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Decay of the Lowest $T=2$ State in ^{44}Ti

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The lowest $T=2$ state in ^{44}Ti has been found in the reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti at an excitation energy of 9338 ± 2 keV in ^{44}Ti. The radiative yield has been measured and the γ decay has been studied.

The lowest $T=2$ state in ^{44}Ti has previously been located by use of the reaction[1-3] ^{46}Ti$(p, t)^{44}$Ti. The most recent determination,[3] having the smallest assigned energy uncertainty, gives an excitation energy of 9330 ± 10 keV. We wish to report the γ decay of this state studied by using the reaction ^{40}Ca$(\alpha, \gamma)^{44}$Ti.

A 10–15-μA beam of doubly charged helium ions provided by the 4-MV Van de Graaff accelerator at the National Research Council of Canada was used to bombard evaporated targets of isotopically enriched ^{40}Ca deposited on 0.025-cm gold backings. Details of the targets and experimental techniques will be found in other publications.[4,5] In the region 9.3–9.6 MeV of excitation in ^{44}Ti, ten resonances have been observed using a NaI(Tl) detector to detect γ rays with energies between 6.5 and 7.5 MeV. On examination of the γ decay of these resonances using Ge(Li) detectors the likely candidate for the $T=2$ state was found at a ^{4}He energy of 4645 ± 5 keV by comparison with resonances previously studied.[4] A Ge(Li) γ-ray spectrum observed at 0° is shown in Fig. 1. The two most prominent γ rays have energies (at 90° to the beam direction) of 7215.4 ± 2.0 and 2122.0 ± 1.0 keV. Including nuclear recoil following γ-ray emission the sum of these two γ-ray energies places the resonance at 9338 ± 2 keV, in good agreement with the ^{4}He energy (using a Q value of 5118 ± 10 keV[4]) and with the location of the $T=2$ state as determined in the (p, t) work of Rapaport *et al.*[3]

In previous α-capture work[4] and in the (p, t) experiments[2,3] no level has been observed at 2122 keV. Furthermore, both γ rays show the full Doppler shift which in the case of the 2122-keV transition means that the lifetime of the emitting state is less than approximately 10^{-14} sec. A state at 2122 keV with such a lifetime would have to have spin 1 with an $E1$ enhancement of $\gtrsim 0.8 \times 10^{-2}$ W.u. [Weisskopf units] or an $M1$ enhancement $\gtrsim 0.3$ W.u. These would be unusually large for $\Delta T = 0$ dipole transitions in a self-conjugate nucleus. The conclusion is that the γ-ray cascade from the resonance consists of the 2122-keV γ ray followed by the 7216-keV γ ray to the ground state.

The inset in Fig. 1 shows that the angular distributions of both γ rays are isotropic to within the statistical error. This is consistent with the lowest $T=2$ state having a J^π of 0^+ and with the $l=0$ angular distribution of the (p, t) reaction to the 9330-keV level.

The state at 7216 keV is likely a $T=1$ state of spin 1, because of the expected decay properties of $T=2$ states and because the experimental value of $\omega\gamma$ (see below) limits the 2122-keV radiation to dipole character. A state at 6600 ± 10 keV has been assigned in the (p, t) work of Rapaport *et al.*[3] as the $T=1$ analog of the 2^+ ground state of ^{44}Sc. The spin-1 state is thus 616 ± 10 keV above the $T=1$, 2^+ state. In ^{44}Sc there are two states near 600 keV and in particular a 1^+ state at 669 keV.[6,7] It is likely that the 7216-keV state is the analog

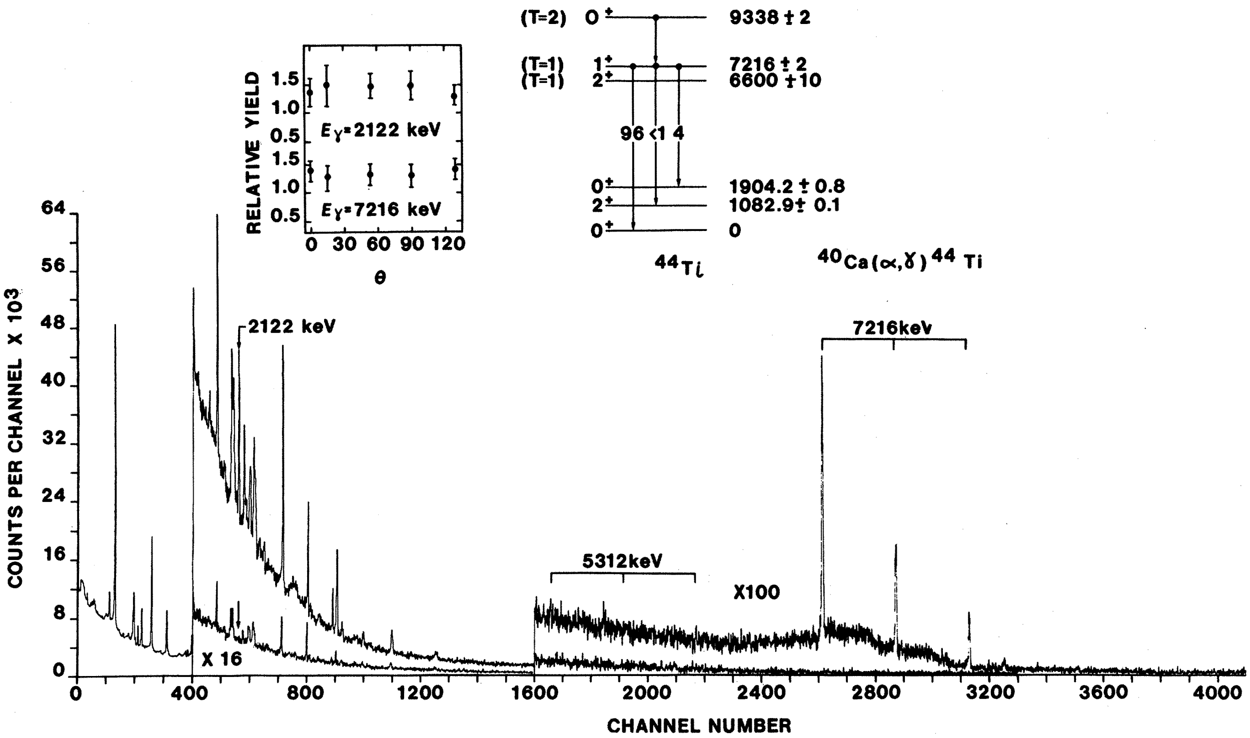

FIG. 1. Spectra of γ rays at 0° for a $^4He^{++}$ beam on a 10-keV-thick ^{40}Ca target. The upper curve shows the spectrum on resonance at $E(^4He^{++}) = 4.645$ MeV with an accumulated charge of 0.69 C. The lower curve shows portions of an off-resonance run for a $^4He^{++}$ energy 20 keV below the resonance and with an accumulated charge of 0.34 C, but with a different target-detector distance. The arrow on the lower curve near channel 550 indicates the expected position of the 2122-keV peak. The lowest channel corresponds to $E_\gamma \simeq 1$ MeV. The inset on the left shows the angular distribution of the primary γ ray from the resonance (2122 keV) and of the most prominent secondary from the 7216-keV level to the ground state. The inset on the right shows the proposed decay scheme of the $T=2$ and $T=1$ states.

of this 1^+ state in ^{44}Sc. The other state, at 632 keV,[7] is either 3^- or 4^-.

The strengths of transitions from the $T=2$ and $T=1$ states are shown in Table I and Fig. 1. It is assumed that unobserved transitions have zero strength. There may be a transition from the resonance to the first excited state but it is so weak that it has not been possible to decide whether it is resonant at the same energy as the $\Delta T=1$ transitions. Consequently an upper limit on a $\Delta T=2$, $E2$ transition of 1% is assigned.

The radiative yield of the resonance, $\omega\gamma = (\Gamma_\alpha \Gamma_\gamma/\Gamma)_{c.m.}$, has been determined from the thick-target yield of γ rays as described in Ref. 4, and a value for $\omega\gamma$ of 0.12 eV has been obtained, with an estimated uncertainty of 20%. Since the resonance may have a proton decay width Γ_p, a search for a 373.4-keV γ ray from the decay of ^{43}Sc (22% branch,[8] $T_{1/2} = 3.94$ h) was made by recording the background spectrum from the target for about 1.5 half-lives following a bombardment on resonance of about 2 half-lives. No evidence for the γ ray was found and a limit on Γ_p/Γ_γ of ≤ 0.05 (2 standard deviations) can be put on the total proton width.

An upper limit on Γ of 4.5 keV is obtained from the yield curve. If $\Gamma_\alpha \gg \Gamma_\gamma$, then Γ_γ for the $T=2$ state is 0.12 eV and the reduced transition strength $|M(M1)|^2$ for the 2122-keV decay is about 0.6 W.u. (If this transition were $E2$, its enhancement would be >375 W.u.) A $\Delta T=2$, $E2$ transition to the first excited state then has a reduced transition strength of $\lesssim 0.004$ W.u. This upper limit is about 10 times weaker than that found for the corresponding transition in self-conjugate nuclei in the s-d shell.[9-10]

Wave functions have been calculated for the ground and first excited states and for the $T=1$, 1^+ and $T=2$, 0^+ states of ^{44}Ti with four valence nucleons in the f-p shell and using the renor-

TABLE I. Branching ratios and transition strengths.

Transition (E_x in keV)	Branching ratio Expt (%)	Branching ratio Theory[a] (%)	$\Gamma_\gamma(M1)$ Expt (eV)	$\Gamma_\gamma(M1)$ Theory[a] (eV)
9338 → 7216	99	100	0.12[c]	0.85
→ 1083	0.9 ± 0.4	⋯		
→ 0	0.2 ± 0.4	⋯		
7216 → 1904	4.0 ± 1.3	b		b
→ 1083	< 1.0	3		0.17
→ 0	96	97		5.78

[a]An $(fp)^4$ shell model calculation. See text.
[b]The 1.90-MeV level does not occur in an $(fp)^4$ calculation.
[c]Assuming $\Gamma_\alpha \gg \Gamma_\gamma$.

malized two-body matrix elements of Kuo and Brown.[11] The first excited 0^+ state is not accounted for by the $(fp)^4$ calculation. With these wave functions $M1$ transitions between the different isospin states have been calculated and are shown in the table. Bare-nucleon g factors have been used in the dipole operator. The branching ratios of the $T=1$, 1^+ state to the ground and first excited states are qualitatively accounted for although the nonobservation of a transition to the first excited state may indicate considerable dilution of the $(fp)^4$ purity of the latter state. The 4% branch to the excited 0^+ state at 1.90 MeV, however, may indicate relatively little mixing between the underlying configurations forming the ground and 1.90-MeV states. The absolute strength of the $T=2$ to $T=1$ transition is calculated to be too strong by a factor of 7. A similar result was noted in ^{28}Si where the discrepancy was attributed to the simplicity of the shell-model wave functions used.[10]

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