aligned is complicated by the presence of the (unknown) population parameters. This type of correlation is often called a triple correlation since it is defined by three directions in space; the incident beam direction and the directions of the two γ rays. The system has azimuthal symmetry about the incident beam direction, which will define the z axis. With θ_1 and θ_2 the polar angles of the first and second γ ray in the cascade, and ϕ the relative azimuthal angle, the correlation function is given by[12]

$$W(\theta_1,\theta_2,\phi)=\sum_{KMN} A_{KM}{}^N Q_K Q_M \times \bar{P}_K{}^N(\cos\theta_1)\bar{P}_M{}^N(\cos\theta_2)\cos N\phi. \quad (1)$$

$\bar{P}_K{}^N(\cos\theta)$ is a normalized associated Legendre polynomial and Q_K and Q_M are the appropriate finite-geometry correction factors. The quantities $A_{KM}{}^N$ are functions of the unknown parameters and can be written:

$$A_{KM}{}^N=\sum_m P(m) \sum_{L_1L_1'L_2L_2'} \frac{\delta_1{}^{x_1}}{1+(\delta_1)^2}\frac{\delta_2{}^{x_2}}{1+(\delta_2)^2} C_{KM}{}^N, \quad (2)$$

where J_1, J_2, and J_3 are the spins of the initial, intermediate, and final state in the cascade, and L_1, L_1' and L_2, L_2' are the multipolarities of the first and second γ ray. The quantity $P(m)$ is the population parameter of the mth magnetic substate. The parameters δ_1 and δ_2 are the mixing ratios of the first and second γ ray, and x_1 and x_2 take on the values 0, 1, and 2, depending on the values of L_1, L_1' and L_2, L_2'. The coefficients $C_{KM}{}^N$ are the geometrical coefficients for the cascade and were tabulated by Smith[14] for a wide range of values of the arguments. The mixing-ratio phase convention used in this work is the convention defined by Litherland and Ferguson,[11] and Smith[14]; this convention for the phase agrees with the convention of Biedenharn and Rose[15] for emission matrix elements.

The method of analysis used in the present work is somewhat different from the method described in a previous report.[16] In the past the experimental data was taken in the various geometries described by Litherland and Ferguson.[11] The correlation in each geometry can be described by an expansion in Legendre polynomials. The analysis of the correlation data was performed in two stages. First, the data from each geometry was fit to an expansion in Legendre polynomials, and the normalized coefficients in the expansion were determined. The coefficients from each geometry were then used as data in the second stage of the fit, which determined the unknown parameters by means of a nonlinear least-squares fit. While this procedure did work fairly well in most cases, it is clearly objectionable to perform the analysis indirectly in two stages and, in addition, convergence difficulties were sometimes encountered. The procedure used here was to perform the fit directly to the experimental data using a method which is quite similar to a method described in detail by Smith.[17] This method avoided all of the difficulties encountered in fitting to the Legendre polynomial coefficients, and the analysis is somewhat simpler to perform.

The theoretical expression for each correlation measurement, given by Eq. (1), can be placed in a form suitable for the analysis by first summing over K, M, and N. If each measurement is labeled by the index i, the results can be written:

$$W_i=\sum_m P(m) G_{m,i}(J_1,J_2,J_3,\delta_1,\delta_2), \quad (3)$$

where

$$G_{m,i}=\sum_{L_1L_1'L_2L_2'} \frac{\delta_1{}^{x_1}}{1+(\delta_1)^2}\frac{\delta_2{}^{x_2}}{1+(\delta_2)^2} \times \sum_{KMN} C_{KM}{}^N Q_K Q_M X_{KM}{}^N(\theta_1{}^{(i)},\theta_2{}^{(i)},\phi^{(i)}). \quad (4)$$

Because the spins J_1, J_2, and J_3 are quantized parameters, the procedure followed in the analysis is to first assume a set of values for the spins, and to then perform the analysis using the continuous parameters $P(m)$, δ_1, and δ_2 as unknowns. This is repeated for all possible spin combinations and the results are compared to find the correct solution.

Equation (3) is a nonlinear function of δ_1 and δ_2. These unknowns are treated as fixed parameters in the fit and a complete search is made through the region $-\infty<\delta<+\infty$. Upon fixing δ_1 and δ_2, Eq. (3) becomes linear in the remaining unknowns, the set of $P(m)$, and these parameters can be determined by a standard linear least-squares fit. This procedure yields the approximate location of the best fit to the data, and the values of the $P(m)$, δ_1 and δ_2 so determined are then used as initial values in a nonlinear fit to find the exact location of the best fit. This method of analysis has been used for a number of triple-correlation measurements and has yielded satisfactory results in each case. The application of this method to the present work will be described in Sec. IV.

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[11] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).

[12] A. J. Ferguson, *Angular Correlation Methods In Gamma-Ray Spectroscopy* (John Wiley & Sons, Inc., New York, 1965).

[13] C. Broude and H. E. Gove, Ann. Phys. (N. Y.) **23**, 71 (1963).

[14] P. B. Smith, in *Nuclear Reactions*, edited by P. M. Endt and P. B. Smith (North-Holland Publishing Company, Amsterdam, 1962), Vol. II, p. 248.

[15] L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. **25**, 729 (1953).

[16] S. M. Matin, D. J. Church, and G. E. Mitchell, Phys. Rev. **150**, 906 (1966).

[17] P. B. Smith, Can J. Phys. 42, 1101 (1964).

III. EXPERIMENTAL APPARATUS AND PROCEDURES

Since the experimental arrangements used in this work were described elsewhere,[16] they will not be discussed here in detail. Triple correlation measurements were made on the nuclei ^{46}Ti, ^{48}Ti, and ^{54}Fe. The states of interest were produced by proton inelastic scattering, with the outgoing beam unobserved. The proton beam was obtained from the Columbia University Van de Graaff accelerator. The γ-ray detectors were 3-in.$\times$3-in. NaI(Tl) crystals. The coincidence measurements were made using a standard fast-slow coincidence circuit. The data were recorded by observing the total coincidence spectra (true plus chance) and the chance spectra in the two halves of a 512-channel pulse-height analyzer. One of the detectors was fixed throughout the experiment at 90° to the incident proton beam. The other detector moved over the edges of the octant defined by $0°\leq\theta\leq90°$ and $90°\leq\phi\leq180°$. This geometrical arrangement has been described in some detail by Broude and Gove.[13]

The targets used in these experiments were relatively thick (about 150–250 keV thick to 5.0-MeV protons). The targets were backed by either 0.010-in. Au or 0.020-in. Ta foils. This was sufficient to stop the incident beam, but did not significantly attenuate the γ rays.

Both of the Ti targets were foils prepared by Oak Ridge National Laboratory. These targets were backed by 0.010-in. Au foils. The enriched ^{46}Ti foil (77.1% ^{46}Ti) was 3.0 mg/cm^2 thick. The ^{48}Ti foil (99.4% ^{48}Ti) was 3.9-mg/cm^2 thick. The ^{54}Fe target was prepared by placing approximately 4.0 mg of enriched Fe_2O_3 (97.4% ^{54}Fe) on a 0.020-in. thick Ta foil containing a circular indentation 1-cm in diameter. The Fe_2O_3 was heated beyond its melting point and upon cooling an adhesive deposit of Fe_2O_3 was formed on the backing. This target contained about 3.5 mg/cm^2 of ^{54}Fe.

IV. EXPERIMENTAL RESULTS

A. General Remarks

All of the nuclei studied in these experiments were even-even nuclei with ground-state spin 0 and first excited state spin 2. Triple correlation measurements were made between γ-ray transitions from an excited state to the first excited state, and transitions from first to ground. All of the cascades studied were therefore of the form J-2-0, and the unknowns in the analysis were the spin J of the initial state, the population parameters $P(m)$ of the initial state, and the mixing ratio of the first gamma ray in the cascade. In analyzing the data, spin values 0 through 4 were considered for the initial state. Since the incident proton energy never exceeded 5.2 MeV in these experiments, it is highly improbable that levels with spins greater than 4 would be excited with appreciable strength. In addition such levels are expected to have lifetimes for decay to the first-excited state which are longer than 20 nsec and would not be observed in coincidence measurements. Pure quadrupole radiation was used when the fits were made for spin 0 and spin 4. A dipole-quadrupole mixture was used for spins 1, 2, and 3.

The procedure followed in the analysis was described in Sec. II. A separate fit was made for each of the spins 0 through 4. For spins 0 and 4 the unknowns in the analysis were the population parameters $P(m)$, which are $(J+1)$ in number. For spins 1, 2, and 3 the unknowns were the mixing ratio δ, as well as the $P(m)$. A complete search was made through the region $-\infty<\delta<+\infty$ and a χ^2 was determined for each value of δ in this region. The final results of the analysis will be presented in a plot of the χ^2 versus the mixing ratio δ, for each of the spins 1, 2, and 3. The χ^2 values for spins 0 and 4 are also included. The χ^2 values reported here were normalized by dividing by the number of degrees of freedom in the fit, and therefore have an expectation value of one.

The value of the 1% limit is also presented. The probability of an experiment yielding a χ^2 whose value is above this limit is less than 1%. The value of the limit is a function of the number of unknowns in the fit, but because of the large number of data points in the fits ($\sim$36) the value of this limit is essentially constant over the range of the parameters considered here and a unique 1% limit is included on each plot.

B. ^{46}Ti

The 2.01-, 2.61-, and 2.96-MeV levels in ^{46}Ti were studied at an incident proton energy of 5.00 MeV. The excitation energies of the 2.61-MeV and 2.96-MeV levels were measured using a Ge(Li) detector. The direct and the coincidence γ-ray spectra measured at this energy are shown in Fig. 1. The coincidence spectrum was gated by the 0.89-MeV γ-ray transition from the first excited state to the ground state. The 0.99- and 1.43-MeV γ-ray peaks in the direct spectrum are due to transitions in ^{48}Ti, the major contaminant in the target. Low-energy γ rays were rejected in the coincidence circuit, which accounts for the low-energy cutoff in the coincidence spectrum. A similar cutoff will be present in each of the coincidence spectra shown here. It should be noted that the presence of the 0.89-MeV peak in the coincidence spectrum is due to genuine coincidence with the Compton scattered "tails" of higher-energy γ rays. The Compton tails of these transitions lie under the 0.89-MeV γ-ray peak and appear in the coincidence window.

2.01-MeV Level

This level had previously been assigned spin 4.[18] In the present work the best fit was obtained for spin 4, but spin 3 with $\delta=-0.28\pm0.05$ also gave an acceptable fit. The spin 4 assignment was not in question, however, and the present work is consistent with this assignment.

[18] *Nuclear Data Sheets*, compiled by K. Way *et al.* (National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 60-2-31.

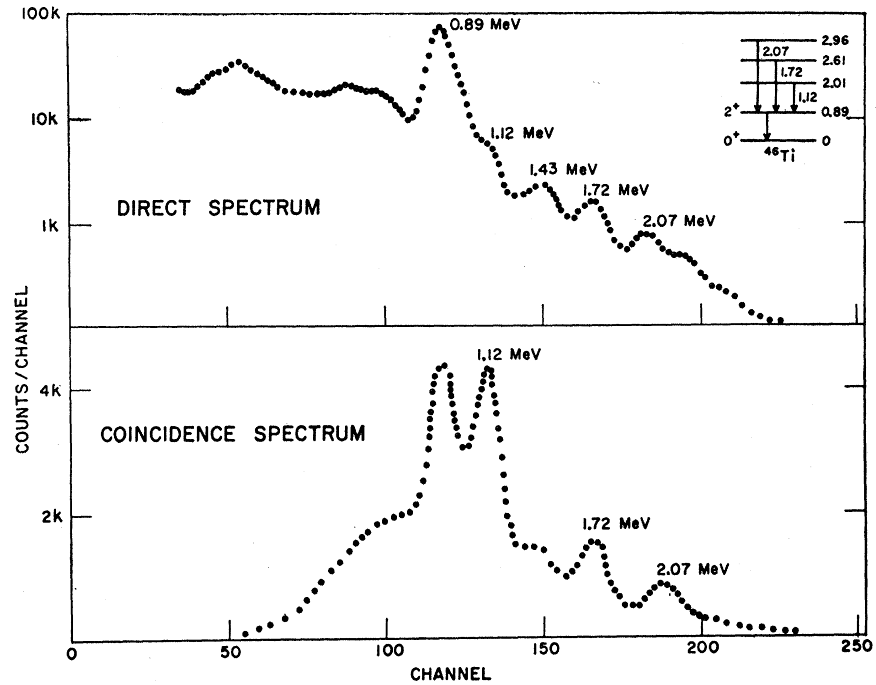

FIG. 1. Direct and coincidence γ-ray spectra from ^{46}Ti. The incident proton energy was 5.00 MeV. Note that the direct spectrum is plotted on a logarithmic scale and the coincidence spectrum on a linear scale.

2.61-MeV Level

A new level in ^{46}Ti at 2.61-MeV excitation energy was observed recently during an investigation of inelastic proton scattering from ^{46}Ti.[19] The present work confirmed the existence of this level, and the χ^2 plot shown in Fig. 2 permits a spin-0 assignment to the 2.61-MeV level. The 0-2-0 correlation pattern is very distinct and as a result spins 1 through 4 are rejected with confidence. The experimental data and the theoretical fit for a 0-2-0 spin sequence are shown in Fig. 3.

2.96-MeV Level

There were two acceptable fits for the 2.96-MeV level, obtained for spin 2 and spin 3. The χ^2 plot for this level is shown in Fig. 4. The best fit was obtained for spin 2, with a mixing ratio for the decay to the 0.89-MeV level of $\delta=-1.07\pm0.15$, but a spin-3 assignment with $\delta=+0.26\pm0.05$ cannot entirely be excluded by these data. The spin-2 assignment is strongly favored, however, on the basis of the following arguments.

The correlation measurements being reported here cannot determine the parity of the 2.96-MeV level, but it is very unlikely that this is a 3^- state due to the value of the mixing ratio obtained for the spin-3 assignment. The present work would require $\delta(M2/E1)=0.26\pm0.05$ for the transition from the 3^- state to the 2^+ state at 0.89-MeV. On the other hand a 3^+ assignment seems improbable since no low-lying 3^+ level has been observed in an even-even nucleus in this mass region. In addition the values of the population parameters obtained for the spin-2 and spin-3 fits also support the spin-2 assignment. These parameters are listed in Table I. The values of the population parameters obtained for spin 2 are quite consistent with the values obtained for a number of spin-2 levels in neighboring nuclei,[16,20,21] measured under similar conditions. These results are

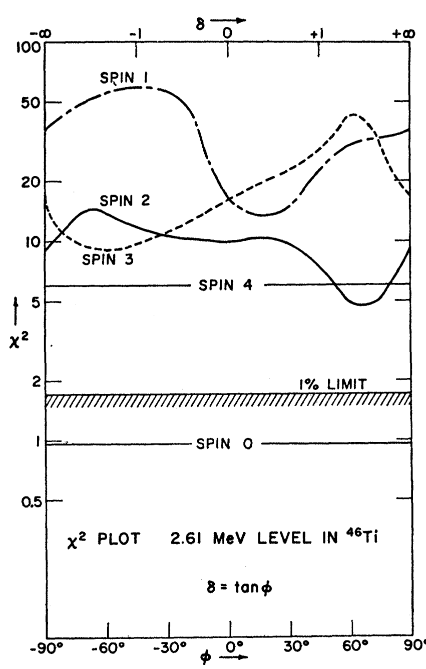

FIG. 2. The χ^2 plot for the 2.61-MeV level in ^{46}Ti.

[19] N. R. Roberson and H. O. Funsten (private communication).

[20] P. J. Twin and J. C. Willmott, Nucl. Phys. **78**, 177 (1966).

[21] G. Kaye and J. C. Willmott, Nucl. Phys. **71**, 561 (1965).

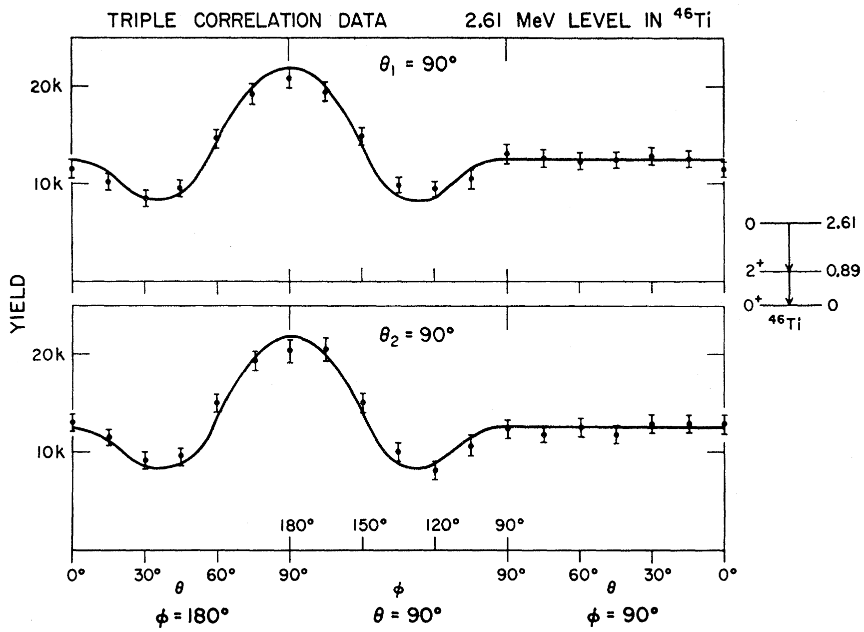

FIG. 3. Triple correlation data for the 2.61-MeV level in ^{46}Ti. The solid line is the theoretical fit obtained for a 0-2-0 cascade.

also in good agreement with the predictions of the statistical model,[22] which should provide a qualitative description of the production of these levels under the conditions of the present experiment. The population parameters obtained for spin 3 are not consistent with the statistical model, and are rather anomalous in character. The best fit was obtained with $P(0)$ and $P(2)$ negative. These unphysical parameters were set equal to zero and the final value of χ^2 represents the fit with this constraint on $P(0)$ and $P(2)$. It is difficult to understand how such unusual values of the population parameters could result under the conditions of the present experiment, with the target about 150-keV thick and the outgoing beam unobserved. The above arguments, while not conclusive, do strongly favor a spin-2 assignment to this level. The experimental data and the theoretical fit for a spin-2 assignment are shown in Fig. 5.

TABLE I. Results obtained for the 2.96-MeV level in ^{46}Ti. Only spin 2 and spin 3 were within the 1% limit. The initial fit for spin 3 gave negative population parameters for $P(0)$ and $P(2)$. The results listed here were obtained with $P(0)$ and $P(2)$ set equal to zero.

Spin	χ^2	δ	$P(0)$	$P(1)$	$P(2)$	$P(3)$
2	1.14	-1.07 ± 0.15	0.44	0.18	0.10	...
3	1.54	$+0.26\pm0.05$	0.0	0.21	0.0	0.29

C. ^{48}Ti

A new level at 3.00-MeV excitation energy in ^{48}Ti was observed recently by Belote *et al.*[23] These workers discovered this state during an investigation of the energy levels in ^{48}Ti by means of proton inelastic scattering. The present work was undertaken in order to confirm the existence of this level, and to determine its spin. Triple correlation measurements were made at an incident proton energy of 4.75 MeV. The direct and coincidence spectra are shown in Fig. 6. The peak at 1.43 MeV in the coincidence spectrum is primarily due to transitions from the 2.42-MeV level to the first excited state, with a small admixture of 1.31-MeV radiation from the 2.30-MeV level. The 2.42-MeV level

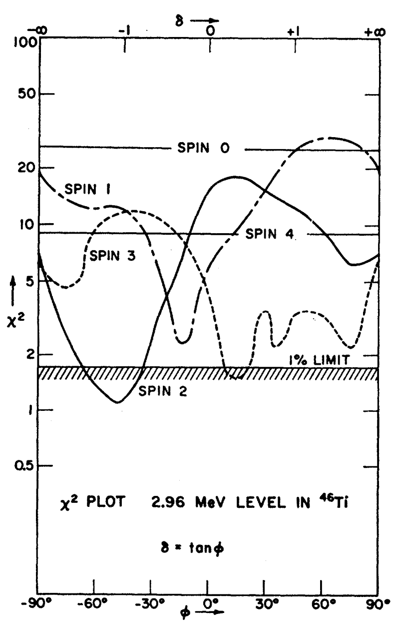

FIG. 4. The χ^2 plot for the 2.96-MeV level in ^{46}Ti.

[22] E. Sheldon and D. M. Van Patter, Rev. Mod. Phys. 38, 143 (1966).

[23] T. A. Belote, W. E. Dorenbusch, O. Hansen, and A. Sperduto, Phys. Letters 14, 323 (1965).

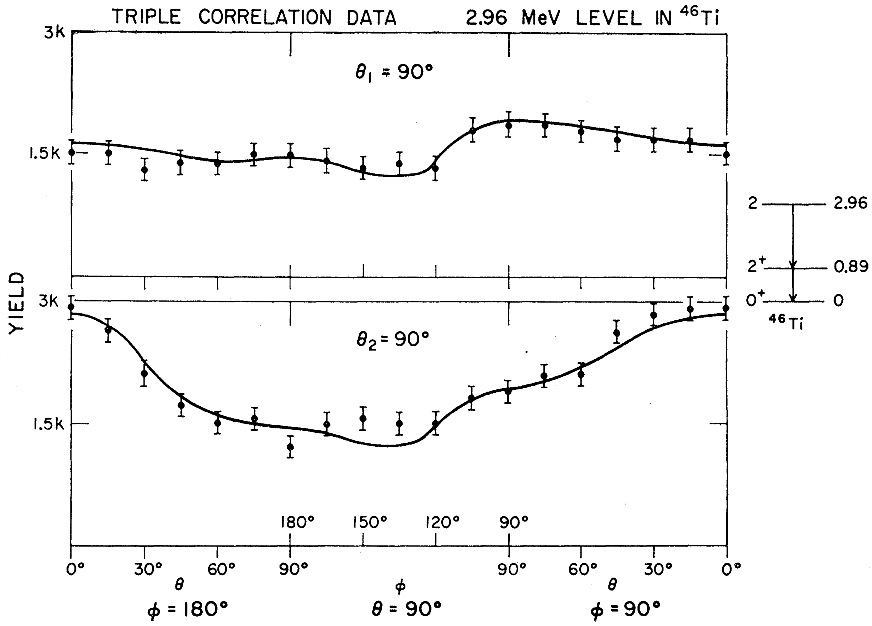

FIG. 5. Triple correlation data for the 2.96-MeV level in ^{46}Ti. The solid line is the theoretical fit obtained for a 2-2-0 cascade, with $\delta=-1.07\pm0.15$.

was previously studied in this laboratory,[16] using triple correlation techniques, and assigned spin 2. The results of the present experiment were in agreement with this assignment.

The coincidence counting rate between the 2.01- and 0.99-MeV γ rays was quite low. For this reason, the measurements were made only over one octant. This provided sufficient experimental information to make a spin-0 assignment to the 3.00-MeV level, as demonstrated by the χ^2 plot given in Fig. 7. The correlation data and the theoretical fit for a 0-2-0 sequence are shown in Fig. 8.

D. ^{54}Fe

The 2.56-MeV level in ^{54}Fe was recently assigned spin 0 by Belote *et al.*[24] This assignment was made using direct reaction theory to interpret the angular distribution of deuteron inelastic scattering from ^{54}Fe. This

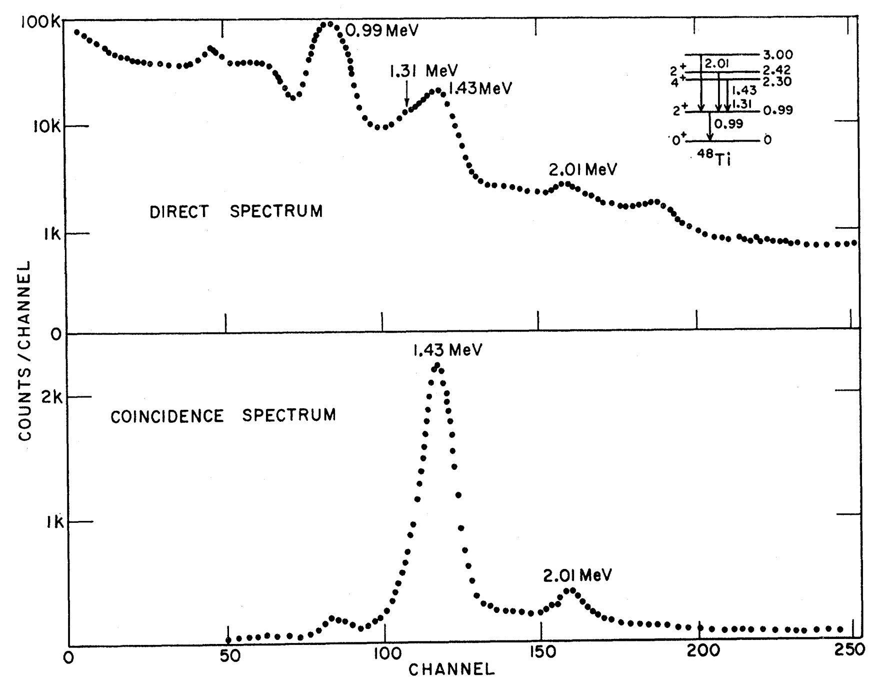

FIG. 6. Direct and coincidence γ-ray spectra from ^{48}Ti. The incident proton energy was 4.75 MeV. Note that the direct spectrum is plotted on a logarithmic scale and the coincidence spectrum on a linear scale.

[24] T. A. Belote, W. E. Dorenbusch, and O. Hansen, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove (Academic Press Inc., New York, 1966), p. 350.

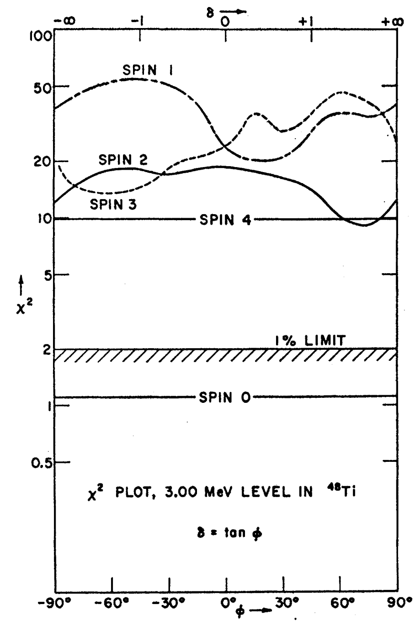

FIG. 7. The χ^2 plot for the 3.00-MeV level in ^{48}Ti.

method, while often yielding useful and reliable results, does assume a special reaction model and spin assignments based on reaction models are sometimes incorrect. It was felt, therefore, that it would be useful to verify the spin-0 assignment to the 2.56-MeV level using γ-ray angular-correlation techniques.

This level is a member of a triplet of states at 2.56-, 2.54-, and 2.53-MeV.[25] γ rays from these three levels could not be resolved using NaI(Tl) crystals. Therefore, a bombarding energy was chosen (5.15 MeV) at which the yield from the 2.53- and 2.54-MeV levels was small compared to the yield from the 2.56-MeV level. This energy was determined using a Ge(Li) detector. The relative yield from each of the three levels was measured as a function of incident proton energy. The γ-ray spectrum was recorded in 2000 channels, using a PDP-4 computer on-line. The relevant portion of the spectrum recorded at 5.15 MeV is shown in Fig. 9. The yield from the 2.56-MeV level was approximately five times the combined yield from the 2.53- and 2.54-MeV levels. In most cases this would not be a satisfactory ratio, but it was quite adequate here due to the unique nature of a 0-2-0 correlation pattern.

The direct and coincidence spectra observed at 5.15 MeV, with the NaI(Tl) crystal, are shown in Fig. 10. The poor energy resolution is primarily due to high-counting rates, and consequently the 1.41- and 1.55-MeV γ-ray peaks were not resolved. The energy window was set on the unresolved peak, which accounts for the peak in the coincidence spectrum at about 1.41 MeV.

The χ^2 plot for the 2.56-MeV level is shown in Fig. 11, and permits a spin-0 assignment to the 2.56-MeV level. The fit was surprisingly good considering the presence of the 1.12- and 1.13-MeV γ rays. This may be because of an overestimation of the actual contribution of these gamma-rays during the correlation measurements, or may be because of taking too large a correction for the background due to the 1.41- and 1.55-MeV γ rays. This background could quite easily resemble the contribution to the correlation due to the 1.12- and 1.13-MeV γ rays, and therefore taking too large a background subtraction could result in a fairly pure 0-2-0 pattern. The experimental data and the theoretical fit for a spin-0 assignment are shown in Fig. 12.

V. DISCUSSION

It is interesting to note that of the eleven stable even-even nuclei in the $1f_{7/2}$ shell, ten of these nuclei are now definitely known to possess low-lying spin-0 excited states. These nuclei are listed in Table II, along with the excitation energies of the spin-0 levels. The fact that a low-lying spin-0 excited state has not been observed in

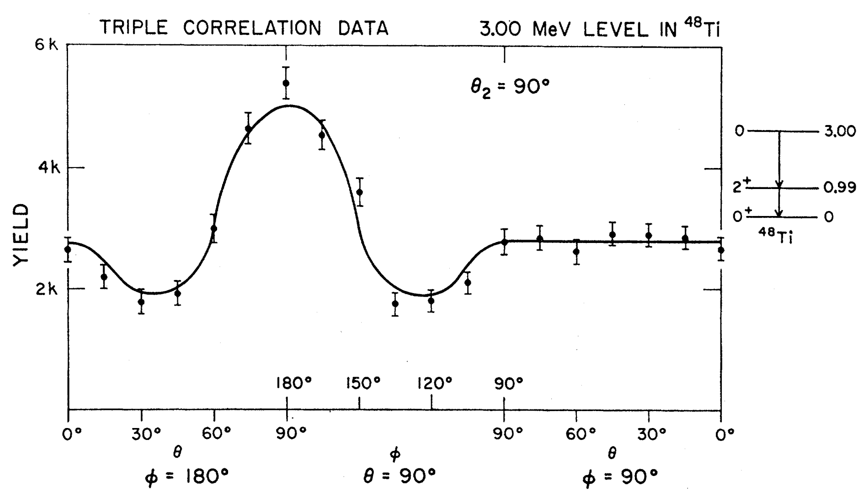

FIG. 8. Triple correlation data for the 3.00-MeV level in ^{48}Ti. The solid line is the theoretical fit obtained for a 0-2-0 cascade.

[25] A. Sperduto and W. W. Buechner, Phys. Rev. 134, B142 (1964).

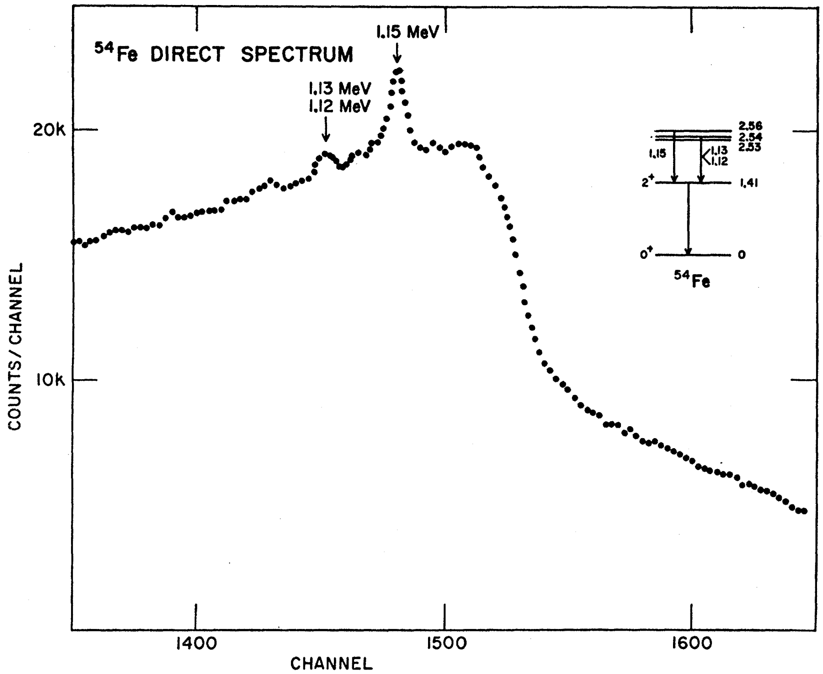

FIG. 9. γ-ray spectrum from ^{54}Fe observed using a Ge(Li) scintillation detector. Presented here is the region of the spectrum containing transitions from the 2.56-, 2.54-, and 2.53-MeV levels to the 1.41-MeV level. The incident proton energy was 5.15 MeV.

^{50}Cr is particularily interesting. Although the mechanism responsible for these levels is not completely understood, it is difficult to see why a spin-0 level is not present in ^{50}Cr. It is possible that such a level does exist in ^{50}Cr and has not yet been observed. However, this does not seem very probable since this nucleus has been studied in some detail.[20,26]

The systematic occurrence of low-lying spin-0 excited states throughout the $1f_{7/2}$ shell has not received a satisfactory theoretical explanation. While the existence of spin-0 excited states points strongly to collective forms of excitation, it is possible that these states are the result of configuration mixing and can be explained within the framework of the shell model. There have

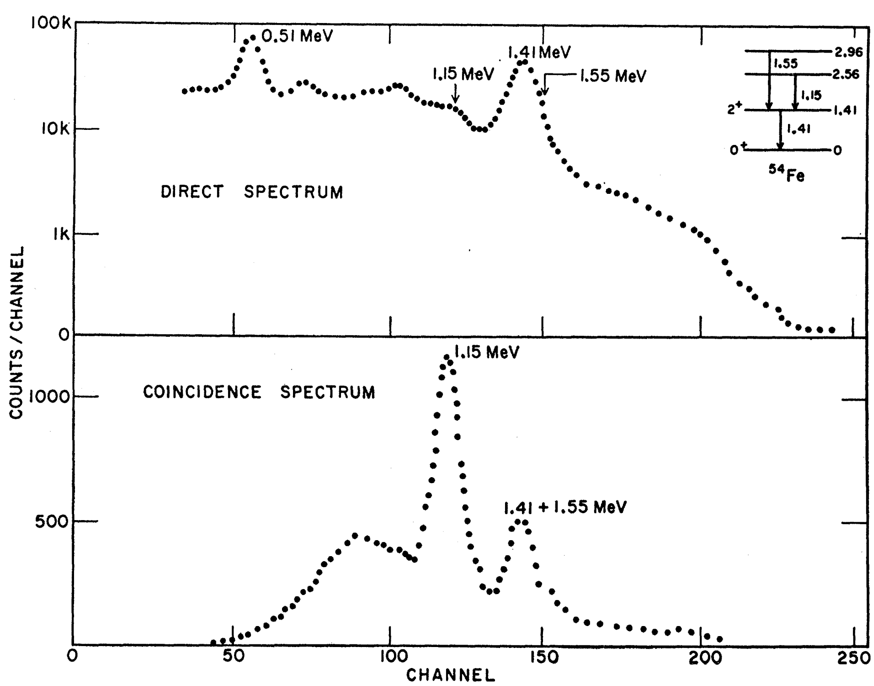

FIG. 10. Direct and coincidence γ-ray spectra from ^{54}Fe. The incident proton energy was 5.15 MeV. Note that the direct spectrum is plotted on a logarithmic scale and the coincidence spectrum on a linear scale.

[26] D. J. Church, Ph.D. thesis, Columbia University, 1967 (unpublished).

TABLE II. Low-lying spin-0 excited states observed in stable even-even nuclei in the $1f_{7/2}$ shell.

Nucleus	Excitation energy (MeV)	Reference
^{40}Ca	3.35	18
^{42}Ca	1.84	18
^{44}Ca	1.88	a
^{46}Ca	2.58	b
^{48}Ca	4.28	c
^{46}Ti	2.61	Present work
^{48}Ti	3.00	Present work
^{50}Ti	3.88	d
^{50}Cr	None observed	
^{52}Cr	2.65	21
^{54}Fe	2.56	Present work

[a] S. M. Matin, D. J. Church, R. Horoshko, and G. E. Mitchell, Phys. Letters **15**, 51 (1965).
[b] R. J. Peterson (private communication).
[c] S. Hinds, J. H. Bjerregaard, O. Hansen, and O. Nathan, Phys. Letters **21**, 328 (1966).
[d] S. Hinds and R. Middleton, Nucl. Phys. **92**, 422 (1967).

been a number of recent theoretical investigations, from both points of view, into the properties of the Ca isotopes.[2–4,7] Both approaches have been relatively successful, but the results are of a preliminary nature and these models have not yet been applied to other nuclei in the $1f_{7/2}$ shell. The only theoretical model which has been applied to all nuclei in the $1f_{7/2}$ shell is the pure-configuration shell model.[1] However, from the experimental information that has become available in the last few years it is clear that the $1f_{7/2}$-shell region of the periodic table is quite complicated and cannot be explained satisfactorily by a pure-configuration shell model.

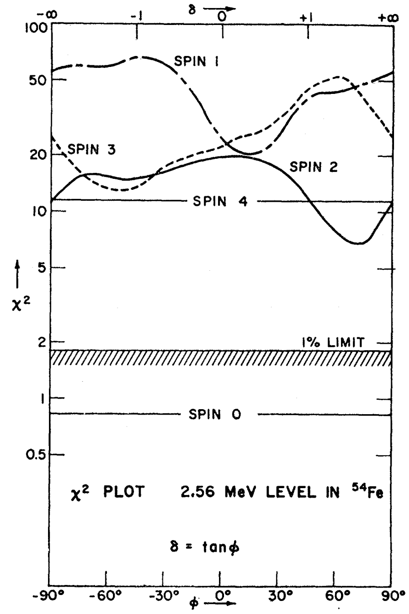

FIG. 11. The χ^2 plot for the 2.56-MeV level in ^{54}Fe.

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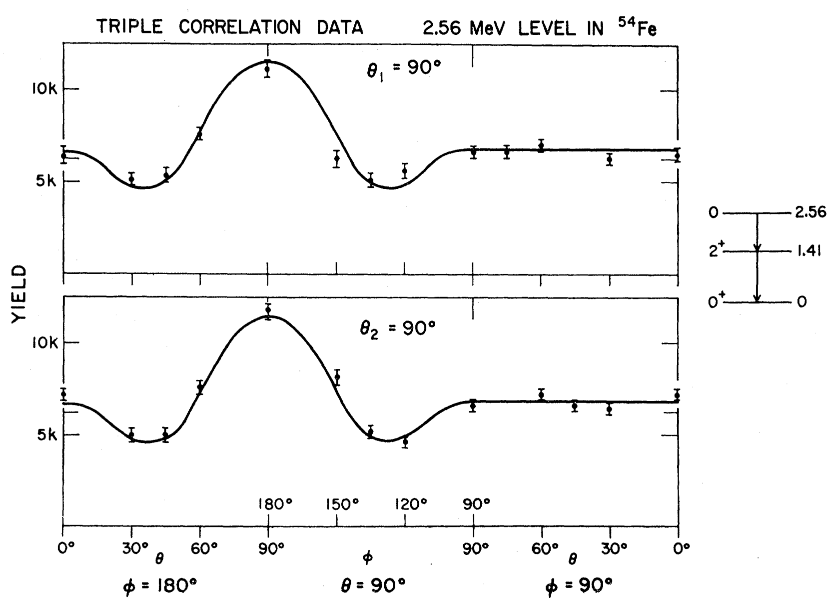

FIG. 12. Triple correlation data for the 2.56-MeV level in ^{54}Fe. The solid line is the theoretical fit obtained for a 0-2-0 cascade.