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Decays of the lowest $T = 2$ state in ^{44}Ti

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The $^{46}\mathrm{Ti}(p,t)^{44}\mathrm{Ti}$ reaction is used to populate the lowest $T = 2$ level and decay products from the level are detected in coincidence. The branching ratio for isospin forbidden α decay to ^{40}Ca(g.s.) is $\Gamma_\alpha/\Gamma = (32 \pm 5)\%$; the directly measured γ-decay branching ratio is $\Gamma_\gamma/\Gamma = (54 \pm 11)\%$. The proton decay branching ratio is found to be less than 4%.

[NUCLEAR REACTIONS $^{46}\mathrm{Ti}(p,t)$, $E_p = 42$ MeV. Measured charged particle and γ branching ratios from 9.338 MeV $(0^+, 2)$ level. Measured charged particle branching ratios from 9.298 MeV level.]

The decays of $T = 2$ levels in self-conjugate nuclei can provide information about the charge-dependent nuclear force and also directly probe the isospin properties of the electromagnetic interaction itself. Under favorable circumstances the absence of radiative decays to lower $T = 0$ levels can be interpreted in terms of limits on possible isotensor electromagnetic currents.[1] The lowest $T = 2$ level in ^{44}Ti at 9.338 MeV with $J^\pi = 0^+$ has already been studied experimentally with these points in mind.[2-4] Figure 1 shows a partial level scheme for ^{44}Ti. In common with the corresponding levels in other $4n$ self-conjugate light and medium weight nuclei all particle decay channels of the lowest $T = 2$ state are isospin forbidden. In lighter nuclei isospin forbidden particle decays are the principal decay modes of the $T = 2$ states.[5] However, due primarily to the increasing height of the Coulomb barrier in heavier systems, the particle widths decrease steadily, and in ^{44}Ti γ decays are significant. ^{44}Ti is also the heaviest system for which absolute decay widths can be determined because suitable targets do not exist for resonance studies of $T = 2$ states in $4n$ self-conjugate nuclei heavier than ^{44}Ti.

In this paper we present results from an experimental determination of the particle and γ-decay branching ratios for the 9.338 MeV level in ^{44}Ti. We combine these results with other information about the $T = 2$ level and summarize the properties that are important for considerations of isospin mixing. The present study is a continuation of a previous experiment[6] in which an upper limit on charged particle decays are found. The general conclusion that γ-decay strength is significant is verified in the present work, but the measured branching ratio for α decay is significantly larger than the 8% upper limit from Ref. 6. Reanalysis of the previous data indicated that an error was made in that work in accounting for a large fraction of the singles counts inadvertently not prescaled, but it is not clear that this error can completely explain the discrepancy. The two experiments are similar, but there are several improvements in the present work. The beam dump was moved out of the scattering chamber to a shielded area several meters away, thus reducing backgrounds. In addition, a thicker target led to an increased count rate and allowed the measurement to be repeated under different conditions. In the present work both α and γ decays were detected, and the sum of

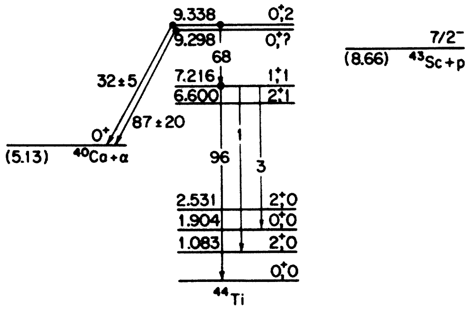

FIG. 1. A partial level scheme of ^{44}Ti. The γ-decay branching ratios of the 7.216 MeV level are taken from Ref. 4. The γ-decay branching ratio of the 9.338 MeV level is obtained from the present α-branching ratio with the assumption $\Gamma_\alpha + \Gamma_\gamma = \Gamma$.

the resultant branching ratios is in satisfactory agreement with the conclusion that all of the decay strength has been seen.

In this work the 9.338 MeV level was populated by the ^{46}Ti (p,t) ^{44}Ti reaction with a 42 MeV proton beam from the Princeton AVF cyclotron by bombarding a ~1 mg/cm^2 target isotopically enriched to 84% ^{46}Ti. Outgoing tritons at - 22.5° were momentum analyzed in a quadrupole-dipole-dipole-dipole spectrometer (QDDD) having a 14 msr solid angle. Tritons were detected in the focal plane with a 2.5 cm thick by 50 cm long resistive-wire proportional counter filled with a mixture of argon and 10% methane. The proportional counter was backed with a plastic scintillator forming a ΔE-E combination that was used in particle identifier mode to discriminate tritons from other particles of similar rigidity. Counts in the focal plane from inelastically scattered protons were reduced with the aid of an electrostatic deflector. The experimental geometry is shown in Fig. 2.

Charged particles were detected with surface barrier detectors located inside the scattering chamber ~4 cm from the target at 120° to the beam direction. A mask with an ~8 mm diameter hole covered this detector but the effective solid angle was determined by a calibration reaction to be discussed later. Data giving consistent results were taken with two different detector systems: in one case (run 1) a combination of a 16 μm thick "ΔE" (50 mm^2) and 50μm thick "E" (100 mm^2) used in particle identifier mode and the 50 μm detector by itself in another (run 2). A 1000 μm thick veto detector was used in both cases. The beam current was limited to ~100 nA in run 1 and the rates in the various elements of the detector were kept below 20 kHz to reduce the effects of pulse pileup. In run 2 the γ decays were measured simultaneously and the beam current was reduced to ~50 nA to prevent loss of resolution in the γ detector.

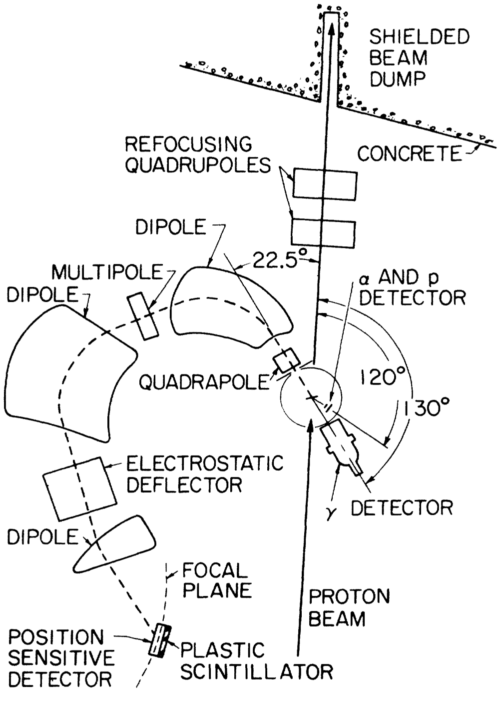

FIG. 2. Schematic of the experiment showing the various elements of the QDDD spectrometer and the charged particle and γ detectors. The proton beam is refocused into a shielded Faraday cup after passing through the ^{46}Ti target.

γ rays were detected with a 10 cm × 13 cm NaI (Tl) detector located 24 cm from the target at 130° to the beam direction. A quadrupole doublet focused the proton beam which passed through the target into a Faraday cup 7 m from the target; the beam dump was shielded with 1.5 m of concrete so that the main source of background γ radiation was the target. 1 cm of lead was placed between the NaI detector and the target in order to reduce the background of low energy γ rays from radioactivity induced in the target.

Coincidences between signals in the QDDD focal plane and either the charged particle detector or the γ-ray detector were processed with a standard system of fast electronics based on a time-to-amplitude converter (TAC). The TAC was started by a signal derived from a fast beam burst pickup, in fast coincidence with signals from the focal plane scintillator, and was stopped by a timing signal from one of the surface barrier detectors. This technique allowed us to enhance the real to random coincidence ratio by using the beam arrival time ($\Delta t \leq 1$ ns) as a much more precise time reference than the triton arrival time ($\Delta t \leq 70$ ns).

The principal requirements for a recorded event were simultaneous signals in the ΔE-E focal plane detector with energies that correspond to a triton. For a coincident event an additional requirement was a coincident output from either the "triton-particle" or "triton-γ" TAC. A sample of one-tenth of the singles triton events was collected simultaneously. The singles sample was corrected for prescaling and used with coincidence events to calculate branching ratios.

The energy signal from the γ-ray detector, the charged particle detectors, the outputs of the two TAC's, and the position signal from the resistive wire detector were fed into separate analog to digital converters. Data were written on magnetic tape event-by-event by a Sigma 2 computer and the analysis was performed off-line.

Figure 3(c) shows the singles triton spectrum in the region of the ^{44}Ti $T = 2$ state from run 1. The

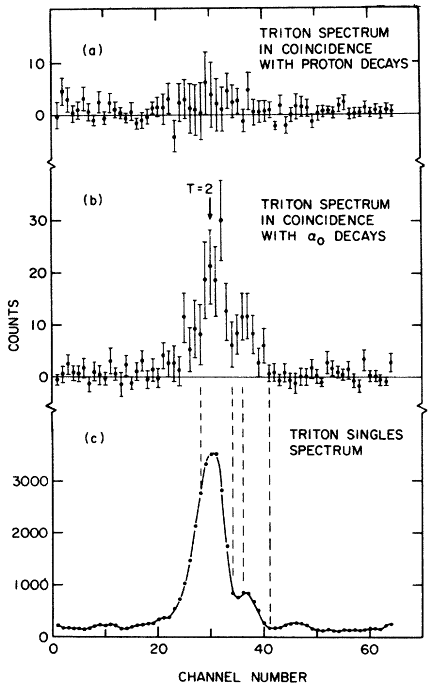

FIG. 3. Triton spectra (a) in coincidence with protons, (b) in coincidence with α particles, and (c) in singles (the prescaled noncoincidence sample). The region around the $T=2$ states used in computations of branching ratios is shown by the dashed line.

energy resolution is limited by triton straggling in the thick target. The smaller peak to the right of $T=2$ state in Fig. 2 has previously been identified as $J^\pi=0^+$ ($E_x=9.298$ MeV).[2,8] Data taken with a thinner target and better resolution indicate that another level at ≈9.36 MeV is weakly populated in the (p,t) reaction.[7] We made a preliminary measurement of its angular distribution which indicated that this level is not 0^+. It is interesting to note that a level at about this energy was also seen in the ^{40}Ca (α,γ) ^{44}Ti reaction.[3]

Figure 4 shows the α spectrum in coincidence with tritons in a window around the $T=2$ state. The energy of the peak in the α spectrum is in good agreement with the value (4.25 MeV) expected from calculations of the three-body kinematics for α decay of the $T=2$ state with our geometry. The charged particle detector was independently energy calibrated with α particles from ^{241}Am decay.

A triton spectrum in coincidence with protons and α particles from the decay of ^{44}Ti is shown in Figs. 3(b) and 3(c). Branching ratios were obtained from the peak areas in these spectra after correcting for the measured coincidence counting efficiency of the system, the transformation of detector solid angle from the center of mass of the decaying ^{44}Ti to the laboratory frame, and a small (~5%) correction for pileup. A spectrum of γ rays in coincidence with tritons populating the $T=2$ state (from run 2) is shown in Fig. 5. The main γ rays are at 7.2 and 2.1 MeV as expected from the results of Ref. 4 (see Fig. 1).

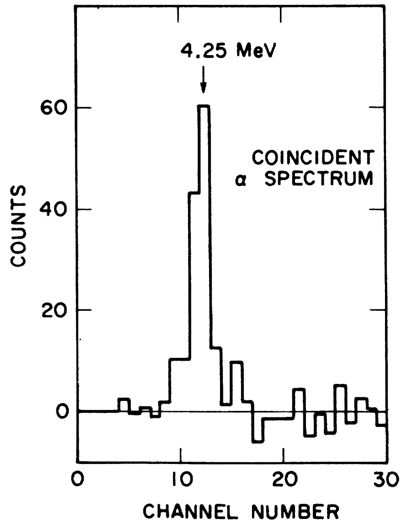

FIG. 4. α-particle spectrum in coincidence with tritons from the $T=2$ state (from run 1).

The coincidence counting efficiencies for charged particles and γ rays were found by performing a similar measurement of the decays of the 8.92 MeV level of ^{13}N populated in the ^{14}N(p,d) reaction. For this determination an adenine target replaced the ^{46}Ti target and the QDDD was readjusted to detect deuterons of the correct rigidity—all other parameters of the experiment were unchanged. The ^{13}N (8.92 MeV, $J^\pi=\frac{1}{2}^-$) level isotropically emits protons to the ground and 4.4 MeV first excited states of ^{12}C. Since the 8.92 MeV level is very wide (230 keV[8]), radiative deexcitation should

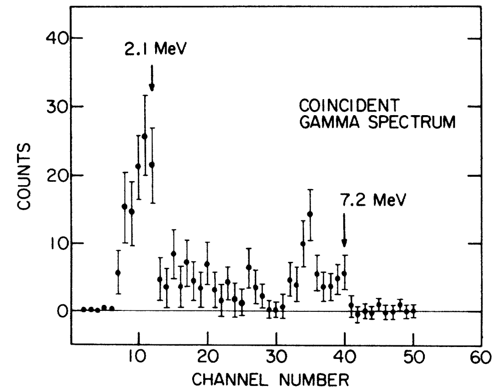

FIG. 5. γ spectrum in coincidence with tritons from the $T=2$ state (from run 2).

TABLE I. Results for the decay branching ratios for the 9.338 MeV $T=2$ and the 9.298 MeV level in ^{44}Ti.

State	Decay mode	Run 1	Run 2	Combined result
9.338 MeV	α_0	35 ± 5	27 ± 6	32 ± 5
($J^\pi = 0^+, T = 2$)	p_0	<8	<5	<4
	γ	···	54 ± 11	54 ± 11
9.298 MeV	α_0	100 ± 25	60 ± 35	87 ± 20
($J^\pi = 0^+, T = ?$)	p_0	<9	<9	<6

be negligible and we assume that the two proton branches sum to 100%. The relative proton branching ratio was measured to be $(\Gamma_{p_0}/\Gamma_{p_1}) = 1.6 \pm 0.2$. This determined the γ-ray yield and permitted us to determine the coincidence detection efficiency for the 4.4 MeV γ ray. The ratio of efficiencies at 7.2 and 4.4 MeV was determined from the tables of Marion and Young and Miller and Snow.[9]

Our results for particle and γ decay branching ratios from two runs are shown in Table I. The errors in the branching ratios include the sysmatic errors from the calibration measurement and from extrapolating the γ-detection efficiency at 4.44 to 7.2 MeV. In a recent study of the lowest $T=2$ state in ^{44}Ti using the ^{40}Ca(α,γ) ^{44}Ti reaction, Dixon *et al.*[4] obtained $\Gamma_\alpha\Gamma_\gamma/\Gamma = 0.24 \pm 0.05$ eV. Combining this result with our branching ratio for α decay, $(\Gamma_\alpha/\Gamma = 32 \pm 5)\%$ gives $\Gamma_\gamma = (0.75 \pm 0.19)$ eV. This corresponds to 3.8 W.u. (Weisskopf units) for an *M*1 transition and is in remarkably close agreement with the $(fp)^4$ shell model calculation of Simpson *et al.*[3] (4.3 W.u.). Under the assumption that the $T=2$ level decays only by α and γ emission, the total width is $\Gamma = (1.10 \pm 0.28)$ eV and the α width is $\Gamma_\alpha = (0.35 \pm 0.07)$ eV. The Wigner limit for α decay is $\Gamma_w \approx 6000$ eV resulting in a reduced α width of 6×10^{-5}. This value is typical for isospin forbidden α decays of $T=2$ levels.[5]

The limit on proton decays of the $T=2$ state is only a slight improvement on the 5% limit found in Ref. 3 by another method. This measurement was hampered by the background of high energy protons from elastic scattering. It should be noted, however, that the Wigner limit for proton decay to ^{43}Sc(g.s.) and ^{43}Sc(0.152) are only $\Gamma_w \sim 3 \times 10^{-2}$ eV and $\Gamma_w \sim 2 \times 10^{-2}$ eV. Thus with any reasonable inhibition because of isospin, proton decay is negligible as we have assumed above. The sum of the experimental γ- and α-decay branching ratio is $86 \pm 12\%$, only slightly more than one standard deviation from the 100% expected.

TABLE II. Results for the γ decay widths of the $T=2$ level. The values are obtained from combining the result for Γ_α/Γ with those values of $\Gamma_\alpha\Gamma_\gamma/\Gamma$ from the work of Dixon *et al.* (Ref. 4). Upper limits are (1σ).

Transition	ΔT	Γ_γ (eV)	$\lvert M\rvert^2$ (W.u.)
9.338 → 7.216 (*M*1)	1	0.75 ± 0.19	3.8
9.338 → 1.083 (*E*2)	2	$<2.2 \times 10^{-3}$	$<7.9 \times 10^{-3}$
9.338 → 2.531 (*E*2)	2	$<6.9 \times 10^{-3}$	$<6.4 \times 10^{-2}$

The results for charged particle decays of 9.298 MeV are also shown in Table I. A small value for Γ_α/Γ would have suggested that any $T=0$ component in this state is small. The measured branch is consistent with 100%, however, and thus it does not aid in determining isospin. No significant limit was placed on the γ-branching ratio. We note that this level would appear narrow with our experimental energy resolution even if it were pure $T=0$.

Table II summarizes the γ decay widths for the $T=2$ state to lower levels. Of special interest are the upper limits for $\Delta T = 2$ transitions to lower $T=0$ states; the limit obtained in Ref. 4 for the transition to the 1.083 MeV level is one of the lowest obtained to date for a $\Delta T = 2$, *E*2 transition. (See Ref. 10 for a summary of previous measurements.) Such transitions could arise from isospin mixing or from an isotensor component of the electromagnetic current operator.

In conclusion, we find that the lowest $T=2$ level in ^{44}Ti decays by isospin forbidden α-particle decay and isospin allowed γ emission with comparable strengths. The measured branching ratio for α decay combined with previous radiative capture studies[4] placed a limit of $<7.9 \times 10^{-3}$ W.u. on $\Delta T = 2$, *E*2 transitions.

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