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Evidence for Rotational Bands in ^{44}Ti

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The results of measurements of γ-ray angular distributions, γ-γ coincidences, and attenuated Doppler shifts for the reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti are presented, providing strong evidence that twelve of the fourteen excited states below 4.1 MeV can be grouped into four rotational-like bands.

The energy levels of the nucleus ^{44}Ti have been studied recently by a variety of methods, including the reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti, the (p,t) reaction on ^{46}Ti, and α-transfer reactions such as (^{6}Li, d) and (^{16}O, ^{12}C). One motivation for studying ^{44}Ti was to see if its spectrum exhibited a simplicity similar to that of ^{20}Ne; but the early experiments[1] showed that there are many more levels at low energy in ^{44}Ti than in ^{20}Ne and that the first four excited states in ^{44}Ti could be described in first approximation by the vibrational model. However, because of the strong transition observed between the 2^+ and 0^+ members of the two-phonon state the authors speculated that these levels might alternatively be the first two members of a rotational-like band. There was not sufficient evidence to suggest a particular structure for the more highly excited states. Here we shall present a summary of the results of further α-capture experiments which provide strong evidence that twelve of the fourteen excited states of ^{44}Ti below about 4.1 MeV can be grouped into four rotational-like bands.

The reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti has been studied using the 4-MV Van de Graaff accelerator of the National Research Council in Ottawa. Experimental details of γ-ray angular-distribution experiments and attenuated Doppler-shift measurements are presented in Ref. 1 and by Dixon, Storey, and Simpson.[2] These experiments have continued and in addition γ-γ coincidence experiments have been carried out to detect weak, low-energy transitions between the bound states, transitions which in some cases are obscured by contaminant lines in singles Ge(Li) spectra. In these experiments an annular NaI(Tl) detector was used to select the high-energy primary γ decays from a resonant state, and a Ge(Li) detector in coincidence recorded the low energy γ-ray spectrum at 0°.

Figure 1 displays the proposed band structure in a plot of E_J versus $J(J+1)$. The evidence for spin assignments in given below. Figure 2 is a decay scheme, separating the levels into the proposed bands, and showing the branching ratios and $E2$ enhancements which are the prime evidence linking certain levels into bands. A summary of the new evidence follows, band by band.

Ground-state band.—States at 1083 keV (2^+), 2454 keV (4^+), and 4015 keV (6^+) form a band based on the ground state. The spin, parity, and lifetime of the first two states are established in Refs. 1 and 2 and in other recent works.[3-5] The 4.02-MeV state is assigned a spin and parity

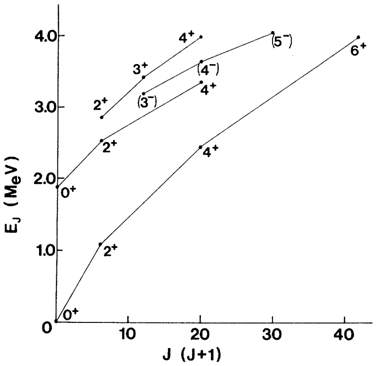

FIG. 1. Energy levels of the proposed bands of ^{44}Ti versus $J(J+1)$.

of 5^- or 6^+ by the (p,t) work.[3] This is consistent with the only γ decay observed in singles or coincidence to the 4^+ state at 2.45 MeV. Taking the state to be either 5^- or 6^+, the angular distribution of the 1561-keV γ-ray de-exciting this state[6] is only consistent with 6^+. The lifetime[7] of this state is 0.56 ± 0.08 psec. The resulting $E2$ enhancements in this band, which agree very well with shell-model calculations,[2,8] are shown in Fig. 2.

Excited 0^+ band.—It is proposed that the states at 1905 keV (0^+), 2531 keV (2^+), and tentatively 3365 keV (4^+) form a band. The spin, parity and lifetime of the first two states are discussed in Refs. 1–3 and 5. Recently, Baer *et al.*[9] have suggested an $L = 2$ or 3 assignment in the (p,t) reaction feeding the 1.90-MeV level. The γ-ray angular distributions[1] rule out spin 3 for the level, but a spin of 2 cannot be eliminated.[10] The nonobservation of a crossover γ ray ($< 5\%$), the (p,t)[3] and $(^6\mathrm{Li}, d)$[5] data, and the γ-ray angular distributions are all consistent with 0^+, and we shall adopt it.

In γ-ray singles[1] and coincidence[6] spectra a 626-keV γ-ray associated with the $(2.53 \rightarrow 1.90)$-MeV transition has been observed, with a corresponding $E2$ strength of 24 W.u. (Weisskopf units) (Fig. 2).

More problematic is the 3.37-MeV state. The (p,t) work[3,4,9] and the $(^6\mathrm{Li}, d)$ work[5] are unanimous in assigning an L transfer of 4 for feeding this state. This is consistent with the only observed γ decays being to 2^+ states. Its lifetime[6] is 0.5 ± 0.1 psec. In coincidence spectra we have some evidence for an 834-keV γ ray corresponding to a $(3.37 \rightarrow 2.53)$-MeV branch of $(7 \pm 3)\%$. The $E2$ strengths for the decays from the 3.37-MeV level are given in Fig. 2. The assignment of this state

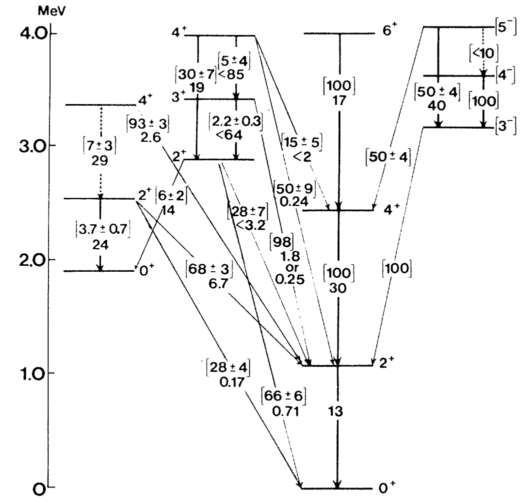

FIG. 2. Band structure and transition strengths in ^{44}Ti. The heavy arrows show in-band transitions, and the lighter arrows some of the cross-band transitions. Numbers in brackets are branching ratios in percent, while those without brackets are $E2$ strengths in Weisskopf units. Some $E2$ strengths are shown as upper limits because of a lack of knowledge of the mixing ratio for the transition. To avoid cluttering the figure, errors on the $E2$ strengths are not given, but can be found from the errors in the branching ratios and lifetimes (Ref. 2 and present report). Levels at 3.75 and 3.94 MeV are not shown in the figure.

to the excited 0^+ band should perhaps be considered tentative until the 834-keV transition is confirmed. Strohbusch *et al.*[5] originally suggested this assignment based on $(^6\mathrm{Li}, d)$ stripping strengths.

The excited 2^+ band.—The states at 2886 keV (2^+), 3415 keV (3^+), and 3980 keV (4^+) are assigned to a band. The spin, parity, and lifetime of the 2.89-MeV state are discussed in Refs. 1-3. The 3.42-MeV state has not been observed in the high-resolution (p,t) work.[3] The fact that the (p,t) reaction excited all but two of the states below 4.1 MeV seen in α capture strongly suggests unnatural parity for this state. The γ-ray angular distributions[1] restrict its spin to 2 or 3, while the mixing ratio for the $3.42 \rightarrow 1.08$ MeV transition[1] combined with the lifetime[2] rules out 2^-. Thus we assign 3^+ as its spin and parity. The 4^+ assignment for the 3.98-MeV level is based primarily on the (p,t) work,[3] and the γ decay of this level is consistent with this.

The γ decay of these levels and $E2$ strengths where known are shown in Fig. 2. The mixing ratio of the $(3.42 \rightarrow 2.89)$-MeV transition is not known and the $E2$ strength of 64 W.u. assumes pure $E2$.[11] The errors quoted on branches from the 3.98-MeV level are statistical only, but there may be some systematic uncertainties. Because most of these transitions are only seen in the coincidence spectra taken with one geometry, one source of systematic uncertainty is the unknown correlations. Another source was caused by the overlap of the 2.90-MeV γ ray (3.98 → 1.08 MeV) and 2.89-MeV γ ray (2.89 → 0 MeV) in the spectra, the latter being fed both directly from the resonance and via the 3.98-MeV level, and there is some uncertainty in subtracting out the latter's contribution. The (3.98 → 2.89)-MeV γ ray showed a line shape indicating that the lifetime of the 3.98-MeV level is 0.9 ± 0.3 psec. Pure $E2$ transitions are assumed in calculating $E2$ strengths.

The 3.18-MeV band.—A band is identified with the states at 3176, 3645, and 4059 keV. Of these only the 3.65-MeV level is not seen in the (p, t) work,[3] strongly suggesting unnatural parity for it since it is only the second state up to 4.1 MeV not fed in (p, t) reaction. Rapaport *et al.*[3] tentatively assign $L = 2$ to the 3.18-MeV state, Kong-a-Siou *et al.*[4] are definite about $L = 2$, and Baer *et al.*[9] allow $L = 2$, 3, or 4. In the high-resolution work of Rapaport *et al.*[3] the 4.06-MeV level is fed by $L = 4$. However, the γ decay and lifetimes of these levels are difficult to reconcile with the spins and parities suggested by the (p, t) work. It is difficult to understand the nonobservation of a transition 3.18 → 0 MeV (< 10%) and the long lifetime ($\tau \gtrsim 3$ psec) of this state if it is 2^+. Similarly, the 4.06-MeV state appears to decay only to the 2.45-MeV (4^+) state and to the 3.18-MeV state with a lifetime[6] of 2^{+2}_{-1} psec and this would be surprising if it were 4^+. Finally, the unnatural-parity state at 3.65 MeV decays only to the 3.18-MeV state. If it were 3^+ there should be a decay to the 1.08 (2^+) MeV state, but this has not been seen (< 8%).

An alternative set of spins is consistent with the γ-decay scheme, namely 3^-, 4^-, and 5^-. The angular distributions of the γ rays from these levels are consistent with these spin assignments; in particular the $3^- \to 2^+$ and $5^- \to 4^+$ transitions can be fitted with $\delta = 0$. Although our angular distributions cannot rule out the positive-parity sequence (2^+, 3^+, 4^+) suggested by the (p, t) work, for the present we shall consider it a negative-parity band.[12] The strong $5^- \to 3^-$ transition (40 W.u. $E2$) and the 100% (3.65 → 3.18)-MeV branch clearly show the connection of these states.

In general, cross-band transitions are weak. However, there is some band mixing as shown by a few moderately strong cross-band transitions. There is a transition of moderate strength (7 W.u.) from the 2^+ member of the excited 0^+ band to the 2^+ member of the ground band.[2] There may also be a 14-W.u. transition from the 2^+-band head to the excited 0^+-band head. The (3.42 → 2.53)-MeV branch (not shown in Fig. 2) is < 1.5% (2 standard deviations) and hence < 3 W.u. if pure $E2$. Other possible cross-band transitions not shown in Fig. 2 are either obscured by other γ rays in the spectra or have such low energies that our present upper limits on the intensities (typically a few percent) are not very meaningful.

The levels of the ground-state and 2.89-MeV bands and the $E2$ transitions within them are very well fitted by the asymmetric rotor model[13] with an asymmetry parameter $\gamma \sim 20°$. The excited 0^+-band energies can be reasonably well fitted by including β vibrations[14] and the $E2$ transition strengths including β vibrations are being investigated.

In conclusion, we have presented strong evidence for the first time indicating that twelve of fourteen states[15] below 4.1 MeV are grouped into four bands which follow approximately a $J(J+1)$ sequence. γ-ray branches connecting states within a band have been observed, and in many cases these have large $E2$ strengths. Cross-band transitions are generally weak, with a few possible exceptions. It will be interesting to try to extend these bands to higher spin.

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[10]The presence of ^{48}Ti in ^{46}Ti targets used in the (p,t) reaction raises some questions about the reliability of the low-resolution experiment of Ref. 9 for the 1.90-MeV level.

[11]A $|\delta|=1.0$ would give 32-W.u. $E2$ and 3×10^{-3}-W.u. $M1$ components for this transition. The latter is reasonable for $\Delta T=0$ transitions in self-conjugate nuclei.

[12]If the negative parity assignment is correct, then the sequence 3^-, 4^-, 5^- seems novel in this region. In other nuclei, such as ^{40}Ca, the sequence is 3^-, 5^-, 4^-. The latter sequence is improbable in ^{44}Ti in view of the nonobservation of the second level and the strong feeding of the third level in the (p,t) reaction (Ref. 4).

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Comparison of Vector Analyzing Powers in (d, d) with Those in $(d, ^3\mathrm{He})$ and (d, t) $l=0$ Transfer Reactions*

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Vector-analyzing-power angular distributions for deuteron elastic scattering and $l=0$ pickup reactions on the same target are compared for $^{32}\mathrm{S}(d,d)^{32}\mathrm{S}$ with $^{32}\mathrm{S}(d,^3\mathrm{He})^{31}\mathrm{P}$, $^{30}\mathrm{Si}(d,d)^{30}\mathrm{Si}$ with $^{30}\mathrm{Si}(d,t)^{29}\mathrm{Si}$, and $^{14}\mathrm{N}(d,d)^{14}\mathrm{N}$ with $^{14}\mathrm{N}(d,t)^{13}\mathrm{N}$ at a deuteron lab energy of 15 MeV. The strong similarities between the two angular distributions for each target suggest that an alternative to the distorted-wave Born-approximation description of these direct transfer reactions may be appropriate.

The purpose of this Letter is to present experimental data which show the strong similarity of vector analyzing powers[1] of (d,d) to those of $(d, ^3\mathrm{He})$ or (d,t) direct reactions in which the transferred nucleon initially has orbital angular momentum $l=0$ (called $l=0$ transfer). In a pickup reaction, such as $(d, ^3\mathrm{He})$ or (d,t) at sufficiently high energies that direct-reaction mechanisms predominate, if the outgoing particle consists of a deuteron loosely associated with the transferred nucleon, then it may be scattered similarly to an elastically scattered deuteron having the same momentum as the deuteron component of the outgoing particle. If $l=0$, there is no orbital angular momentum transfer, since the nucleon is captured into ^{3}He or ^{3}H with zero orbital angular momentum. The polarization effects in the transfer reaction and in the elastic scattering may then be similar.

The weakly bound projectile (WBP) model[2] has been used in the analysis of polarization effects in $l=0$ (d,p) reactions. One of the first predictions[2] of the model, which agrees quite well with experiment,[2,3] was that the proton polarization produced in an $l=0$ (d,p) stripping reaction initiated by an unpolarized incident deuteron beam should equal the proton polarization in (p,p) for the same scattering angle and outgoing energy. It is straightforward but lengthy to show that, starting from Eq. (18) of Pearson and Coz,[2] the corresponding prediction for the pickup reactions $(d, ^3\mathrm{He})$ or (d,t), under the same assumptions as in the WBP model, with modifications of only the spins, is that the vector analyzing power for $l=0$ transfer should be equal to that in (d,d) at the same scattering angle and incident deuteron energy.

The above WBP-model predictions follow directly from the analytical formulas. On the other hand, in the distorted-waves Born-approximation model, which is commonly used to describe such transfer reactions, no such parameter-independent predictions relating analyzing powers in $l=0$ transfer reactions to those in elastic scattering are made, and to our knowledge no similarities have been suggested by detailed calculations. There are objections[4] to the formalism of the WBP model originally presented by Pearson and Coz,[2] and an alternative development of the formalism starting from a similar physical viewpoint as in the WBP model has been proposed by Butler and co-workers.[5] The experimental results reported here suggest that some description similar to the WBP model is physically ac-