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Gamma-ray spectroscopy studies of ^{52}Ti†

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Nuclear properties of the excited states of ^{52}Ti were measured using the ^{50}Ti$(t, p\gamma)$ reaction at a bombarding energy of $E_t = 2.9$ MeV. Angular correlations of γ rays were obtained using an array of five NaI(Tl) counters in time coincidence with an annular particle detector positioned near 180°. Unique spin assignments for some of the excited states were obtained in addition to multipole-mixing-ratio and branching-ratio information. Nuclear lifetimes were measured using the Doppler-shift-attenuation method. Some of the measured excitation energies, spins, and mean lifetimes [E_x (keV), J, and τ (psec)], respectively, are as follows: (1047.1 ± 0.3, 2, $4.8^{+8.0}_{-2.1}$); (2259.4 ± 0.6, 2, $0.05^{+0.03}_{-0.02}$); (2427.9 ± 1.5, 2, ≤ 0.1); and (3582.5 ± 2.0, ≥ 1, ≤ 0.09).

[NUCLEAR REACTIONS ^{50}Ti(t,p), $E = 2.9$ MeV; measured $\theta_{p\gamma}$, E_γ, $T_{1/2}$, Γ, δ for transitions in ^{52}Ti. Deduced J, π for levels.]

I. INTRODUCTION

Shell-model calculations are no longer limited to nuclei which may be described as closed core plus a few valence particles, but increasingly predict properties of nuclei characterized by many valence particles distributed over a wide range of valence orbitals. Thus it is important to experimentally study those nuclei which have a large number of valence protons or neutrons as well as those which are near a closed shell.

The present report deals with one such nucleus, ^{52}Ti, which is a neutron-rich nucleus having $T_z = 4$ and which can be formed conveniently with the ^{50}Ti$(t, p\gamma)^{52}$Ti reaction ($Q_0 = 5.70$ MeV). The only previous work published on the spectroscopy of this nucleus is that of Williams, knight, and Leland[1] and Casten *et al.*[2] from Los Alamos. The ground state was shown to be $J^\pi = 0^+$ by a study[1,2] of the (t,p) reaction, where the two-particle transfer was shown to have $L = 0$ character. The first excited state at 1.05 MeV was associated with an $L = 2$ transfer and consequently was assigned a spin and parity $J^\pi = 2^+$. Aside from the observation[1] of a state at 2.43-MeV excitation, no further data have been reported.

The present experiment consisted of a study involving proton-γ-ray angular-correlation and Doppler-shift-attenuation measurements. This experimental study has yielded previously unavailable information on spins, parities, γ-ray-branching and multipole-mixing ratios, and mean nuclear lifetimes. The experimental details of the present report can be found in Secs. II and III, while Sec. IV presents a synthesis of the results.

The lower excited states of ^{52}Ti should belong predominantly to a $(\pi f_{7/2})^2(\nu p_{3/2})^2$ configuration. There have been no theoretical calculations made for the spectroscopy of ^{52}Ti excited states. However, it should be possible to get some idea of the level structure to be expected from a consideration of the nuclei ^{50}Ti and ^{58}Ni which have the configurations $(\pi f_{7/2})^2$ and $(\nu p_{3/2})^2$, respectively. An analysis based on this approach is given in the final section of this paper.

II. PARTICLE-γ-RAY ANGULAR CORRELATIONS

The angular-correlation studies were performed at a beam energy of $E_t = 2.9$ MeV. The target for this work consisted of ~150 μg/cm^2 of ^{52}Ti (isotopically enriched to 67% ^{52}Ti, 33% ^{48}Ti) deposited by evaporation onto a 0.0025-cm Ta foil. The target was situated at the center of an angular-correlation spectrometer which consisted of five 10-× 10-cm NaI(T1) detectors positioned at angles (or angles analytically equivalent to) 5, 35, 45, 60, and 90° with respect to the beam axis. These detectors were located 20 cm from the target spot. Reaction protons were observed in a 1000-μm-thick annular-silicon counter positioned at an angle of 171 ± 4° in the laboratory system, which was shielded from the scattered tritons by 10.3-mg/cm^2 of Al foil. A proton spectrum in coincidence with all γ rays is given in Fig. 1(a).

All NaI(T1) γ-ray spectra were recorded in coincidence with the proton spectra obtained with the annular particle counter. The data were handled by conventional modular electronics coupled to analog-to-digital converters which were interfaced to an SEL-810A computer used "on line." This arrangement allowed the collection of three-parameter data onto magnetic tape with simultaneous on-line and/or subsequent off-line data analysis. For further details in regard to the operation of the angular-correlation spectrometer see previous published papers using this system.[3]

Since the target composition was 33% ^{48}Ti, it was necessary to distinguish the groups corresponding to ^{52}Ti states from those resulting from the ^{48}Ti$(t,p)^{50}$Ti reaction. This was accomplished by substituting a ^{48}Ti (~99.9% enriched) target for the enriched ^{50}Ti target. The resulting proton spectrum shown in Fig. 1(b) was subtracted from the spectrum of Fig. 1(a) after being normalized in intensity to the high-energy ^{50}Ti proton groups. This subtraction process yielded the spectrum shown in Fig. 1(c) in which the groups corresponding to ^{52}Ti levels are clearly identified. A similar subtraction process was carried out in the analysis of all γ-ray spectra although in most cases (except for the highest-lying states) this was not actually necessary to obtain reliable angular correlations and branching ratios. Figure 2 illustrates this subtraction procedure for γ-ray spectra coincident with protons populating the 2.26-MeV level.

The angular-correlation data were analyzed by a least-squares-fitting procedure (and χ^2 analysis in terms of initial spins) with the theoretical angular distributions calculated according to the formulas of the "method II geometry" of Litherland and Ferguson.[4] A least-squares fit to an expansion of even-order Legendre polynomials was also made and the resulting coefficients are given in Table I. In an ideal colinear geometry only γ rays from $m=0$ and ± 1 substates can be observed[4] but in practice a small contamination from $m=\pm 2$ substates is always present due to the finite solid angle subtended by the particle detector. In the present analysis it was assumed that the relative population of the $m=\pm 2$ to the 0 substate was less than 5%. The finite-solid-angle effect was in most cases small and was included in the analyses. Whenever possible the χ^2 analysis for a given state included data on all γ rays whose observed angular correlations are dependent on the alignment of the initial state. Table II lists the measured multipole-mixing ratios obtained from the analyses.

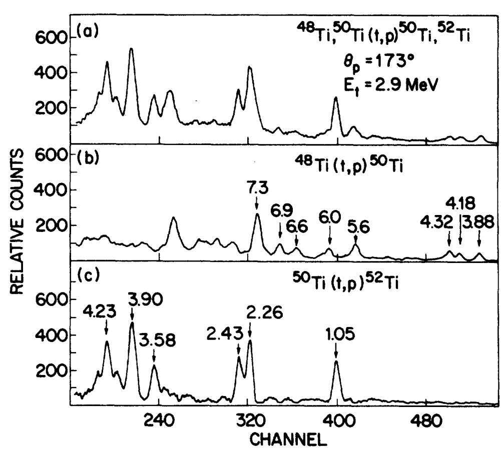

FIG. 1. The proton spectra measured in time coincidence with all γ rays observed by the five NaI(Tl) detectors (a) using a target consisting of 33% ^{48}Ti and 67% ^{50}Ti and (b) using a target of 99.9% ^{48}Ti. The proton spectrum in (c) was obtained by subtracting spectrum (b) from spectrum (a) and thus should represent ^{52}Ti states. Random coincidences have been subtracted from all spectra. The peaks are labeled by the excitation energies (MeV) of the states to which they correspond.

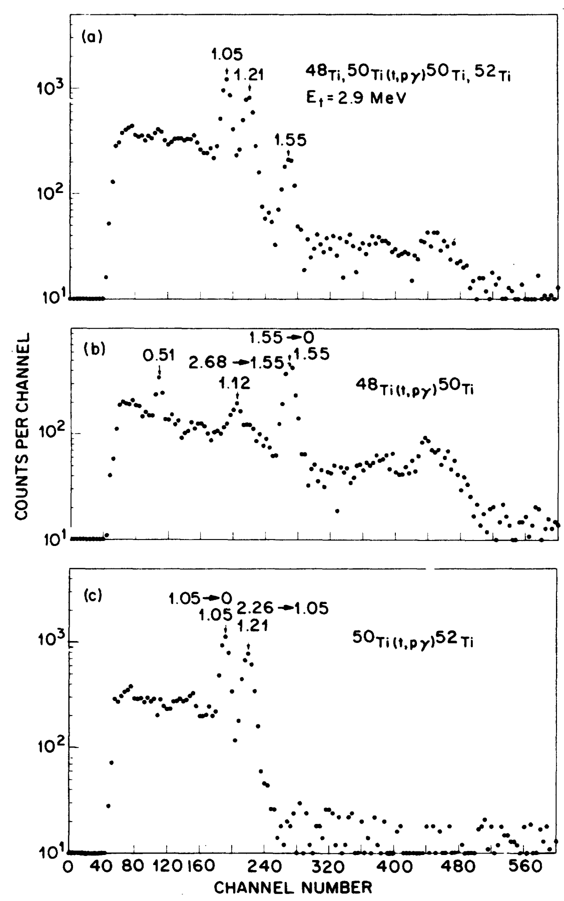

FIG. 2. The γ-ray spectrum obtained in coincidence with protons whose energy corresponds to excitation of the 2.26-MeV state (a) using a target consisting of 33% ^{48}Ti and 67% ^{50}Ti and (b) using a target consisting of 99.9% ^{48}Ti. Spectrum (c) was obtained by subtracting spectrum (b) from (a). Random coincidences have been subtracted from all of these spectra. The photopeaks of the γ rays are labeled by their associated energy in MeV.

TABLE I. The Legendre-polynomial-expansion coefficients for the angular correlations obtained in the present experiment for the decay of some of the ^{52}Ti states. The analyses include the appropriate correction for the solid angle of the γ-ray detectors.

State (keV)	E_i (keV)	E_f (keV)	a_2/a_0	a_4/a_0
1047	1047	0	0.73 ± 0.06	-1.62 ± 0.07
2259	2259	1047	0.47 ± 0.07	-0.05 ± 0.08
	1047	0	0.36 ± 0.14	0.64 ± 0.15
2428	2428	1047	-0.07 ± 0.14	-0.08 ± 0.15
	1047	0	0.30 ± 0.09	0.82 ± 0.10
3582	3582	1047	0 ± 0.15	0 ± 0.16
	1047	0	0.24 ± 0.03	0.17 ± 0.03
3900	3900	1047	-0.30 ± 0.11	0.06 ± 0.12
	3900	2259	-0.03 ± 0.09	0.05 ± 0.10
	2259	1047	0.55 ± 0.10	0.49 ± 0.10
	1047	0	0.33 ± 0.05	-0.07 ± 0.05
4230	4230	0	-0.87 ± 0.08	0.06 ± 0.09
	4230	1047	-0.30 ± 0.06	0.15 ± 0.07
	1047	0	0.32 ± 0.08	0.15 ± 0.08

III. Ge(Li) SPECTROMETER MEASUREMENTS

A 20-cm^3 Ge(Li) detector was used to obtain γ-ray spectra in coincidence with particles stopped in the 1000-μm-thick annular-silicon counter. The Ge(Li) detector was positioned alternately at 30 and 120° for the data collection, so that lifetime information could be obtained from the observed Doppler-shift attenuations. Also extracted from these spectra were branching-ratio information and excitation energies; these are given in Fig. 3. The energy calibration for the Ge(Li) detector was obtained from ^{52}Cr (1434.19-keV) and ^{18}O (1982.2-keV) lines which appeared in the coincident γ-ray spectra as well as from radioactive calibration sources. The target for this work consisted of a ^{50}Ti foil having an areal density of 3 mg/cm^2. This is a "thick" target for the triton beam as well as for the recoiling ^{52}Ti ions.

TABLE II. Multipole-mixing ratios for various γ-ray transitions in ^{52}Ti as observed in the present studies.

E_i (keV)	E_f (keV)	J_i	J_f	Multipole-mixing ratio [a]
2259	1047	2	2	-0.03 ± 0.10
2428	1047	2	2	0.39 ± 0.08
3900	1047	1	2	≤ -0.08, 0.70 ± 0.35
		2	2	≥ 0.46
		3	2	-0.07 ± 0.10
3900	2259	1	2	undetermined
		2	2	0.31 ± 0.22
		3	2	-0.18 ± 0.18
4230	1047	1	2	-0.12 ± 0.13
		2	2	$+0.51 \pm 0.16$
		3	2	-0.04 ± 0.11

[a] The mixing ratio is defined in terms of $\langle L+1\rangle/\langle L\rangle$ and has the phase of Ref. 4 and of H. J. Rose and D. M. Brink [Rev. Mod. Phys. 39, 306 (1967)].

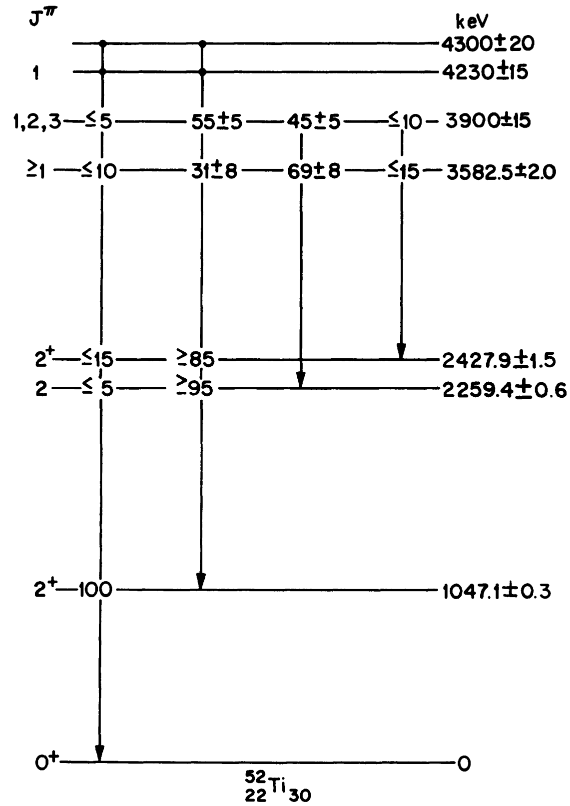

FIG. 3. A summary of spectroscopic information obtained in the present experiment for the excited states of ^{52}Ti. The dots represent those transitions which were observed experimentally but for which no corresponding branching ratio could be assigned. The data for states with $E_x \geq 3900$ keV were obtained only with NaI(Tl) detectors.

In order to compute an average recoil velocity, the yield as a function of energy for the proton groups populating the ^{52}Ti states was deduced from a shape analysis of the "thick"-target proton spectra taken in coincidence with various γ rays. This information was translated into an average

TABLE III. A summary of the mean-lifetime information obtained in this experiment for excited states of ^{52}Ti.

State (keV)	E_γ (keV)	$F(\tau_m)$	τ_m (psec)
1047	1047	0.044 ± 0.029	$4.8^{+8.0}_{-2.1}$
2259	1212	0.854 ± 0.063	$0.05^{+0.03}_{-0.02}$
2428	1381	≥ 0.75	≤ 0.10
3582	1323	≥ 0.76	≤ 0.09

velocity for the recoiling ^{52}Ti ions which was used to compute the attenuation factors $F(\tau_m)$. The lifetimes were calculated using the stopping theory of Lindhard, Scharff, and Schiøtt[5] and the approximate nuclear-scattering theory of Blaugrund.[6] In the absence of pertinent experimental information, the value for the electronic stopping parameter K_e for Ti slowing down in Ti was calculated to be 3.046 keV cm^2/μg and assigned an uncertainty of ±15%. The Doppler-shift-attenuation factor and the mean lifetime derived therefrom are given in Table III as $F(\tau_m)$ and τ_m, respectively.

IV. RESULTS

A. 1047-keV state

The angular-correlation data obtained for the 1047-keV transition were found to contain a very large A_4 term (see Table I) which immediately implies a spin assignment of $J \geq 2$ for the 1047-keV state. The least-squares analyses resulted in χ^2 values of 557, 2.3, and 532 for spin assignments of $J=1$, 2, and 3, respectively. Since the 0.1% confidence limit is at a χ^2 value of about 5.4, the spin of this state is $J=2$. The measured lifetime of $4.8^{+8.0}_{-2.1}$ psec corresponds to an $E2$ strength of 12^{+9}_{-7} W.u. (Weisskopf units) and an $M2$ strength of 500^{+500}_{-290} W.u. Because this latter value is too high to be typical of $M2$ strengths, it can be safely assumed that the parity of this state is positive. This is in agreement with the $J^{\pi}=2^+$ assignment from previous work.[1]

B. 2259- and 2428-keV states

The proton groups corresponding to these two states are illustrated in Fig. 1 and the coincident γ-ray spectra associated with the 2259-keV state are given in Fig. 2. As can be seen, the groups are reasonably well separated in energy and the coincident γ-ray spectrum for each state was obtained from that portion of each proton group which was completely free from overlap with its neighbor. The observed angular correlations for γ-ray transitions from the 2259-keV state are illustrated in Fig. 4 along with the corresponding least-squares fit and χ^2 analyses. The best fit is for a spin assignment of $J=2$; the corresponding mixing ratio is given in Table II. Using the measured lifetime and mixing ratio one obtains $M1$ and $E1$ strengths ~0.37 and ~0.008 W.u., respectively, for the 2259- to 1047-keV transition; thus no parity assignment can be made.

The observed angular correlations for the γ rays from the 2428-keV state were very similar to those for the 2259-keV state. The analyses resulted in χ^2 values of 39, 18, 2, 19, and 18 for the various spin possibilities $J=0$ to 4, respectively. The 0.1% confidence limit is at a χ^2 value of 4.3; hence, one obtains a unique spin assignment of $J=2$ for the 2428-keV state. Using the measured lifetime limit and mixing and branching ratios one obtains for the 2428- to 1047-keV transition $M1$ and $E2$ strengths of ≥ 0.12 and ≥ 11 W.u., respectively, and $E1$ and $M2$ strengths of ≥ 0.003 and ≥ 467 W.u., respectively. The $M2$ strength is too large while the $M1$ and $E2$ strengths are typical, implying a positive parity for this state.

C. 3582-keV state

The proton group leading to the 3582-keV state, as illustrated in Fig. 1, was well resolved from nearby states. The angular correlations were analyzed for two γ rays cascading from this state, and the Legendre polynominal-expansion coeffi-

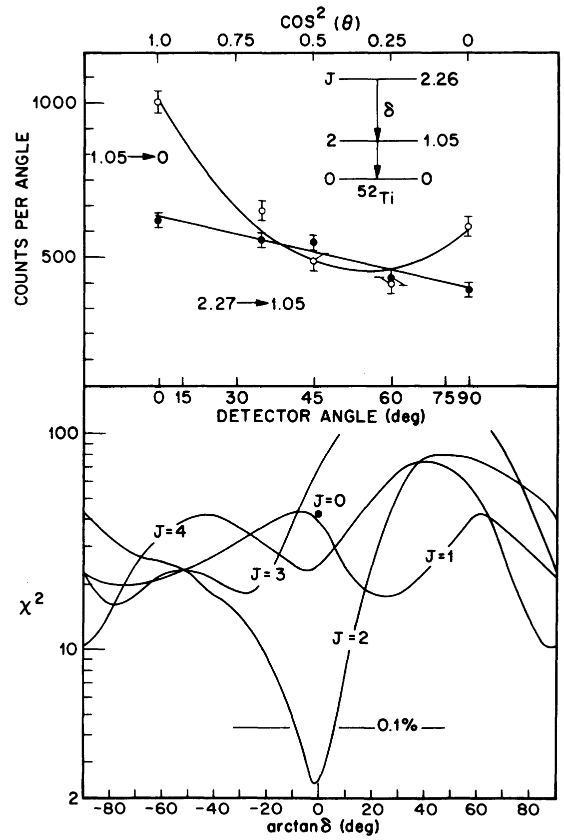

FIG. 4. The angular correlations of the γ rays cascading from the 2.26-MeV state and the associated χ^2 analyses. The solid lines through the data points represent the best fit for spin $J=2$ and have been corrected for the solid angle of the γ-ray detectors. The finite-size effect of the particle counter has been included in the analyses.

cients are given in Table I. The 3582 → 1047-keV transition has an isotropic correlation, but the 1047 → 0-keV transition is anisotropic implying that the 3582-keV state must have a spin of $J \geq 1$. Unfortunately, no further information can be extracted from the angular correlation for this transition due to the fact that the 1047-keV state is being fed by two cascade routes from the same state (see Fig. 3). The angular correlation for the 3582 → 2259-keV transition could not be reliably extracted from the data because of nearby peaks.

D. 3900-keV state

Angular correlations of four γ rays cascading from this state were obtained and the corresponding Legendre-polynominal-expansion coefficients are given in Table I. As in the case of the 3582-keV state, the 1047 → 0-keV transition is fed in parallel which makes it difficult to obtain meaningful information from that transition alone. The angular correlation for the 3900 → 1047-keV transition was analyzed separately and acceptable fits were found for $J = 1$, 2, and 3. The angular correlations for the 3900 → 2259 → 1047-keV cascade were analyzed simultaneously but no further spin limitations could be made. The multipole-mixing ratios resulting from these analyses are given in Table II.

E. 4230-keV state

An angular correlation was extracted from the data for the 4230 → 0-keV transition and the Legendre polynominal coefficients are given in Table I. The analyses of these data resulted in χ^2 values of 2.3, 146, and 167 for the spins $J = 1$ to 3, respectively. Since the 0.1% confidence limit is at a χ^2 value of 5.4, the spin of this state is $J = 1$. Along with the above transition, γ-ray lines corresponding to a cascade through the 1047-keV state were also observed in coincidence with the 4.23-MeV proton group of Fig. 1. The analysis of the angular correlation for this cascade gave acceptable fits for $J = 1$, 2, and 3, and the corresponding mixing ratios are given in Table II.

Because of the low efficiency of the Ge(Li) counter for γ rays of this energy and the weak population of this state, the decay modes could only be obtained from the data taken with the NaI(T1) counters. In addition to this, the proton groups in this region of excitation (see Fig. 1) are not adequately resolved; this introduces uncertainty in establishing accurate branching ratios for states at this excitation as well as to leave open the possibility that this proton group might represent a doublet of states.

V. DISCUSSION

Although no calculations on the structure of ^{52}Ti have been reported, one might hope to get a first-order approximation to the level structure by comparison with the excited states of ^{50}Ti and ^{58}Ni. The former nucleus has a closed neutron shell and two $f_{7/2}$ protons, while the latter has a closed proton shell and two $p_{3/2}$ neutrons. Figure 5 illustrates the experimentally known level schemes of the above three nuclei. The three low-lying 2^+ states in ^{52}Ti can probably be explained as a mixture of the configurations $(f_{7/2})^2{}_2 \times (p_{3/2})^2{}_0$, $(f_{7/2})^2{}_0 \times (p_{3/2})^2{}_2$, and $(f_{7/2})^2{}_2 \times (p_{3/2})^2{}_2$. Since the (t, p) reaction would be expected to populate preferentially those states where only the $(p_{3/2})^2$ neutron configuration is excited, the relatively equal population of the three 2^+ states indicates that the three basic configurations are probably rather well mixed, accounting for the spread of excitation energies shown in Fig. 5. Although there is no experimental evidence for $J^{\pi} = 4^+$ and 6^+ states, one would expect to see the states based on the $(f_{7/2})^2{}_4 \times (p_{3/2})^2{}_0$ and $(f_{7/2})^2{}_6 \times (p_{3/2})^2{}_0$ configurations which correspond to the second and third excited states of ^{50}Ti. If these states are relatively pure $(f_{7/2})^2$ configurations, however, they might not be populated readily with the (t, p) reaction. The comparisons shown on Fig. 5 suggest that there should be many more ^{52}Ti levels in the excitation region $E_x < 4$ MeV than

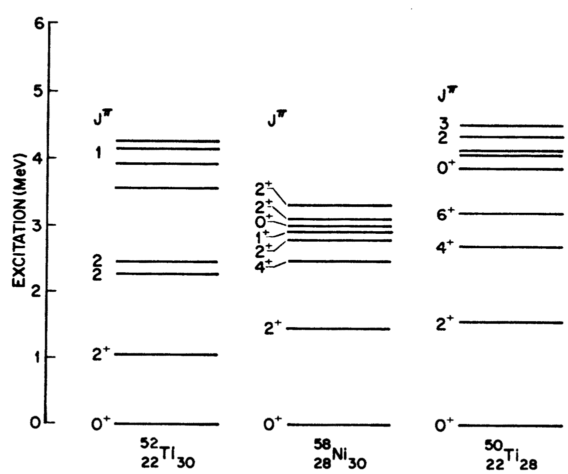

FIG. 5. The experimentally observed level schemes of ^{52}Ti, ^{58}Ni, and ^{50}Ti.

were actually observed in the present experiment. If these levels are weakly excited in the (t,p) reaction, they might be seen with a magnetic spectrometer although they were not reported in Refs. 1 and 2. In any case, more experimental data as well as detailed theoretical calculation are needed in order to clarify the spectroscopy of ^{52}Ti.

Note added in proof: A recent report by Horie and Ogawa which appeared in Nucl. Phys. A216, 407 (1973) contains the results of shell-model calculations for the nucleus ^{52}Ti. The authors calculate states of $J^{\pi}=2^{+}$ at excitations of 0.99 and 1.81 MeV. They find that the lower state is predominantly of the $(f_{7/2})^2{}_0 \times (p_{3/2})^2{}_2$ configuration and the upper of the $(f_{7/2})^2{}_2 \times (p_{3/2})^2{}_0$ type. The former configuration would presumably correspond to the experimentally observed 1047-keV state since it is strongly populated[1] with an $L=2$ angular momentum in the two-neutron transfer. No other $J^{\pi}=2^{+}$ states are reported but the authors do report a $J^{\pi}=4^{+}$ and 3^{+} state at 2.40 and 2.42 MeV, respectively, which are based on the $(f_{7/2})^2{}_2 \times (p_{3/2})^2{}_2$ configuration coupled to these J^{π} values. As was pointed out in the text no experimental evidence for these states has been found in the present study.

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