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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 $m=\pm2$ 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 $m=\pm2$ 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.

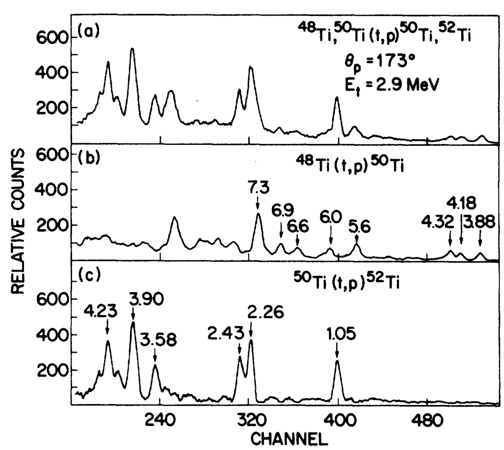

FIG. 1. The proton spectra measured in time coincidence with all γ rays observed by the five NaI(Tl) detectors (a) using a target consisting of 33% ^{48}Ti and 67% ^{50}Ti and (b) using a target of 99.9% ^{48}Ti. The proton spectrum in (c) was obtained by subtracting spectrum (b) from spectrum (a) and 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.

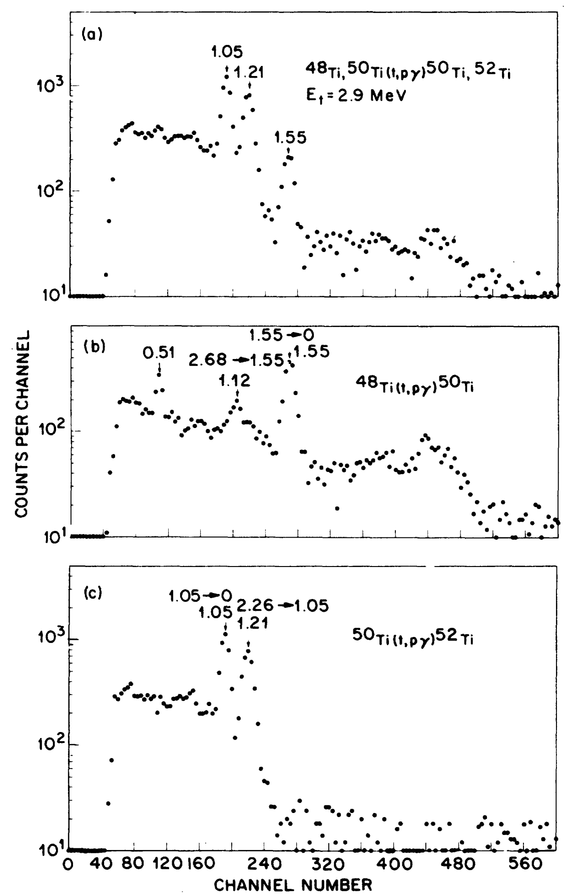

FIG. 2. The γ-ray spectrum obtained in coincidence with protons whose energy corresponds to excitation of the 2.26-MeV state (a) using a target consisting of 33% ^{48}Ti and 67% ^{50}Ti and (b) using a target consisting of 99.9% ^{48}Ti. Spectrum (c) was obtained by subtracting spectrum (b) from (a). 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.

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 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 ± 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)].

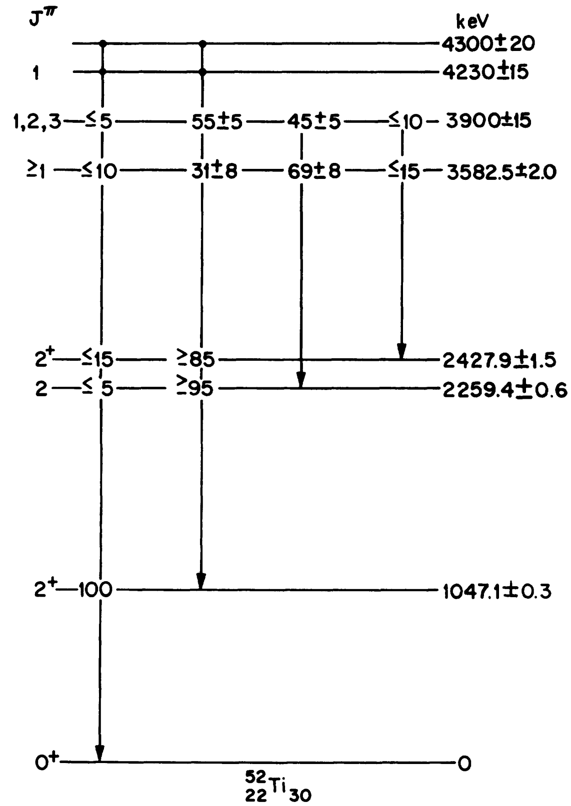

FIG. 3. A summary of spectroscopic information obtained in the present experiment for the excited states of ^{52}Ti. The dots represent those transitions which were observed experimentally but for which no corresponding branching ratio could be assigned. The data for states with $E_x \geq 3900$ keV were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

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-

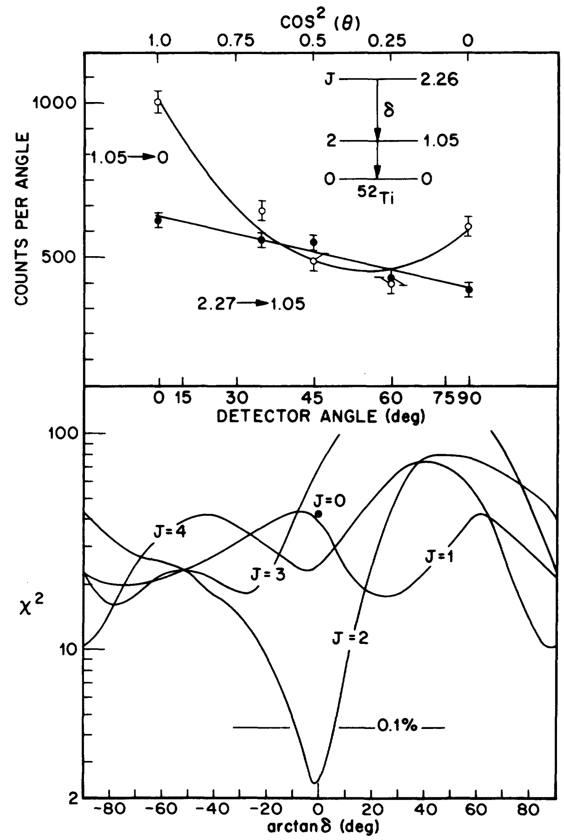

FIG. 4. The angular correlations of the γ rays cascading from the 2.26-MeV state and the associated χ^2 analyses. The solid lines through the data points represent the best fit for spin $J=2$ and have been corrected for the solid angle of the γ-ray detectors. The finite-size effect of the particle counter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

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. [illegible] 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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