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Levels in ^{55}Mn following inelastic neutron scattering

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The gamma ray decays of many levels in ^{55}Mn have been studied following their formation in neutron inelastic scattering. Angular distributions have been measured at incident neutron energies of 2.20, 2.73, and 3.15 MeV. Branching ratios and multipole mixing ratios were determined for several transitions. The 2.199 MeV state is assigned $7/2^-$ and the 2.366 MeV state is tentatively assigned $9/2^-$.

NUCLEAR REACTIONS ^{55}Mn $(n,n'\gamma)$, $E=2.20$, 2.73, and 3.15 MeV; measured $\sigma(E_\gamma,\theta)$. ^{55}Mn deduced levels, J, σ, γ branching. Natural target.

I. INTRODUCTION

Calculations of the energy levels for the $Z=25$, $N=30$ nucleus have been made during the past decade using two approaches. The first are shell-model calculations such as those made by Schwarz[1] involving $1f_{7/2}$ protons and $2p_{3/2}$, $1f_{5/2}$ neutrons outside a ^{48}Ca core. McGrory[2] and Vervier[3] performed similar calculations using different neutron configurations. The second approach incorporates the Bohr-Mottelson strong coupling model for $1f_{7/2}$ shell nuclei as further developed by Malik and Scholz.[4] More recently Comfort *et al.*[5] have calculated properties of ^{55}Mn using a similar model, whereby a single nucleon is coupled to a statically deformed core. Although this second method has been particularly successful in predicting low-lying energy levels and level spacings, additional spin and multipole mixing ratio measurements are needed to test the validity of this model. The results of the present work add further information regarding the γ-ray decay of ^{55}Mn and provide additional data which can be compared to the two types of model calculations.

Since ^{55}Mn is 100% naturally abundant, it has been investigated in several experiments. Studies of inelastic proton scattering[6-8] have provided level energies to within a few keV. Additional information regarding level energies, spins, lifetimes, and branching ratios comes from the reactions ^{54}Cr(^{3}He,d)^{55}Mn,[9] ^{52}Cr$(\alpha,p\gamma)^{55}$Mn,[10,11,12] ^{51}V(^{7}Li,$p2n$)^{55}Mn,[13] ^{54}Cr$(p,\gamma)^{55}$Mn,[14] and ^{55}Mn$(\alpha,\alpha')^{55}$Mn.[15] The β decay of ^{55}Cr has been used to accurately determine[16] the energies of some levels and resonance fluorescence measurements[17] give estimates of partial widths involving $M1$ and $E2$ transitions.

Although the ground state of ^{55}Mn is known to be $J^\pi=\frac{5}{2}^-$, which precludes the strong alignment of states with $J\leq\frac{5}{2}$ formed by the $(n,n'\gamma)$ reaction, this reaction has been used to make spin assignments for the lower levels based on a comparison of theoretical cross-section calculations with experimental measurements.[18,21] Spin assignments made in this manner usually are not unique whereas γ-ray angular distribution data can provide a more satisfactory test of possible spin values.

II. EXPERIMENTAL METHODS

The present measurements were made using a small sample, close geometry technique which has been described in detail elsewhere.[22] The University of Alberta Van de Graaff accelerator was terminal pulsed at a frequency of 2 MHz with a pulse width of approximately 10 ns. The target consisted of 17 g of MnO_2 located approximately 0.5 cm from the tritium neutron production target. A NE213 neutron detector served as a neutron flux monitor. Two large volume Ge(Li) detectors with 10% relative efficiency were mounted on the same goniometer table, 45 cm from the scatterer. A resolution of 3.1 keV full width at half maximum (FWHM) was measured for each detector at 1.173 MeV. A pulser signal was input to each Ge(Li) preamplifier to measure the live time of the analyzer and to detect any gainshifts which might occur during the experiment. Data were accumulated at angles on both sides of the beam axis to minimize the effects of beam shifts during the course of the experiment. The Ge(Li) detector signals were timed with reference to the passage of the beam pulses through an insulated electrode in the beam line. The resulting time separation of the neutrons and γ rays was observed with the aid of time to pulse height converters. The γ-ray peak in the time spectrum was used as a gate to reduce the number of recorded events in the energy spectra due to neutrons striking the detector. A typical time spectrum and part of a gated γ-ray spectrum showing the higher energy transitions is shown in Fig. 1.

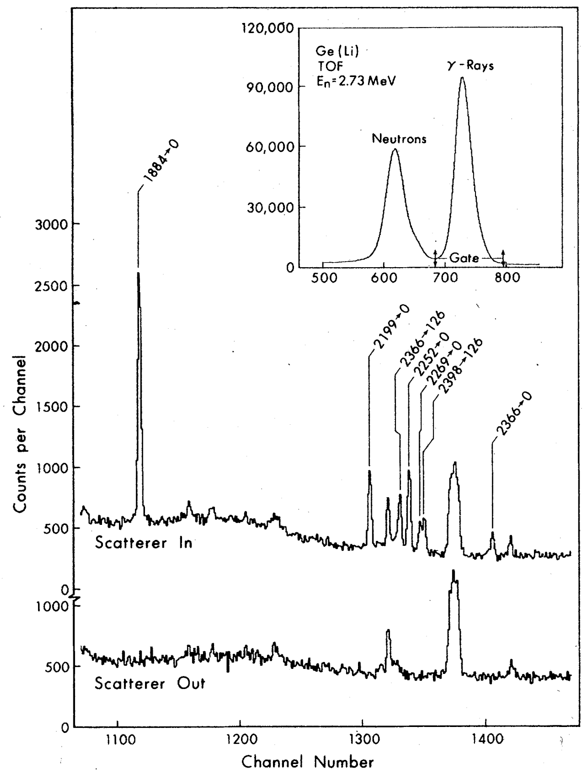

FIG. 1. Part of a Ge(Li) spectrum at $E_n = 2.73$ MeV, $\theta = 90°$ showing some of the higher energy transitions with the MnO_2 scatterer in place and the background with the scatterer removed. The time-of-flight spectrum is shown in the insert.

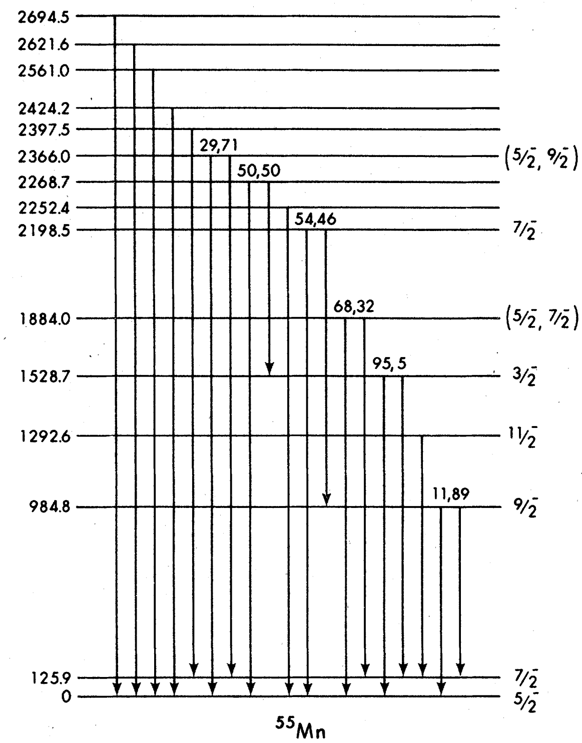

FIG. 2. Energy levels and γ-ray transitions observed in the present work. The energy of the first excited state is obtained from the mean energy differences of transitions originating from the 985, 1529, 1884, and 2199 keV levels. Standard errors are ± 0.3 keV for levels up through 2252 keV and ± 0.4 keV for levels above 2252 keV.

Angular distribution spectra were obtained at maximum neutron energies of 2.20, 2.73, and 3.15 MeV. The γ decays with energies greater than 350 keV identified in this work are shown in Fig. 2. Although the gamma transitions shown were clearly identified, several were too weak to analyze for angular distributions. In these cases the intensities were obtained from spectra at $\theta = 50°$, which is close to the zero of $P_2(\cos\theta)$. The sign of the mixing ratio parameter follows the phase convention of Rose and Brink.[23]

III. RESULTS AND DISCUSSION

In the following discussions, it is assumed that all of the levels under consideration have negative parity.

The 1293 keV level. The region surrounding 1293 keV in ^{55}Mn has been the object of considerable inquiry since Peterson *et al.*[24,25] found evidence for a $\frac{1}{2}^-$ or $\frac{3}{2}^-$ state at 1290 keV which decayed entirely to the ground state. The state at 1293 keV is known to decay predominantly to the first excited state, with the remaining intensity to the 985 keV level. A search at several neutron energies for either a 1293 → 0 or 1290 → 0 transition proved negative. The previous assignment of $\frac{11}{2}^-$ for the 1293 keV level is consistent with the present data but not uniquely so as shown in Fig. 3. The observed minimum of the χ^2 plot at $\arctan\delta = 3° \pm 4°$ indicates the multipolarity of this transition to be most likely pure $E2$.

The 1884 keV level. This level has two decay branches, to the ground state and the first excited state. Previous experiments[13,19,21] have limited this level to $\frac{5}{2}^-$ or $\frac{7}{2}^-$, and our measurements are consistent with either of these assignments. Deformed-model calculations[6] predict a spin of $\frac{7}{2}^-$ and a ground state branching ratio of 87%, while shell-model calculations[3] give the ground state branch as nearly 100%. Our measurements yield a value of 68% ± 4% for the ground state branching ratio, in contrast with earlier $(n,n'\gamma)$ experiments[18,20] which gave 82% and 59%, respectively. Our analysis of the angular distribution, shown in Fig. 4, gives a mixing ratio of $\arctan\delta = -7° \pm 7°$, in agreement with an earlier result.[11]

The 2199 keV level. The 2199 → 985 keV branch

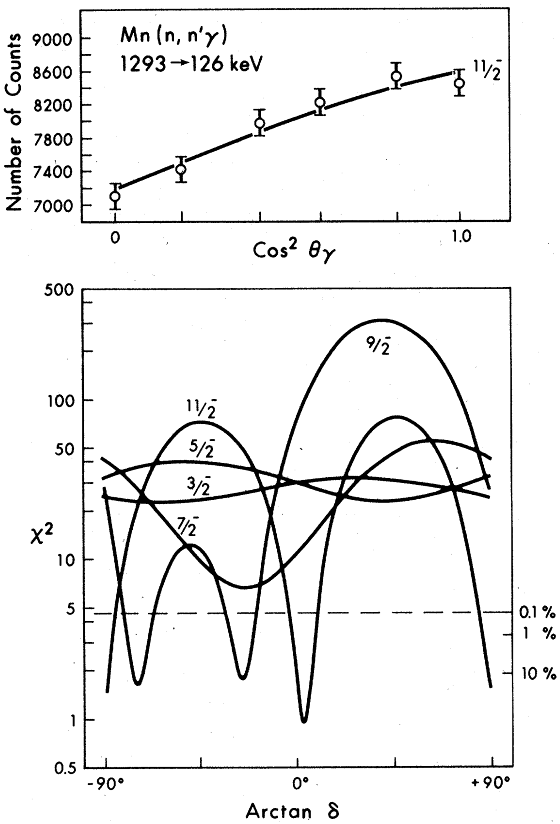

FIG. 3. The angular distribution of the 1293 → 126 keV decay obtained at $E_n = 2.20$ MeV and the corresponding plot of χ^2 versus arctan δ for various spins of the 1293 keV level. The dashed line denotes the 0.1% confidence limit for four degrees of freedom.

has the largest intensity but is located in a region of the spectrum which has a rapidly changing background making intensity values uncertain. The 2199 → 0 branch has been studied previously,[12,17] resulting in the exclusion of $J = \frac{9}{2}$ and the tentative assignment of $\frac{7}{2}$ and $\frac{3}{2}$, respectively. The results of the present work are shown in Fig. 5, where spins of $\frac{3}{2}$ through $\frac{9}{2}$ have been fitted to the data. The assignment of $\frac{7}{2}^-$ to the 2199 keV level identifies it with the third $\frac{7}{2}^-$ level at approximately 2180 keV calculated by Comfort *et al.*[6] The $\frac{7}{2}^-$ level at 2100 keV calculated by McGrory[2] and Vervier,[3] respectively, has the proper energy but should probably be identified with the 1884 keV level.

The $E2/M1$ mixing ratio of arctan $\delta = 17° \pm 14°$ deduced in the present work is consistent with a previous measurement[12] of arctan $\delta = 10° \pm 6°$. A value of arctan $\delta = 10°$ as well as a measured lifetime[11] of 25 fs indicates an $M1$ transition strength of 0.12 W.u., which is typical of nuclei in this region.

The 2252 and 2269 keV levels. The decays from these levels produced angular distributions which, when corrected for sample absorption, were isotropic. This result is in agreement with spin values $\leq \frac{5}{2}$ previously published.[26] Our results show the strength of the 2269 → 0 transition to be equal to that of the 2269 → 1529 transition which is considerably different from earlier work.[12]

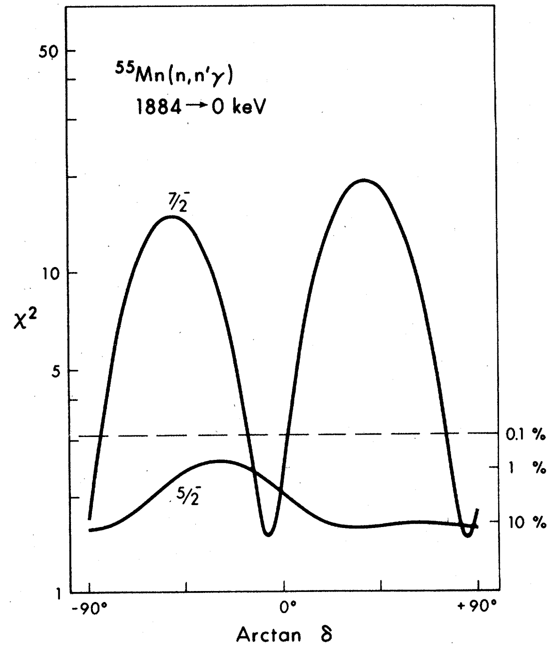

FIG. 4. A plot of χ^2 versus arctan δ assuming $\frac{5}{2}^-$ or $\frac{7}{2}^-$ for the 1884 keV level. The dashed line denotes the 0.1% confidence limit for four degrees of freedom.

The 2366 keV level. This level has branches to the ground and first excited states. Data for the 2366 → 0 branch support the tentative assignment of $\frac{9}{2}^-$ as shown in Fig. 6. This is consistent with the results of Hichwa *et al.*[12] who found either $\frac{5}{2}$ or $\frac{9}{2}$ as the only acceptable possibilities but is in conflict with the results of ^{55}Cr β decay measurements to the 2368.5 keV level by Hill.[16] His work limits the spin possibilities to $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$.

IV. SUMMARY AND CONCLUSIONS

The two neutrons outside the $f_{7/2}$ shell are expected to produce γ decays with strong $M1$ radiation in contrast to the case of ^{51}V which has been shown to be an example of dominant $E2$ radiation due to the presence of the three proton holes in the $f_{7/2}$ shell.[20,27] The values of the multipole mixing parameter (squared) deduced from the decays of the 1884 and 2199 keV levels agree with this expectation.

With the exception of the $\frac{11}{2}^-$ state at 1293 keV,

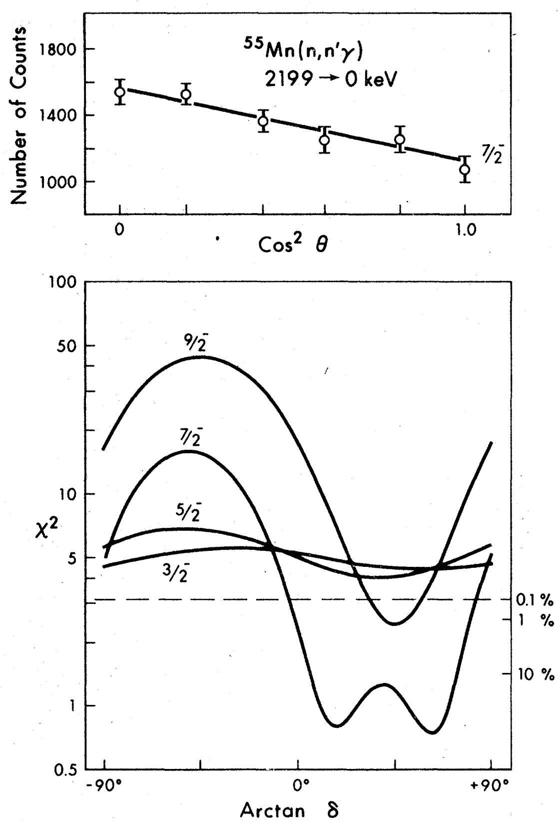

FIG. 5. The angular distribution of the 2199 keV γ ray at $E_n = 2.73$ MeV and the corresponding plot of χ^2 versus arctan δ for various spins of the 2199 keV level. The dashed line denotes the 0.1% confidence limit for nine degrees of freedom corresponding to the simultaneous fitting of two sets of data obtained at maximum neutron energies of $E_n = 2.73$ and 3.15 MeV.

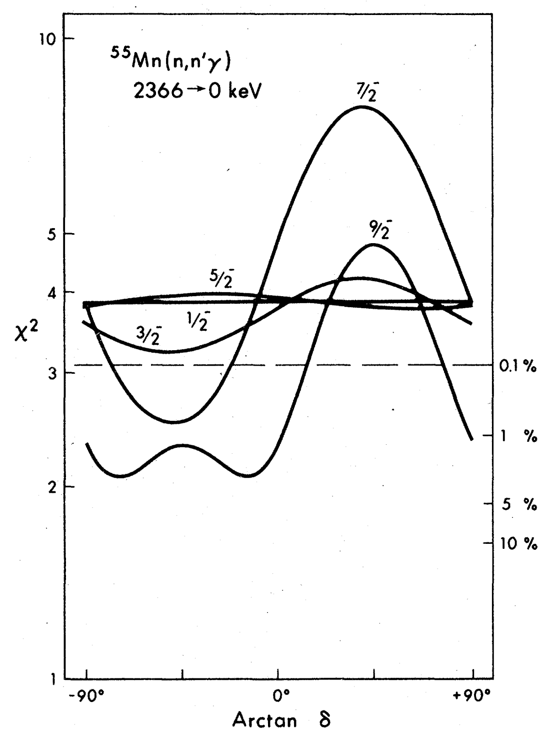

FIG. 6. A plot of χ^2 versus arctan δ for various spins for the 2366 keV level. The dashed line denotes the 0.1% confidence limit for nine degrees of freedom correspongeing to two sets of data obtained at $E_n = 2.73$ and 3.15 MeV.

the measured branching ratios are in fair agreement with the calculation based on the deformed unified model. The assignment of $\frac{7}{2}^-$ to the 2199 keV level is in agreement with the predictions of the above model. The tentative assignment of $\frac{9}{2}^-$ to the 2366 keV level awaits further verification from other experiments.

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