Levels of ^{53}Mn from the ^{53}Cr(p, $n\gamma$)^{53}Mn Reactions*

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In a study of the ^{53}Cr(p, $n\gamma$)^{53}Mn reactions, levels of ^{53}Mn have been found at 377.5, 1288.4, 1440.1, and 1619.1 keV, with uncertainties of ±0.3 keV. The observation of γ-ray anisotropies and (p, n) cross-section ratios permits unique spin assignments to three of the levels. Analysis of the (p, n) cross-section ratios using the Hauser-Feshbach formalism is consistent with the results of earlier experiments for the two lower levels. The spins of the above levels are, in the order given above, $\frac{5}{2}$, $\frac{3}{2}$, $\frac{11}{2}$, and $\frac{9}{2}$. Mixing ratios for the 377.5- and 1619.1-keV transitions are measured to be −0.6±0.3 and −3.2±0.8, respectively.

I. INTRODUCTION

THE properties of the nuclear configuration of $(1f_{7/2})^{\pm 3}$ can be most conveniently found by the study of the nuclei $_{20}^{43}Ca^{23}$, $_{20}^{45}Ca^{25}$, $_{23}^{51}V^{28}$, and $_{25}^{53}Mn^{28}$. Since it is now known that $N=28$ is a particularly stable closed shell[1] and should be subject to less configuration mixing than $Z=20$, an examination of the level structures of ^{51}V and ^{53}Mn should be particularly revealing of the properties of the $(1f_{7/2})^3$ and $(1f_{7/2})^{-3}$ proton configurations, respectively. Of these two nuclei, ^{51}V has been studied extensively both experimentally[2] and theoretically.[3] The levels of ^{53}Mn, on the other hand, have been studied very little. Since insights into the validity of the simple-shell structure[4] and into necessary modifications of the model may come from a comparison of the properties of the two nuclei, we have attempted to add to the experimental knowledge of ^{53}Mn.

Levels of ^{53}Mn have been observed by means of the ^{52}Cr(^{3}He, d)^{53}Mn reaction,[5] the ^{56}Fe(p, α)^{53}Mn reaction,[6] the ^{54}Fe(t, α)^{53}Mn reaction,[7] and the ^{52}Cr(p, γ)^{53}Mn reaction.[8] The various charged-particle reaction-product spectra all show three levels below 1.29-MeV excitation and many levels above 2.2 MeV. The ^{56}Fe(p, α)^{53}Mn study also shows levels near 1.43 and 1.60 MeV. The most detailed information about the lowest-two excited levels comes from γ-ray angular correlation measurements made on γ rays of the ^{52}Cr(p, γ)^{53}Mn reaction[8] and on γ rays of the ^{53}Cr(p, $n\gamma$)^{53}Mn reaction.[9] These three experiments fixed the spins of the first-two excited levels, the branching ratio for decay of the second excited level, and the $M1$, $E2$ mixing ratios of two transitions. Information about excitation energies and spins of the second-through-fifth excited levels has been obtained in the work[6] of Cujec *et al.* on the angular correlations of the ^{50}Cr(α, $p\gamma$)^{53}Mn reactions.

The present experiment was begun to determine properties and decay schemes for all levels below 2-MeV excitation energy. For this purpose, the ^{53}Cr(p, $n\gamma$)^{53}Mn reaction with observation of the γ rays was selected. Measurements were made of the γ-ray energies, 90° excitation functions, and angular distributions. These measurements fix directly and uniquely the level and decay schemes, including branching ratios.

Additional information is obtained through analysis of the angular distributions, which are nearly model-independent tests[10] of the spins of the levels and the multipolarities of the emitted γ rays. The ^{53}Cr(p, n) yields and γ-ray anisotropies were compared to calculations made using the Wolfenstein-Hauser-Feshbach (WHF) formalism,[11] which is appropriate for energy-averaged cross sections. The yield comparisons provide additional support for particular spin assignments, and the magnitudes of the γ-ray anisotropies also fix the mixing ratios δ for some transitions. The

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δ values depend on a quantitative comparison of anisotropies calculated and measured. The δ values and the information about spins obtained from calculations of (p, n) yields are sensitive to the model, and therefore have uncertainty that reflects the degree of confidence in the model. The study of Saad *et al.*[9] has already shown that the WHF calculations provide an excellent fit to the γ-ray angular correlations of the $^{53}Cr(p, n\gamma)^{53}Mn$ reaction to the first excited level of ^{53}Mn.

The experimental approach and analysis of this work is quite similar to that used successfully for the last several years in many $(n, n'\gamma)$ experiments.[10,12] In those experiments the WHF formalism fitted the (n, n') cross sections to within $\pm 25\%$ when the neutron-nucleus potential was carefully chosen.[10] One of the interesting questions raised here was the degree of success with which the same formalism could be used to fit (p, n) yields.

II. EXPERIMENTAL METHOD

The ^{53}Cr target was a thick slurry of Cr_2O_3 on a graphite backing.[13] The target chamber was a pyrex tube with its axis perpendicular to the reaction plane. The proton-beam current was collected and integrated from the insulated target backing. γ rays were detected with a 35-cc Ge(Li) detector. For the excitation functions, it was positioned at 90° and at a distance of 11 cm from the target to the front face of the detector. For the angular-distribution measurements, this distance was 12–18 cm.

Several neutron–γ-ray coincidence runs were also made to identify the transitions coming from the (p, n) reactions. The neutron detector was a 5×5-cm liquid scintillator placed at 30° and 7.5 cm from the target. For the coincidence runs, the Ge(Li) detector was at 90° and a distance of 11 cm from the target. A 7.6×7.6-cm NaI(Tl) monitor was operated at 135° at a distance of 20 cm from the target. It was used to monitor the very intense 377.5-keV first excited state to ground-state transition in ^{53}Mn throughout most of the experiment. The incident beam intensity was $\sim$120 nA for runs in which only γ rays were detected, but was reduced to 4 or 5 nA for coincidence runs. Although the coincidence resolving time (2τ) was only 20 nsec, accidental coincidences were a serious problem if the beam intensity was $\gtrsim$10 nA. Typical angular-distribution or excitation function runs took an hour, while each coincidence run took about 10 h. Alignment of the angular-distribution carriage was checked by measuring angular distributions known to be isotropic. The residual asymmetry correction to the angular-distribution data was $\lesssim 2\%$. Yields were also corrected for absorption in the target backing and then normalized to the monitor counts. For the excitation functions, the yields were normalized to the total incident charge collected from the target.

The multichannel analyzer used to record pulse-height spectra was checked for linearity by simultaneously recording pulses at regular pulse-height intervals from a precision pulser and radiation from ^{22}Na and ^{60}Co sources. The energy calibration of each spectrum was an internal one. The 511-keV line and lines from ^{27}Al and ^{52}Cr appeared as contaminants in much of our spectra. The well-known[14] 842.9- and 1013-keV lines of ^{27}Al and the 1433.6-keV transition[15] in ^{52}Cr were used as standards.

III. RESULTS

Approximately 30 spectra of the type shown in Fig. 1 were obtained and all of them contained the energy calibration lines noted above. The lines identified in ^{53}Mn are at 377.5, 910.8, 1288.4, 1440.1, and 1619.0 keV, all with uncertainties of $\pm$0.3 keV and at 1241.7$\pm$1 keV. Three $^{53}Cr(p, p'\gamma)$ lines observed at 564.1$\pm$0.2, 1004.9$\pm$0.3, and 1980.5$\pm$1 keV fix three excited levels of ^{53}Cr at those energies. The contaminant lines used as energy standards were much more evident at lower proton energies than they are in Fig. 1. The lines attributed to ^{53}Mn are identified in two ways. First, the neutron–γ-ray coincidence spectra selected the transitions belonging to the $(p, n\gamma)$ reactions. A coincidence spectrum is shown in Fig. 2. The lines of Fig. 1 from $(n, n'\gamma)$ and $(p, p'\gamma)$ reactions in ^{27}Al, ^{52}Cr, and ^{53}Cr as well as several background lines are missing or are very weak in Fig. 2. The broad peaks of Fig. 1 near 600, 695, 835, and 1040 keV are transitions produced by neutron inelastic scattering in the Ge(Li) detector. They occur at energies and with intensity ratios expected on the basis of a recent study of the $(n, n'\gamma)$ reactions in the Ge isotopes.[16] The strong transition at 1777.9 keV in Fig. 1 has an effective production threshold of $\sim$3 MeV and grows rapidly in intensity with proton bombarding energy. It is not in coincidence with the neutrons, however, since the small yield in Fig. 2 is consistent with the accidental coincidence rate. To clarify the fact that this was not a ^{53}Mn line, direct measurements of the neutron yields from the $^{53}Cr(p, n)^{53}Mn$ reactions were made. The measurements, carried out at the University of Kentucky pulsed 6-MeV accelerator,[17] showed no neutron groups to levels that could decay by emission of 1777.9-keV γ rays.

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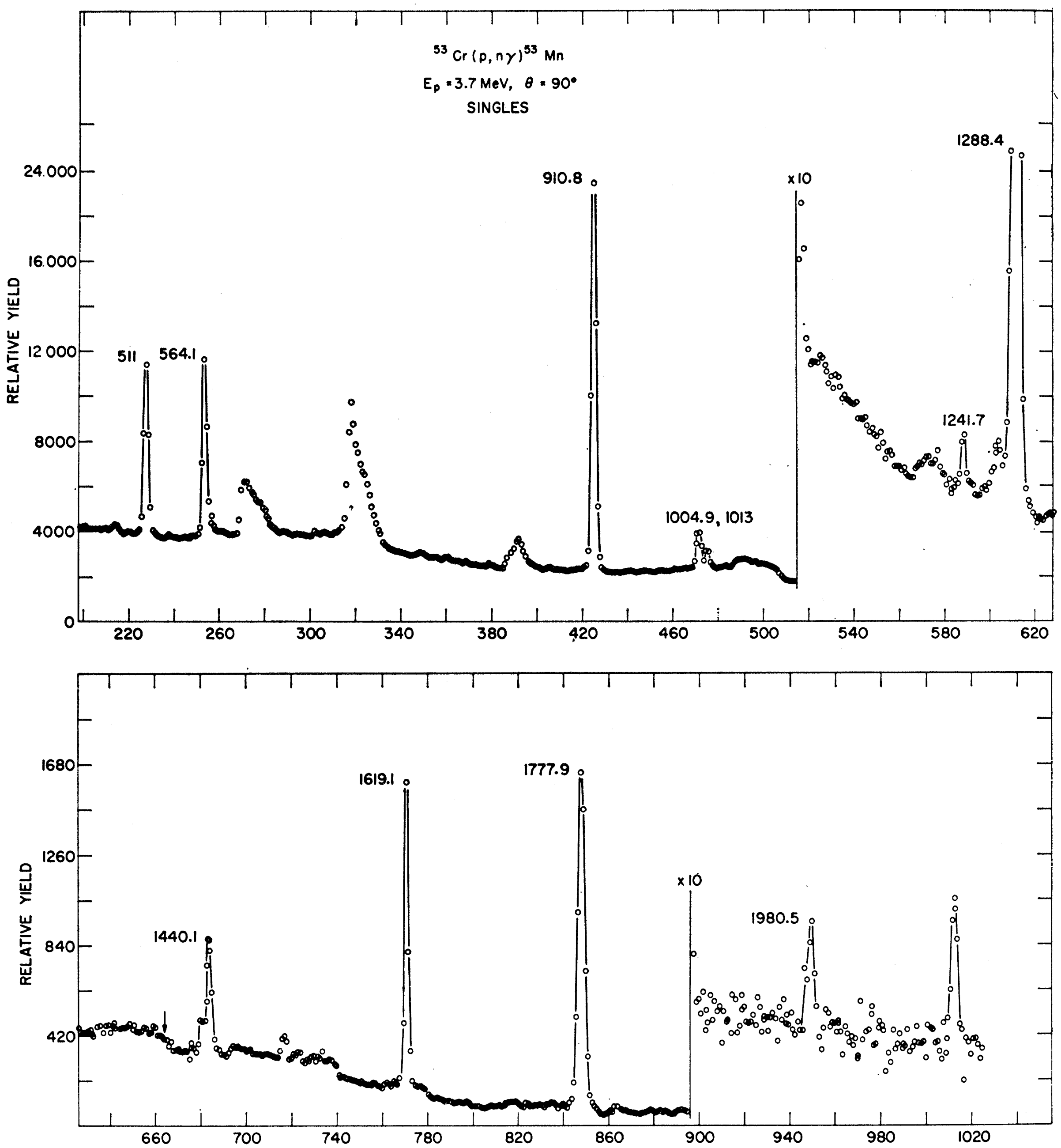

FIG. 1. Singles pulse-height spectrum of γ rays. The energies of the transitions are indicated in keV. The run time is about 10 min.

The second method of identifying ^{53}Mn lines was through the measurement of 90° excitation functions, shown in Fig. 3. The production thresholds of Fig. 3 could be tested to see whether they were consistent with excitation of a ^{53}Mn level of the appropriate energy. The common threshold of the 910.8- and 1288.4-keV lines is consistent with excitation of a level at 1288.4 keV, and the threshold for the 1241.7- and 1619.1-keV lines is correct for excitation of a level near 1619.1 keV. The other thresholds of Fig. 3 are all consistent with excitation of a level whose excitation energy in ^{53}Mn equalled the energy of the γ ray. The thresholds and yields of Fig. 3 together with the γ-ray angular distributions of Figs. 4 and 5 are combined to

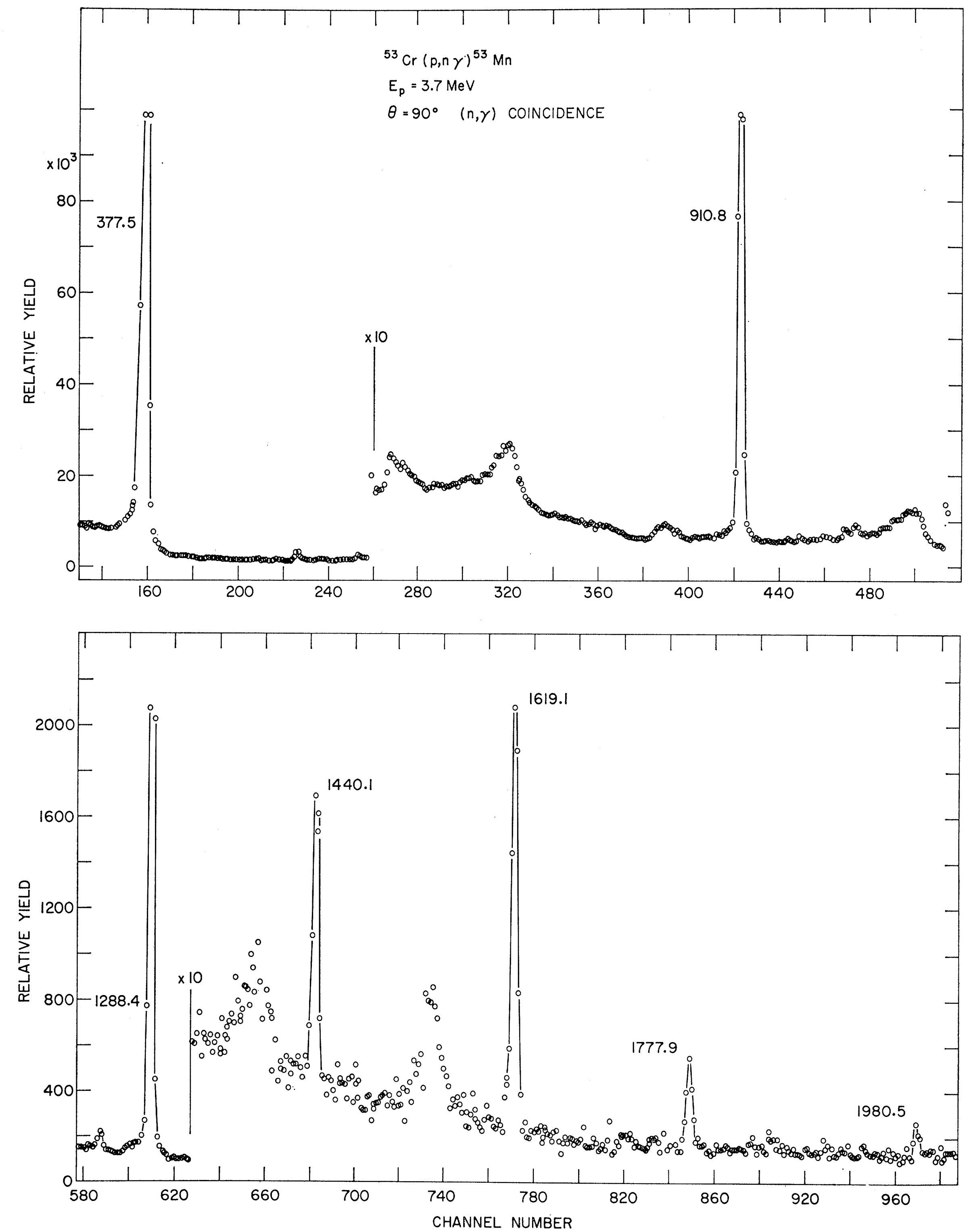

FIG. 2. Pulse-height spectrum of γ rays in coincidence with neutrons detected at 30° from the beam direction. The ratio of intensities of the 1777.9- and 1619.1-keV lines roughly indicates the accidental/true coincidence rates. All labeled lines except that at 1777.9 keV are ^{53}Mn lines.

produce the level and decay schemes shown in Fig. 8, including decay branching ratios.

Some information about spins of the levels in ^{53}Mn is apparent in the dependence on proton energy of the γ-ray yields $y(E_p)$. Near the threshold, the reactions will go primarily by s-wave neutron emission. For example, calculations with the optical-model code ABACUS-2 revised[18] in the mass region $A\sim50$ show transmission coefficients that are large for $l=0$, unusually small for $l=1$, and small for other partial waves when the neutron energy $\lesssim0.6$ MeV. The s-wave neutron emission means high-spin final levels will be fed from high-spin compound-nucleus levels that in turn are excited only by high-orbital-angular-momenta (l_p) incident protons. The energy dependence above threshold will be dominated by the penetrabilities of the different l_p, a rapidly varying dependence for high l_p.

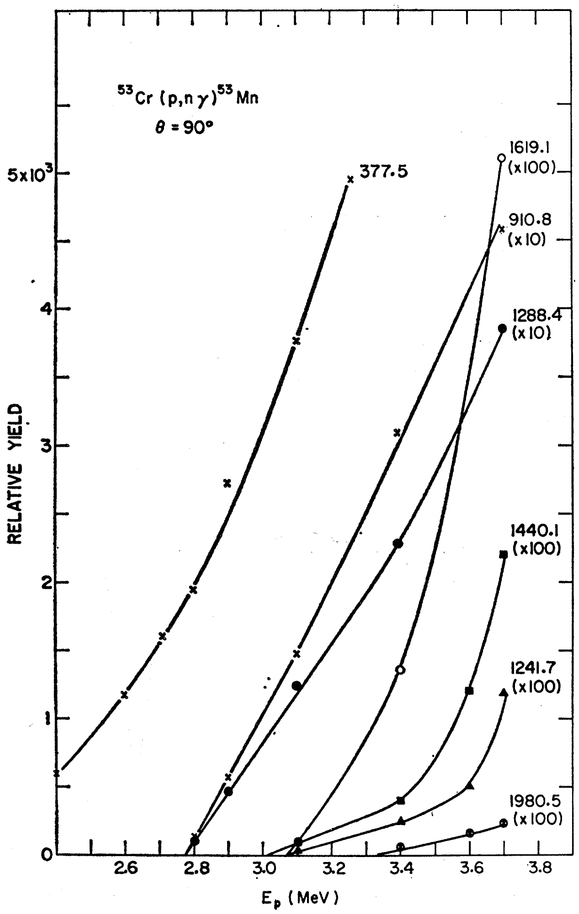

FIG. 3. Excitation functions at 90° for the prominent transitions of Fig. 2. Different plotting symbols are used for different transitions to aid in visualizing the separate curves.

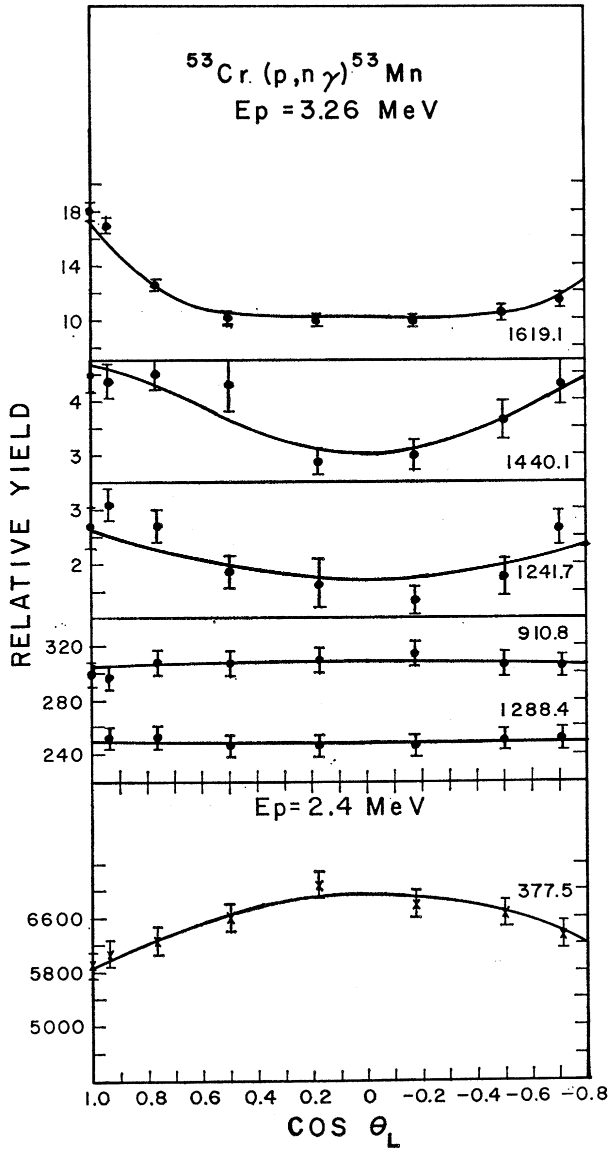

FIG. 4. Angular distributions of ^{53}Mn transitions at $E_p=2.4$ MeV (bottom panel) and at $E_p=3.26$ MeV. All plots have ordinate scales with suppressed zeros.

The yields of Fig. 3, then, immediately suggest high spin for the 1440.1- and 1619.1-keV levels, and comparatively low spins for the levels at 377.5 and 1288.4 keV. Indeed, the $y(E_p)$ for transitions from the 377.5- and 1288.4-keV levels are nicely consistent with recent determinations[8] of $J=\frac{5}{2}$ and $\frac{3}{2}$, respectively.

Angular distributions of the very intense 377.5-keV line were obtained at several proton energies, and angular distributions of the other ^{53}Mn lines were measured at 3.26- and 3.70-MeV proton energy. As is apparent in Fig. 3, only the 377.5-keV line is excited below 2.6-MeV proton energy, so that interpretation of

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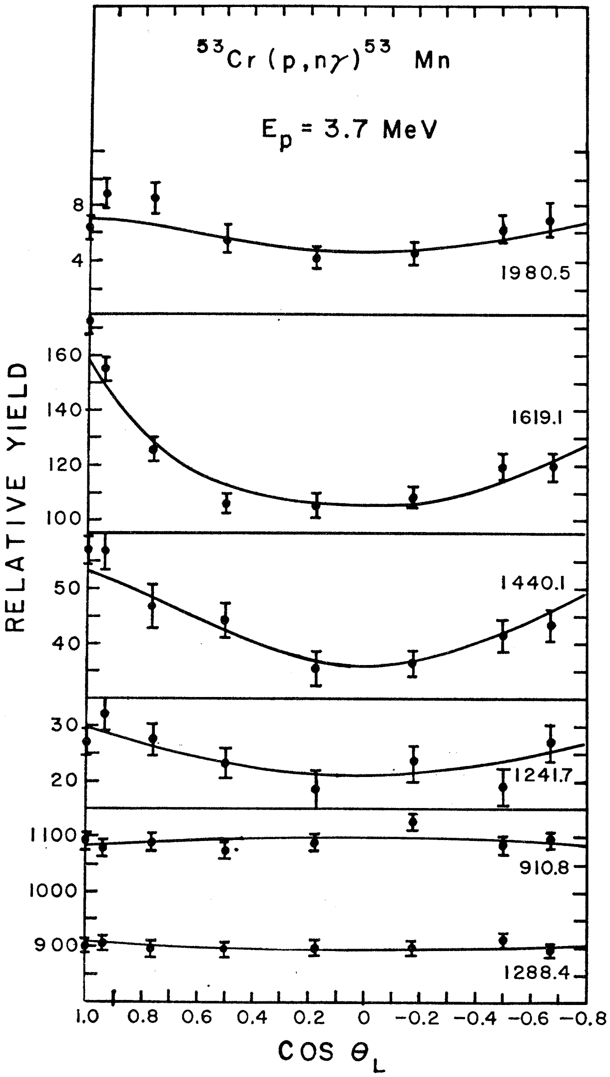

FIG. 5. Angular distributions of ^{53}Mn transitions at $E_p=3.70$ MeV.

its angular distribution is not confused by the presence of cascades. Measurements at $E_p=2.4$ MeV are shown in Fig. 4. Angular distributions for other transitions are shown in Figs. 4 and 5 at $E_p=3.26$ and 3.70 MeV, respectively. All of the distributions are fitted by the method of least squares to the form $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$. The coefficients and uncertainties of the least-squares fits are listed in Table I. Finite-detector size corrections to the angular-distribution coefficients are negligible and were therefore not included in the analysis. The coefficients listed in parentheses are from WHF calculations to be discussed later. Two levels are observed to emit cascade transitions to the first excited level as well as ground-level transitions. Measurements of the branching ratios are contained both in the data of Fig. 4 and that of Fig. 5. The two sets of branching-ratio measurements agree to within 1% and give 57±1% and 89±1% as the ground-level decay probabilities of the 1288.4- and 1619.1-keV levels, respectively. The result for the 1288.4-keV level is in excellent agreement with a reported[8] value of 60% measured in the study of the ^{52}Cr(p, γ) reaction.

IV. ANALYSIS AND INTERPRETATION

The most definite information about spins of the excited levels comes from the γ-ray angular distribu-

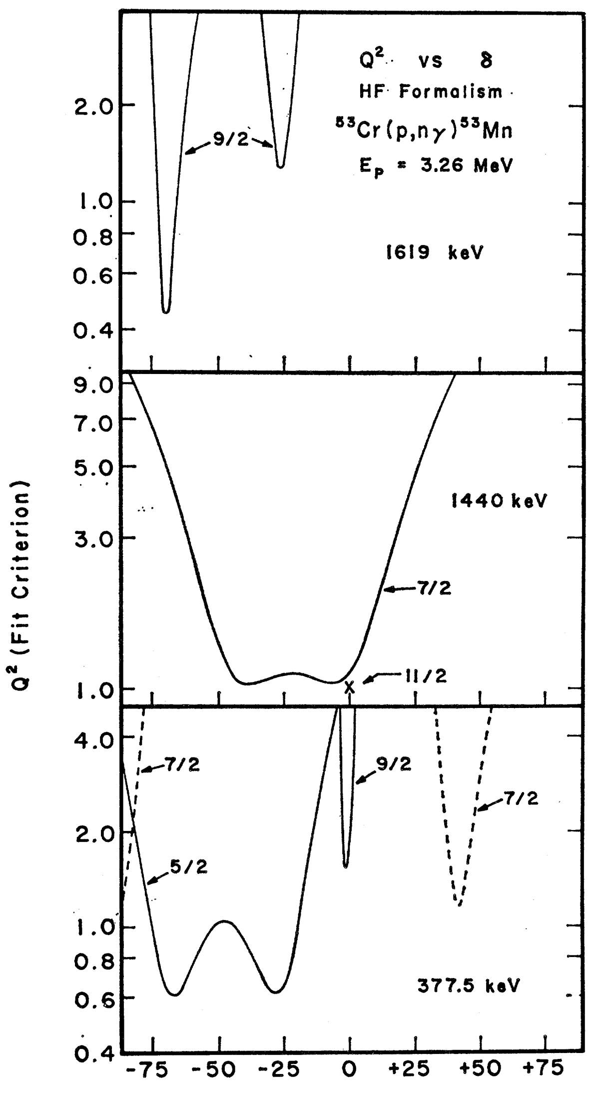

FIG. 6. Statistical criterion of the consistency with which the HF formula fits angular-distribution measurements for three γ rays. Since the HF calculations are δ-dependent, δ is fixed to obtain the minimum of Q^2.

TABLE I. Coefficients of the form $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ for the γ-ray angular distributions. Those with uncertainties are from a least-squares fit to measurements. Those in parenthesis are theoretical calculations for transitions from a level of spin J. E_p denotes the proton energy, E_γ the γ-ray energy, and δ the mixing ratio of the transition.

E_x (keV)	E_γ (keV)	$J_x \rightarrow J_f$	E_p (MeV)	A_2	A_4	δ
377.5	377.5	5/2→7/2	2.40	−0.11±0.02		−0.6±0.3
1288.4	1288.4	3/2→7/2	3.26	0.02±0.02(0.005)		0
	910.8	3/2→5/2	3.26	−0.03±0.02(−0.005)		
			3.70	−0.01±0.01(−0.01)		
1440.1	1440.1	11/2→7/2	3.26	0.36±0.06(+0.33)	−0.18±0.08(−0.08)	0
			3.70	0.33±0.05(0.28)	0.01±0.06(−0.03)	0
1619.1	1619.1	9/2→7/2	3.26	0.41±0.03(+0.33)	0.21±0.03(0.18)	−3.2±0.8
			3.70	0.30±0.03(0.27)	0.14±0.03(0.08)	−3.2±0.8
	1241.1	9/2→5/2	3.26	0.6±0.2(+0.3)	−0.20±0.15(0.04)	0
			3.70	0.34±0.11(0.24)	−0.13±0.11(−0.01)	0

tions. It has been pointed out in other work and in Sec. III that observations near threshold for the reaction correspond primarily to s-wave neutron emission. This leads to an excited-state alignment[10,19] of defined character, one in which the magnetic substates (m_J) which have $|m_J|>J_0$ have small populations. J_0 is the spin of the target ground level. The γ-ray anisotropies are thus a nearly model-independent test of the excited-level spin J. The expected distributions for different possible J are actually calculated in the statistical model of nuclear reactions or WHF formalism,[11] and the comparison of measured and calculated γ-ray angular distributions is discussed separately below for each level. The calculations depend not only on the assignment J but also on the multipole order L of the γ decay and, for mixed multiple transitions, on the mixing ratio δ. The ratio δ is defined $\delta\equiv\langle|L+1|\rangle/\langle|L|\rangle$ with the phase convention of Warburton and Poletti.[20] The results of the assignments and WHF calculations are the solid curves of Figs. 4 and 5, whose expansion coefficients are listed in parenthesis beside the least-squares-fit coefficients in Table I. The comparison of "measured" and calculated coefficients of Table I or the curves of Figs. 5 and 6 show that the WHF formalism does an excellent job of representing the angular distributions at two incident proton energies.

TABLE II. Measured and calculated relative yields to different levels of ^{53}Mn. σ_m denotes measurement normalized to that of the 1288.4-keV level, σ_T denotes HF calculation, J denotes angular momentum, E_x denotes excitation energy, and E_p denotes incident proton energy. The J's deduced in this work are in column 5 and the corresponding σ_T are in column 4.

E_p (MeV)	E_x (keV)	σ_m (mb)	$\sigma_T(J)$ (mb)	J
3.26	1288.4	100	100	3/2
	1440.1	1	1.6	11/2
	1619.1	3.8	6.5	9/2
3.70	1288.4	100	100	3/2
	1440.1	3.2	4.3	11/2
	1619.1	11.7	13.5	9/2

The quality of the angular-distribution fits and the dependence on δ is illustrated graphically in Fig. 6. A statistical measure[21] of the goodness of fit, Q^2, is plotted as a function of δ for transitions from three excited levels. These fits and the comparison of measured and calculated (p, n) cross-section ratios are the basis for the spin assignments to be discussed separately below.

The measured cross-section ratios of Table II and Fig. 7 are obtained from the ^{53}Cr$(p, n\gamma)$ yields after correcting them for the detection efficiency of the 35-cc Ge(Li) detector[22] and also for the effects of cascade transitions. The ratios normalized to the yield for

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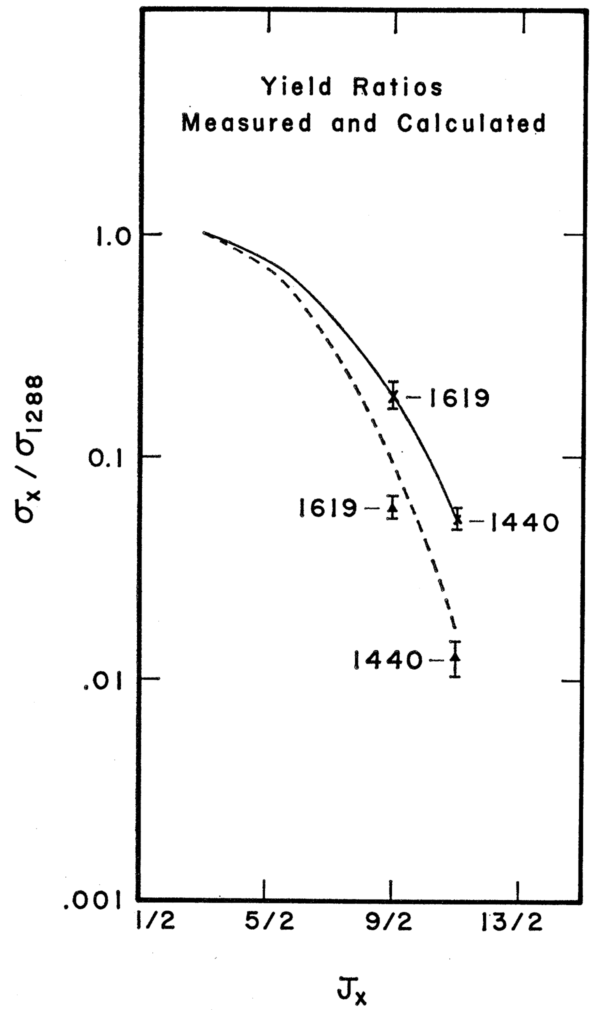

FIG. 7. Semilog plot of the cross sections of the ^{53}Cr(p, n)^{53}Mn reactions to final states of different spin divided by the cross section for excitation of the $\frac{3}{2}^-$ level at 1288.4 keV. The curves are HF calculations for a final state with an assumed excitation energy of 1.5 MeV, the dashed curve calculated for an incident proton energy of 3.26 MeV, and the solid curve for an incident energy of 3.70 MeV. Measured ratios are plotted as points labeled with the excitation energies of the final states. The (Δ) are measured at 3.26-MeV incident energy and the (x) at 3.70 MeV.

excitation of the $\frac{3}{2}$ level at 1288.4 keV are shown in column 3 of Table II. The WHF calculations yield the ratios in column 4 with the spin assignments of column 5.

To test the sensitivity of the cross-section ratios to changes in spin, calculations were made for a level at an assumed excitation energy of 1.5 MeV and with different possible spins. The results (Fig. 7) are the dashed and solid curves for incident protons of 3.26 and 3.70 MeV, respectively. The points plotted with errors are the measured ratios. The excellent agreement of the spin-sensitive ratios helped to fix spin assignments.

A. 377.5-keV Level

The Q^2 of Fig. 6 shows three different attempts to fit with different spins J. The probability (P) that an attempt is consistent with the measurements is $P \lesssim 20\%$ for $J=\frac{7}{2}$ and $\lesssim 10\%$ for $J=\frac{9}{2}$. $P \approx 75\%$ for $J=\frac{5}{2}$, in support of the earlier assignment[8,9] to that level. As already noted, the excitation functions of Fig. 3 support this conclusion. The plot of Fig. 6 also gives $\delta=-2.4_{-2}^{+1}$ or $\delta=-0.6\pm0.3$. Previous work gives $\delta=-0.6$ and -0.47 in Refs. 8 and 9, respectively. The fit of Fig. 4 is calculated for $\delta=-0.6$.

B. 1288.4-keV Level

An excited state with $J \leq J_0$, where J_0 is the spin of the target nucleus, produces γ rays that are nearly isotropic. If $J \leq J_0$, then the residual-nucleus excited state has only magnetic substates with $|m_J| \leq J_0$. Since the (p, n) transition starts from the equally populated substates of the target and excites substates of the residual level having the same set of m_J values as the target, little alignment can occur. The fact that both the ground state and the 910.8-keV cascade transitions from the 1288.4-keV level are nearly isotropic suggests little excited-state alignment, which suggests $J \leq \frac{3}{2}$. Additional help on the assignment comes from the excitation functions of Fig. 3, as noted above. The level has been assigned as $\frac{3}{2}$ in an earlier experiment.[8]

C. 1440.1-keV Level

Figure 6 shows acceptable fits for two possibilities, $J=\frac{7}{2}$ or $\frac{11}{2}$. For all other J values, $Q^2 \geq 10$. Two independent (p, n) cross-section ratio comparisons in Fig. 7 eliminate $\frac{7}{2}$ and confirm $\frac{11}{2}$ as the spin of the level. The fits of Figs. 4 and 5 are for an $\frac{11}{2}$ ($E2$ or $M2$) $\frac{7}{2}$ decay. The $\frac{11}{2}$ assignment is consistent with the angular correlations of Cujec *et al.*,[6] who suggested $\frac{11}{2}$ or $\frac{7}{2}$ for the level.

D. 1619.1-keV Level

The large A_4 is a unique and striking property of a $\frac{9}{2}$($E2$ or $M2$)$\frac{7}{2}$ decay. The plots of Fig. 6 show the only fits for which $Q^2 \lesssim 10$, although calculations have been made for all $J \leq \frac{13}{2}$. From Fig. 6, we determine that $J=\frac{9}{2}$ and $\delta=-3.2\pm0.8$. The solution indicated at arc $\tan\delta=-25°$ is excluded since its probability of being correct is $\lesssim 0.1\%$. Although the assignment in this case is unique, being based on the angular-distribution data alone, the cross-section ratios of Fig. 7 support it and confirm the effectiveness of this method of obtaining a unique assignment for the 1440.1-keV level. The assignment for this level is also consistent with the angular correlations of Ref. 6.

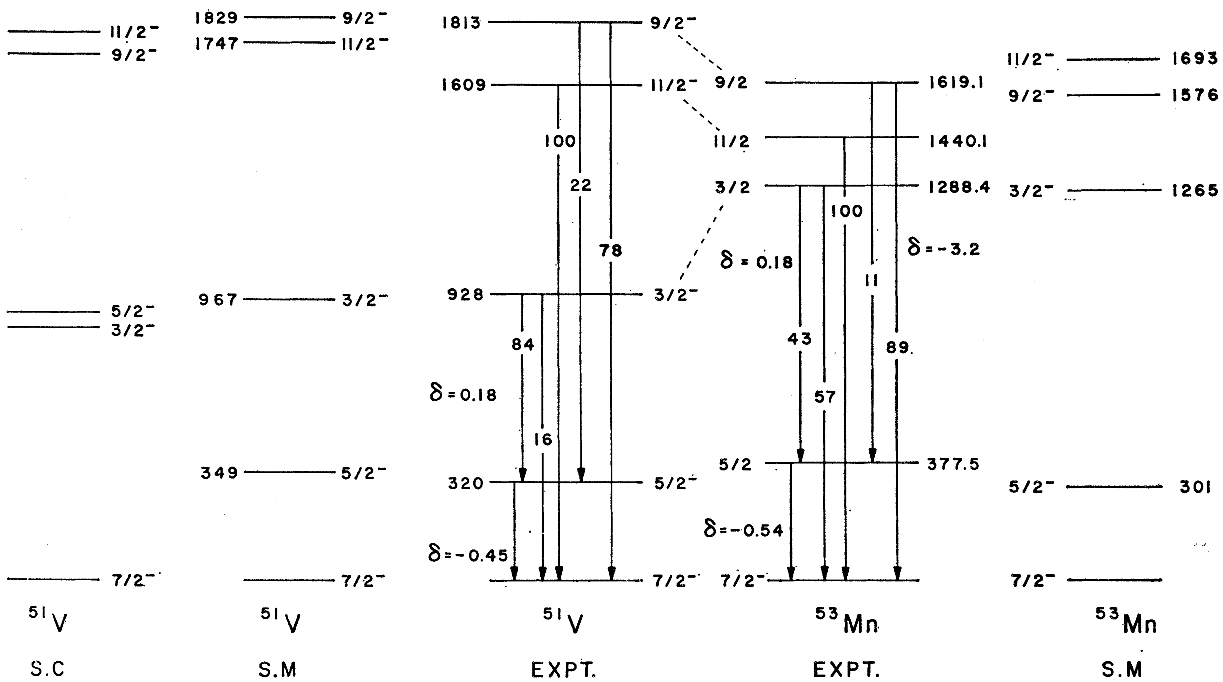

FIG. 8. Summary of measurements and model calculations for the low-lying levels of ^{51}V and ^{53}Mn. The spectra labeled S.M. are effective-interaction shell-model calculations of Lips (Ref. 28), and the S.C. spectrum is a strong-coupling calculation of Scholz and Malik (Ref. 3).

V. SUMMARY AND COMPARISONS WITH OTHER WORK

The excitation energies of four excited levels have been determined in this work to be 377.5, 1288.4, 1440.1, and 1619.1 keV. The lowest two energies have been reported in several experiments that employ magnetic analysis of reaction-product energies. Their results[5–7] are in fair agreement with the present values.

The combination of this and two earlier experiments[8,9] yields unique spin assignments for the four-lowest excited levels as well as the mixing ratios and branching ratios of their decay. Figure 8 presents a summary of this information as well as the corresponding information for ^{51}V, the "cross-conjugate" nucleus. The most notable difference between them is the difference in excitation energies. The transition rates in the two nuclei are remarkably similar, with one important difference to be noted below. The decays of the first excited levels show no appreciable differences.[8] The lifetime in ^{51}V was measured[23] to be $\tau=0.2$ nsec and in ^{53}Mn it was found[24] to be 0.12 nsec. The $E2$, $M1$ mixing ratio of the decay[25] is $\delta=-0.45$ in ^{51}V, and in this and other[8,9] experiments $\delta=-0.54$ in ^{53}Mn, where this value is an average of the results from the three experiments. These data give $E2$ enhancements[2] of 4.5 and 5.0 in ^{51}V and ^{53}Mn, respectively, and an $M1$ inhibition of 350 in each nucleus.

Recent measurements of Coulomb-excitation cross sections in ^{51}V give reduced $E2$ transition probabilities that are completely consistent with the $(1f_{7/2})^3$ configuration[26] for the $\frac{7}{2}\rightarrow J$ transitions. They give an average $E2$ enhancement for the four-lowest excited levels of 2.6, in reasonable agreement with the independently determined value above of 4.5 for the first excited-level decay. In an earlier review of reduced $E2$ transition probabilities,[27] Vervier had noted that the most serious difficulty with the $(1f_{7/2})^3$ configuration was in the $BE2$ for the $\frac{3}{2}\rightarrow\frac{5}{2}$ cascade transition. With the new Coulomb-excitation results,[26] the branching ratio for decay of the $\frac{3}{2}$ level measured by Barrows *et al.*[2] and the $E2$, $M1$ mixing ratio[27] for the $\frac{3}{2}\rightarrow\frac{5}{2}$ transition, the $BE2$ of the $\frac{3}{2}\rightarrow\frac{5}{2}$ transition is here redetermined to be 0.25 of the single-particle value,[26] an order of magnitude less than the speed of the other $E2$ transi-

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tions. Even if the Coulomb-excitation cross section were raised by a factor of 2, this discrepancy would be serious.

The theoretical level schemes (S.M.) in Fig. 8 are from the effective-interaction shell-model calculations of Lips,[28] whose calculations provide a least-squares fit to nuclei with $20<Z<28$ and $N=28$. These spectra represent a substantial improvement over the older $(1f_{7/2})^n$ calculations of McCullen *et al.*,[2] since they include configurations of the form $(f_{7/2})^2p_{3/2}$ for ^{51}V and $(f_{7/2})^4p_{3/2}$ for ^{53}Mn. The results are somewhat similar to those of Auerbach.[29] The success of the model can be further tested by looking at γ-ray transition rates. These are calculated[28] with a free-particle $M1$ operator and $E2$ effective charge of $1.6e$, the value reported[26] to fit the ground-state quadrupole moment and $BE2$ values in ^{51}V. The calculated results are about the same for both nuclei. In both cases, the $E2$ transition rates are well represented, but the calculated $BM1$ strengths are too small by factors of 3–8. An extension of the model to include the $f_{5/2}$ configuration[28] does fit both $E2$ and $M1$ transition rates.

The presently available data may also be interpreted in the strong-coupling model of Scholz and Malik,[2] who use Coriolis coupling of deformed single-particle states to a deformed rotating core. The ground-state quadrupole moment and $E2$ transition rates are well represented by a small negative deformation, with the parameter[2] $\beta=0.15$. This would be quite consistent with the shell-model picture of the nucelus. The calculated excitation energies are given[2] for $\beta=-0.32$ and reproduced in Fig. 8. The calculated $M1$ transition rates are not in agreement with the measurements.

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Scattering of 14.5-MeV Protons from the Even Isotopes of Germanium*

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Protons from the 90-in. cyclotron at Lawrence Radiation Laboratory (LRL)–Livermore have been scattered from enriched targets of ^{70,72,74,76}Ge, with an over-all energy resolution (FWHM) of 70 keV. The incident proton energy was approximately 14.5 MeV, and angular distributions were obtained from 20° to 150°, in 10° intervals. The elastic-scattering results were analyzed using the optical model. Angular distributions were obtained for inelastic proton groups from seven levels in ^{70}Ge, nine levels in ^{72}Ge, eleven levels in ^{74}Ge, and ten levels in ^{76}Ge—all below 3.5-MeV excitation. These included scattering to the quadrupole and octupole one-phonon vibrational levels and scattering to the 0^+, 2^+, 4^+ two-quadrupole–phonon triplet. The data were analyzed using a coupled-channel computer code and a vibrational model of the nucleus. Strengths to excited states (β_I) and spins and parities of levels were determined and are compared with Coulomb-excitation decay studies and with other scattering experiments.

I. INTRODUCTION

PROTON scattering is an established technique for the study of nuclear structure. We are currently engaged in a series of proton-scattering experiments from the even-even isotopes of Cd,[1] Ti,[2] and Ge using a vibrational model and the coupled-channel analysis of Tamura[3] to interpret our data. The germanium isotopes have not been studied extensively by scattering techniques. The energy levels, spins, and parities of ^{70,72,74}Ge have been deduced mainly from the decay of the neighboring isotopes of As and Ga. The results of these decay measurements will be discussed and compared to our results later in this article.

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