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Positive-parity states in ^{43}Ti

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Positive-parity states of ^{43}Ti were studied in the ^{40}Ca(α,n) ^{43}Ti reaction with alpha particles of 20-MeV energy. Using a pulsed beam the mean lifetime of the $3/2^+$ state at 313.0 keV was measured to be $\tau = 18.2 \pm 0.8$ μsec. This leads to a $B(M2)$ value of 0.0334 Weisskopf units, very close to that of the corresponding $3/2^+ \rightarrow 7/2^-$ (g.s.) transition in ^{43}Sc. γ decay of the levels in the mirror nucleus ^{43}Sc suggests that positive-parity states in ^{43}Ti, and only these, decay to the ground state predominantly via the isomeric $3/2^+$ state. Hence the γ rays emitted from positive-parity states are selected by measuring a γ-ray spectrum in coincidence with the delayed 313.0-keV γ rays. Three γ rays of 709.4, 1040.0, and 1170.5 keV were observed which lead to ^{43}Ti states $5/2^+$ (1022.4 keV), $7/2^+$ (1483.5 keV), and $9/2^+$ (2062.4 keV). As with the corresponding states in ^{43}Sc, these states form a quasirotational band based on the $3/2^+$ state. The Coulomb displacement energies E_C(Ti)-E_C(Sc) between these ^{43}Ti-^{43}Sc states are large—about 150 keV—and rather spin independent.

[NUCLEAR REACTIONS ^{40}Ca$(\alpha,n\gamma)$; prompt and delayed n-γ and γ-γ coin with $E_\alpha = 20$ MeV. Singles γ-ray spectrum as function of time with pulsed α beam. Deduced for ^{43}Ti: $\frac{9}{2}^+$ (2062.4) $\rightarrow \frac{5}{2}^+$ (1022.4) $\rightarrow \frac{3}{2}^+$ (313.0) $\rightarrow \frac{7}{2}^-$ (g.s.), $\frac{7}{2}^+$ (1483.5) $\rightarrow \frac{3}{2}^+$ (313.0) $\rightarrow \frac{7}{2}^-$ (g.s.) and $\frac{1}{2}^+$ (999) $\rightarrow \frac{3}{2}^+$ (313.0) $\rightarrow \frac{7}{2}^-$ (g.s.), $\frac{3}{2}^+$ state: $\tau = 18.2 \pm 0.8$ μsec.]

I. INTRODUCTION

Recently the lifetime and the decay of the isomeric $\frac{19}{2}^-$ state in ^{43}Ti were studied.[1] The states involved in the decay of this level showed, in comparison with the analogous states of the mirror nucleus ^{43}Sc, pronounced spin-dependent Coulomb displacement energies. They can be qualitatively understood by assuming that the two valence protons in ^{43}Ti have an interaction energy which differs from that of the two valence neutrons in ^{43}Sc. The measurements also showed that the $\frac{19}{2}^-$ state in ^{43}Ti has a reduced transition probability $B(E2)$ which is nearly a factor of 2 larger than that of the corresponding state in ^{43}Sc. This result is in agreement with the assumption that the $\frac{19}{2}^- \rightarrow \frac{15}{2}^-$ $E2$ transition occurs between states with a $(f_{7/2})^3$ nucleon configuration and, since the protons have a larger effective charge than the neutrons, a larger $B(E2)$ is expected for ^{43}Ti than for ^{43}Sc. However, in this pair of nuclei another set of states with a $(d_{3/2})^{-1}(f_{7/2})^4$ nucleon configuration exists. They have positive parity and will have properties different from states of negative parity. In the present work some of these properties are studied. After presenting the experimental results the Coulomb displacement energies for both the positive-and negative-parity states are compared. Since the positive-parity states in the ^{43}Ti-^{43}Sc pair arise from one-hole-many-particle configurations, as do the negative-parity states in the nuclei ^{19}Ne-^{19}F, the Coulomb displacement energies of these states may depend less on the spin than do those of opposite parity, as observed in the ^{19}Ne-^{19}F pair.[2,3] Of interest also is the $B(M2)$ value of the $\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$ (g.s.) transition which is known to be strongly inhibited in ^{43}Sc with respect to the values obtained for the transition $\frac{7}{2}^- \rightarrow \frac{3}{2}^+$ (g.s.) in the mirror nuclei pair ^{39}Ca and ^{39}K. Using the $B(M2)$ of ^{43}Sc in conjunction with the magnetic moments of the free nucleons, a $B(M2)$ value is expected for ^{43}Ti, which is a factor of 1.65 larger than that of ^{43}Sc. However, if instead of the moments of the free nucleons, the $M2$ reduced matrix elements of the single-neutron and single-proton transition $\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$ are used as derived in Ref. 4, the $B(M2)$ value of ^{43}Ti should be very close to that of ^{43}Sc.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The investigations of the positive-parity states in ^{43}Ti have been performed mostly with an experimental layout similar to that used in the study of the decay of the $\frac{19}{2}^-$ state in ^{43}Ti (Ref. 1). Detailed information can be obtained from this earlier work. For the present studies, as in the earlier work, ^{43}Ti was produced by the ^{40}Ca(α,n)

^{43}Ti reaction. α particles of 20 MeV bombarded an enriched (>99.9%) ^{40}Ca target of about 1-mg/cm^2 thickness. The Ca material was evaporated onto a 0.1-mm thick Pb foil which served as a beam stop.

A. Lifetime of the $3/2^+$ state at 313.0-keV excitation energy

In the earlier experiment,[1] an isomeric state at 313.0 keV was observed with a mean life $\tau > 4$ μsec. This result alone suggests that the state is analogous to the lowest $\frac{3}{2}^+$ state in the mirror nucleus ^{43}Sc, which has an excitation energy of 152.0 keV and a partial mean life $\tau = 656 \pm 10$ μsec (Ref. 5) for the $M2$ transition $\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$ (g.s.). In ^{43}Ti this transition should have a mean life of 17.7 μsec if it is assumed that the reduced $M2$ transition probability $B(M2)$ is the same for ^{43}Sc and ^{43}Ti. The mean lifetime was measured by using a pulsed α beam of 20-MeV energy. The γ rays emitted from the 313.0-keV ^{43}Ti state were recorded and stored in a multichannel analyzer at different times with respect to the beam pulse.[5] The result of such a measurement is presented in Fig. 1 where the number of 313.0-keV γ rays is shown as a function of the time elapsed from the occurrence of the beam pulse. A mean lifetime $\tau = 18.2 \pm 0.8$ μsec is obtained, which indicates that indeed the $B(M2)$ values of the $\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$ transitions in ^{43}Ti and ^{43}Sc are nearly equal.

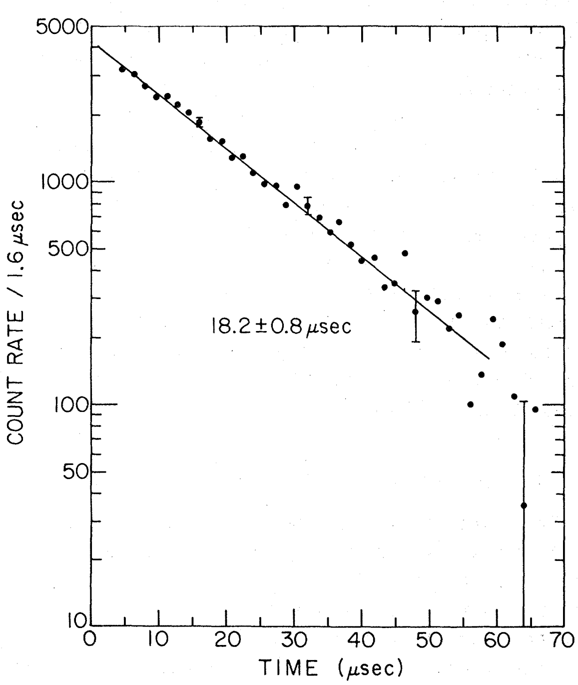

FIG. 1. Number of 313.0-keV γ rays counted in 1.6-μsec wide time bins as a function of time elapsed from the occurrence of the beam pulse.

Very recently the existence of the $\frac{3}{2}^+$ state in ^{43}Ti at an energy of 319 ± 6 keV has been reported.[6] The reaction ^{46}Ti(^{3}He, ^{6}He)^{43}Ti was used in this investigation.

B. n-γ coincidence measurements

As described in the earlier work[1] small cross sections are obtained for the production of ^{43}Ti. However, the reaction ^{40}Ca(α, n)^{43}Ti can be enhanced over other strongly competing channels by measuring n-γ coincidences. The neutrons are selected by pulse-shape discrimination with a stilbene detector. They provide the start pulse of a time-to-pulse-height converter. The γ rays, measured by a Ge(Li) detector, are used as the stop signal. In Fig. 2 γ-ray spectra are shown for different delay times t_D between the neutron and γ-ray pulses. Only three regions of interest are presented, channels 110–350, 520–1220, and 1750–1900. The bottom curve exhibits the γ spectrum which is in prompt coincidence with the neutrons (delay times t_D such that $0 \leq t_D \leq 45$ nsec). Quite a few γ rays, besides those of 1857.7- and 1094.0-keV energy which are known to originate from the $\frac{11}{2}^-$ and $\frac{15}{2}^-$ states in ^{43}Ti, are observed. The other known[1] ^{43}Ti γ rays of 114.7 and 313.0 keV are weak, however, They are emitted by the isomeric states $\frac{19}{2}^-$ ($\tau = 810$ nsec) and $\frac{3}{2}^+$ ($\tau = 18.2$ μsec) which decay very little in the short measuring time of 45 nsec. They appear stronger in Fig. 2(b), where the delay times are $280 \leq t_D \leq 647$ nsec. Also seen in Fig. 2(b) are the 1094.0- and 1857.7-keV lines, which are present through the decay of the $\frac{19}{2}^-$ state. In addition, the γ rays of the corresponding transitions in ^{43}Sc with energies of 136.0, 1157.3, 1830.0, and 152.0 keV are also observable. However, their presence in Fig. 2(b) occurs mainly through accidental coincidences with perhaps some contributions from an incomplete separation of neutrons and γ rays in the stilbene detector. Finally, in Fig. 2(a) the γ rays emitted in the decay of the $\frac{19}{2}^-$ states nearly disappear, since the lifetimes of these states are very much smaller than the delay times $2870 \leq t_D \leq 3237$ nsec. However, the 313.0- and 152.0-keV γ rays from the isomeric $\frac{3}{2}^+$ states remain strong.

In Fig. 3 γ spectra in coincidence not with the neutrons but rather with the γ rays seen in the stilbene crystal are shown. This measurement emphasizes the strongly enhanced ^{40}Ca(α, p)^{43}Sc reaction. The delay times are the same as in Fig. 2. The bottom curve in Fig. 3, which represents mainly prompt γ-γ coincidences, shows many γ rays observed in earlier work and identified as transitions between positive-parity states in

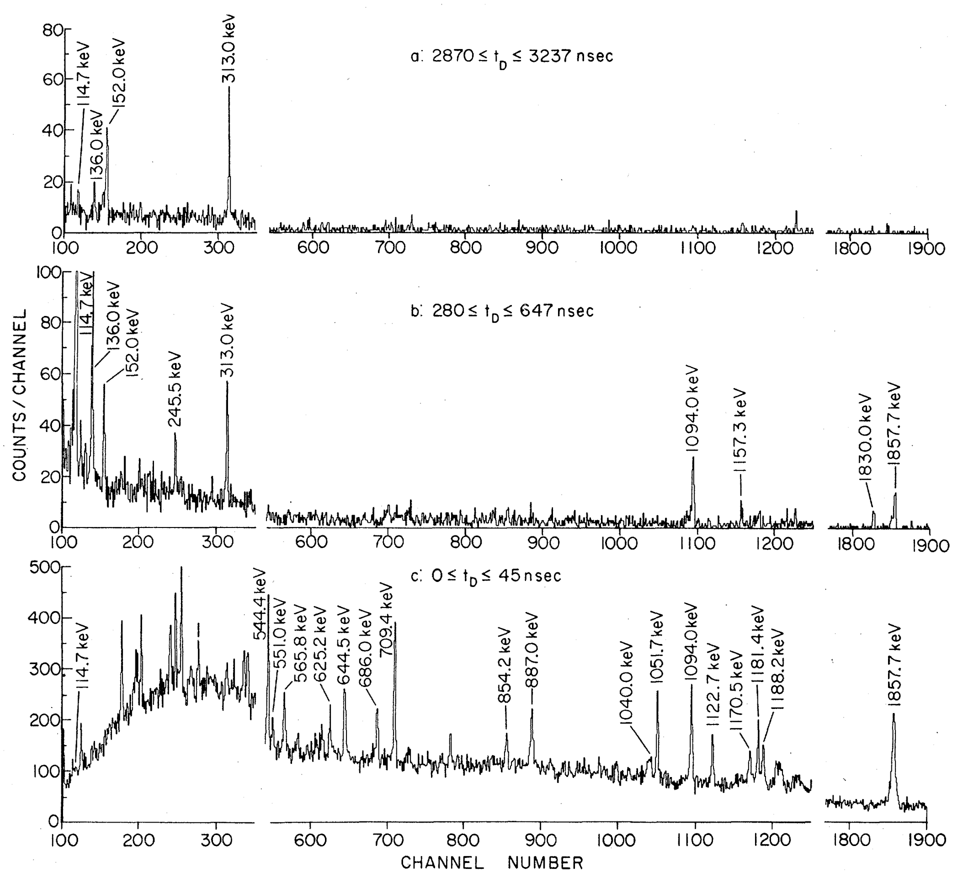

FIG. 2. γ-ray spectra of the Ge(Li) detector measured in coincidence with neutrons detected by the stilbene crystal. (a) γ spectrum is measured with a delay time of $2870 \leq t_D \leq 3237$ nsec with respect to the neutrons. (b) The same as (a) but $280 \leq t_D \leq 647$ nsec. (c) The same as (a) but $0 \leq t_D \leq 45$ nsec.

^{43}Sc (Fig. 4).[7,8] Similar γ rays emitted from positive-parity states are expected in the mirror nucleus ^{43}Ti. They should be observed in the prompt n-γ coincidence measurement shown in Fig. 2(c). However, so many γ rays are exhibited in Fig. 2(c) that, except for the known transitions associated with the negative-parity states, no correlation of corresponding transitions in ^{43}Ti and ^{43}Sc can be attempted.

All γ rays emitted from positive-parity states, except those from the $\frac{3}{2}^{+} \rightarrow \frac{7}{2}^{-}$ transition, are expected to appear as prompt coincidences. Hence they should disappear in the delayed coincidence spectra of Fig. 2(a), Fig. 2(b), Fig. 3(a) and Fig. 3(b). Indeed, those known for ^{43}Sc (see Fig. 4) are not seen in either Fig. 3(a) or Fig. 3(b). Instead, Fig. 3(b), in which delay times in the range $280 \leq t_D \leq 647$ nsec are shown, exhibits the prominent transitions originating in the decay of the isomeric states $\frac{19}{2}^{-}$ (3123.3 keV) and $\frac{3}{2}^{+}$ (152.0 keV). Finally, in Fig. 3(a) the γ ray from the long-lived 152.0-keV isomeric state is the most pronounced one.

C. γ-γ coincidence measurements

From the decay scheme of the mirror nucleus ^{43}Sc (Fig. 4) one can expect that the isomeric $\frac{3}{2}^{+}$ state in ^{43}Ti is populated predominantly by γ rays emitted from positive-parity states. They can be conveniently selected by measuring γ-γ coincidences with the 313.0-keV γ ray in delay. Such a measurement was performed with two Ge(Li) detectors of 70-cm^3 volume each.[1] The results with the delay time t_D limited to the range $170 \leq t_D \leq 6740$ nsec are shown in Fig. 5 where (a) displays the spectrum with the 313.0-keV ^{43}Ti γ ray in delay and (b) shows the γ spectrum in coincidence with the delayed 152-keV γ ray of ^{43}Sc. The level scheme of ^{43}Sc (see Fig. 4) indicates that the 728.3-keV γ ray should be the most prominent peak in Fig. 5(b), while the 1051.7-, 1185.2-, 1209.3-,

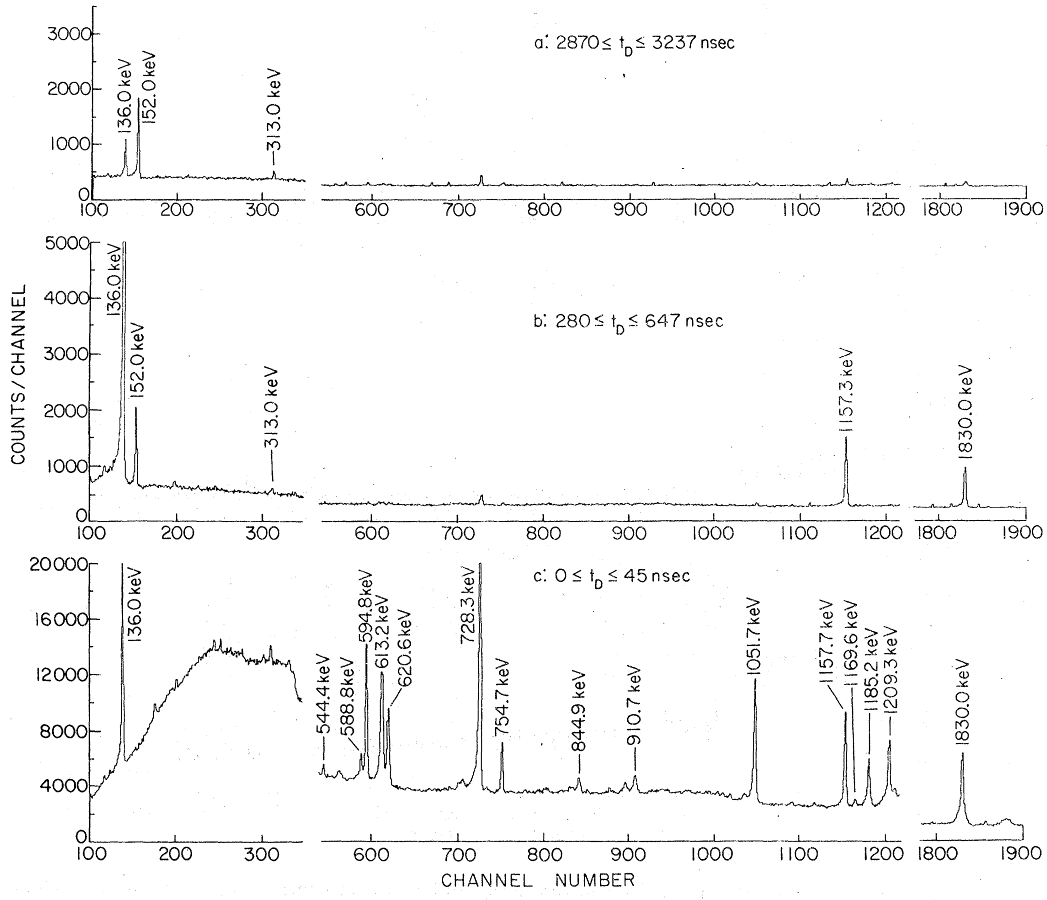

FIG. 3. γ-ray spectra of the Ge(Li) detector measured in coincidence with the γ rays detected by the stilbene crystal. (a) The γ rays of the Ge(Li) detector are measured with a delay time of $2870 \leq t_D \leq 3237$ nsec with respect to the γ rays detected by the stilbene crystal. (b) The same as (a) but $280 \leq t_D \leq 647$ nsec. (c) The same as (a) but $0 \leq t_D \leq 45$ nsec.

and 594.8-keV γ rays might appear more or less pronounced depending on the population of the positive-parity states in the (α, p) reaction and the angular correlation of the γ rays. This is indeed true; we can identify these γ rays, and with them the energies of the ^{43}Sc states with spins[7,8] $\frac{5}{2}^+$, $\frac{7}{2}^+$, $\frac{9}{2}^+$, and $(\frac{13}{2}^+)$. By comparison, Fig. 5(a) should display some of the corresponding γ rays which originate from positive-parity states in the mirror nucleus ^{43}Ti. The strongest γ ray in Fig. 5(a) has an energy of 709.4 keV, close in value (728.3 keV) to the strongest line in Fig. 5(b), and consequently it is assumed that it is emitted in the transition $\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$. As a cross check γ spectra were measured which are in prompt and delayed coincidence with the 709.4-keV γ ray. These measurements confirm that the 709.4-keV γ precedes the 313.0-keV γ ray, and they indicate that the 709.4-keV γ is in prompt coincidence with a 1040.0-keV line. This suggests the γ sequence 1040.0 keV → 709.4 keV → 313.0 keV, which is the only sequence that could be established by prompt γ-γ coincidences except the one already known[1] that is involved in the decay of the $\frac{19}{2}^-$ state. All other ^{43}Ti γ rays are so weak that they do not stand out against the background in prompt γ-γ coincidences.

According to Figs. 4(c) and 5(b) the strongest sequence of two γ feeding the isomeric $\frac{3}{2}^+$ state in ^{43}Sc connects the states $\frac{9}{2}^+ \xrightarrow{1051.7} \frac{5}{2}^+ \xrightarrow{728.3} \frac{3}{2}^+$. Since the only sequence observed in ^{43}Ti exhibits γ rays with energies close to those, we conclude that the $\frac{9}{2}^+$ and $\frac{5}{2}^+$ ^{43}Ti states have been observed. Two more γ rays are displayed in Fig. 5(a) with energies of 686 and 1170.5 keV. The latter one is close in energy to the 1185.2-keV γ ray in ^{43}Sc and it is assumed that it is emitted in the transition $\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$. For the 686-keV γ ray, however, the counterpart is hardly seen in Fig. 5(b). We tentatively assume that the 686-keV γ ray is emitted

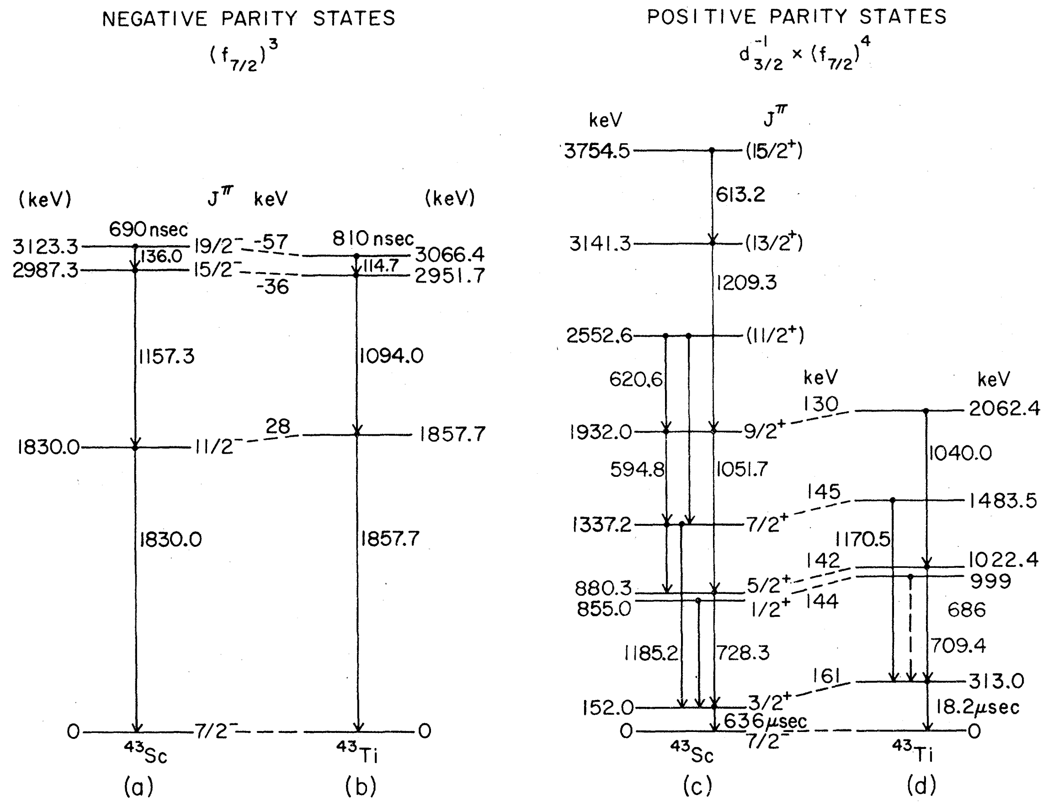

FIG. 4. Level scheme of the positive- and negative-parity states in the mirror nuclei ^{43}Ti and ^{43}Sc. (a) References 10 and 1; (b) Ref. 1; (c) Ref. 5, 7, and 9; (d) present work.

in the transition $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$ since, firstly, the $\frac{1}{2}^+$ state in ^{43}Ti is observed[6] in the ^{46}Ti(^{3}He, ^{6}He) reaction at an energy of 998 ± 10 keV, and, secondly, the corresponding $\frac{1}{2}^+$ state in ^{43}Sc is known[7] to have a 70% branch to the $\frac{3}{2}^+$ state, a 703-keV γ ray being emitted in this transition. This latter γ ray should correspond to the 686-keV γ ray emitted in the mirror nucleus ^{43}Ti. A possible objection to this assignment might be seen in the fact that the $\frac{1}{2}^+$ state is much stronger populated relative to other states in ^{43}Ti than in ^{43}Sc. When a ratio R is defined, where R represents the population strength of the $\frac{1}{2}^+$ state to that of the $\frac{5}{2}^+$ state, the values in the present experiment with $E_\alpha = 20$ MeV are for ^{43}Sc, $R(^{43}\mathrm{Sc}) \approx 1:40$ and for ^{43}Ti, $R(^{43}\mathrm{Ti}) \approx 1:2$. These values are obtained from the intensities of the γ rays emitted in the decay of the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states measured with the γ ray detector at 90° to the incoming α beam and ignoring possible angular distribution of the 728.3- and 709.4-keV γ rays originating from the $\frac{5}{2}^+$ states in ^{43}Sc and ^{43}Ti, respectively. The γ rays representing the $\frac{1}{2}^+$ states have an energy of 703 and 383 keV in ^{43}Sc. For ^{43}Ti the only one available is the proposed 686-keV γ ray for which the same branching ratio is assumed as observed for the 703-keV γ ray in ^{43}Sc. It might be worthwhile to note that at smaller α energies, $E_\alpha = 8$ and $E_\alpha = 10$ MeV, the $R(^{43}\mathrm{Sc})$ value is about 1 : 7.5, measured[8] in singles γ-ray spectra with the detector at 90° to the incoming beam. This ratio is much larger than 1 : 40, the value we observe in our experiment at $E_\alpha = 20$ MeV. It indicates that R is energy dependent and it appears plausible that the very different R values $R(^{43}\mathrm{Sc})$ and $R(^{43}\mathrm{Ti})$ obtained at $E_\alpha = 20$ MeV might be related to the large difference in the proton and neutron separation energies, $S_p = 8.66$ and $S_n = 16.29$ MeV from the compound nucleus ^{44}Ti. Hence the different R values might not rule out the assignment of the 686-keV γ ray to the $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$ transition in ^{43}Ti.

The four ^{43}Ti γ rays with energies of 709.4, 1040.0, 1170.5, and 686 keV which are assumed to be emitted from positive-parity states must also be present in the n-γ coincidence spectrum of Fig. 2(c), and indeed they are.

All these investigations suggest a level scheme

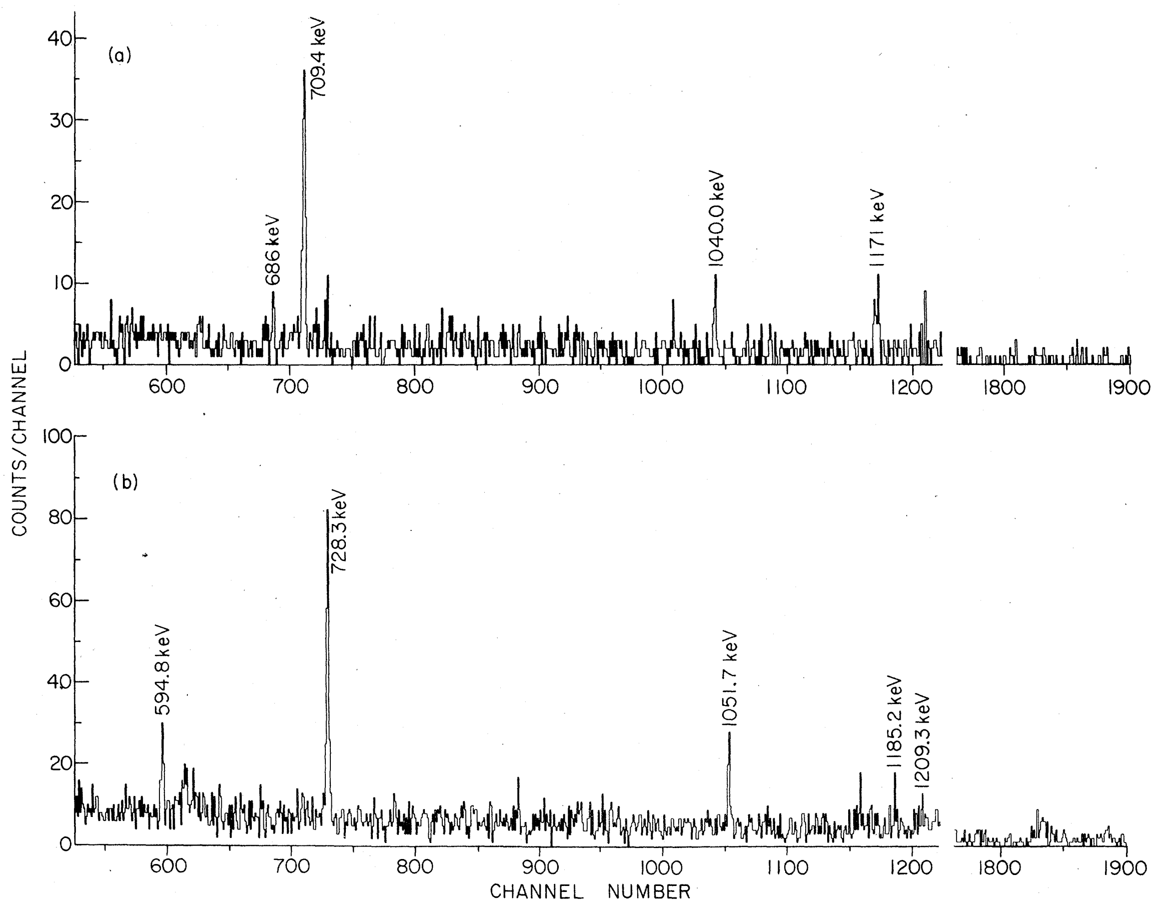

FIG. 5. Delayed γ-γ coincidence spectra measured with two Ge(Li) detectors and with delay times $170 \leq t_D \leq 6740$ nsec. γ spectrum observed in delayed coincidence with (a) 313.0-keV ^{43}Ti γ ray, (b) 152.0-keV ^{43}Sc γ ray.

in ^{43}Ti for some of the positive-parity states which is shown in Fig. 4(d). Additional support for this level scheme will be given in the discussion.

III. DISCUSSION

A. Coulomb displacement energies

The level scheme of ^{43}Ti is displayed in Fig. 4 together with those states in the mirror nucleus ^{43}Sc which are of interest here. The mirror pair reveals a striking difference in the energy shifts of corresponding states $[E_x(\mathrm{Ti}) - E_x(\mathrm{Sc})]$ that depends on the parity of the state. The negative-parity states show energy shifts of +28 to −57 keV, while positive-parity states have energy shifts which are rather large and fairly constant from +130 to +161 keV. This behavior is also indicated in Table I by the Coulomb displacement energies $\Delta E_C = E_C(\mathrm{Ti}) - E_C(\mathrm{Sc})$. One observes that ΔE_C is, firstly, rather strongly spin dependent for the negative-parity states, decreasing in general with increasing spin; and, secondly, ΔE_C is about 150 keV smaller for the negative than for the positive-parity states. This result is rather well understood:

1. The negative-parity states are assumed to have a dominant nucleon configuration of $(f_{7/2})^3$, and the interaction energy between the two valence neutrons in ^{43}Sc is different from that between the two valence protons in ^{43}Ti. This difference is spin dependent and can be calculated from level schemes of neighboring nuclei as shown in Ref. 1. These calculated values of ΔE_C are given in column 4 of Table I.

2. The positive-parity states have a one-hole configuration, namely, $\nu d_{3/2}^{-1} \times (f_{7/2})^4{}_{^{44}\mathrm{Ti}}$ in ^{43}Ti and $\pi d_{3/2}^{-1} \times (f_{7/2})^4{}_{^{44}\mathrm{Ti}}$ in ^{43}Sc. Since the rms radius of the $d_{3/2}$ shell is smaller than that of the $f_{7/2}$ shell the one proton which is promoted from the $d_{3/2}$ into the $f_{7/2}$ shell in the $\frac{3}{2}^+$ state of ^{43}Sc reduces the Coulomb repulsion in this nucleus, thereby enlarging the ΔE_C value. A similar result is to

TABLE I. Coulomb displacement energies $\Delta E_C = E_C(Z_>) - E_C(Z_<)$ for positive- and negative-parity states in the mirror nuclei ^{43}Ti - ^{43}Sc and ^{19}Ne - ^{19}F.

	^{43}Ti - ^{43}Sc						
Negative parity: $(f_{7/2})^3$				Positive parity: $d_{3/2}^{-1} \times (f_{7/2})^4$			
J^π	E_x (^{43}Ti) (keV)	ΔE_C (keV) Exp.[a]	Calc.[a]	J^π	E_x (^{43}Ti) (keV)	ΔE_C (keV) Exp.[b]	Calc.[c]
$\frac{7}{2}^-$	0	7643	7674	$\frac{3}{2}^+$	313.0	7804	7817
$\frac{11}{2}^-$	1857.7	7671	7666	$\frac{1}{2}^+$	999	7787	7754
$\frac{15}{2}^-$	2951.7	7607	7609	$\frac{5}{2}^+$	1022.4	7785	
$\frac{19}{2}^-$	3066.4	7586	7570	$\frac{7}{2}^+$	1484	7791	
				$\frac{9}{2}^+$	2062.4	7773	

^{19}Ne - ^{19}F			
Positive Parity: $(sd)^3$		Negative parity: $p^{-1} \times (sd)^4$	
	Exp.[d]		Exp.[d]
$\frac{1}{2}^+$	4021	$\frac{1}{2}^-$	4187
$\frac{3}{2}^+$	4003	$\frac{3}{2}^-$	4177
$\frac{5}{2}^+$	4062	$\frac{5}{2}^-$	4183
$\frac{9}{2}^+$	4035	$\frac{7}{2}^-$	4172
		$\frac{9}{2}^-$	4188

[a] Reference 1.
[b] Present work.
[c] See text and Ref. 6.
[d] Reference 3.

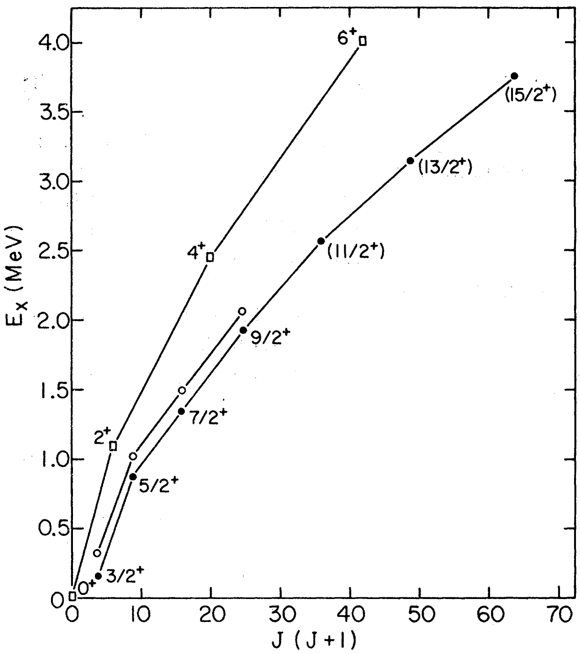

FIG. 6. Excitation energy of some ^{44}Ti, ^{43}Ti, and ^{43}Sc states with spin J as function of $J(J+1)$. Spins are indicated; those only suggested are shown in parentheses (see Fig. 4). Open squares ^{44}Ti, circles ^{43}Ti, and dots ^{43}Sc.

be expected for the $\frac{1}{2}^+$ state, and indeed column 7 of Table I indicates ΔE_C values larger than those of the negative-parity states for both the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states. For both states, $\frac{3}{2}^+$ and $\frac{1}{2}^+$, ΔE_C can be derived from those measured in neighboring mirror nuclei ^{47}Cr-^{47}V, ^{51}Fe-^{51}Mn, and ^{55}Ni-^{55}Co, which have been reported very recently.[6] All these states have the nucleon configuration of $d_{3/2}^{-1} \times (f_{7/2})^m{}_{T=0}$ with $m = 4$, 8, 12, or 16. The authors[6] have shown that the experimental ΔE_C values of one pair of mirror nuclei can be derived from those observed in neighboring mirror nuclei via the equation[11-13]

$$\Delta E_C(A, \tfrac{3}{2}^+) = \Delta E_C(A-4, \tfrac{3}{2}^+) + 2C(\tfrac{3}{2}^+, \tfrac{7}{2}^-).$$

Here $\Delta E_C(A, \frac{3}{2}^+)$ equals, for example, the Coulomb displacement energy of the $\frac{3}{2}^+$ state measured in the pair ^{47}Cr-^{47}V and $\Delta E_C(A-4, \frac{3}{2}^+)$ that to be determined in the nuclei ^{43}Ti-^{43}Sc. The value $2C$ represents the interaction of the $d_{3/2}$ proton hole with the two extra $f_{7/2}$-shell protons present in ^{47}Cr but not in ^{43}Ti. The values of $2C$ derived from the measured ΔE_C values of the next pairs of $T=\frac{1}{2}$ nuclei ^{47}Cr-^{47}V and ^{51}Fe-^{51}Mn are given by $2C(\frac{3}{2}^+, \frac{7}{2}^-) = 625$ keV and $2C(\frac{1}{2}^+, \frac{7}{2}^-) = 640$ keV. This leads to a value of ΔE_C(calc) for ^{43}Ti-^{43}Sc which is presented in column 8 (Table I) and which is in reasonable agreement with the experimental result.

The positive-parity states of Fig. 4 distinguish themselves from those of negative parity not only by the larger Coulomb displacement energies but, except for the $\frac{1}{2}^+$ state, they also belong to a quasirotational band for which the excitation energy of the state with spin J is a smooth function of $J(J+1)$, as indicated in Fig. 6. Since these states are assumed to have a $d_{3/2}^{-1}(f_{7/2})^4{}_{^{44}Ti}$ nucleon configuration, one expects that the states 0^+, 2^+, 4^+, and 6^+ of ^{44}Ti will also exhibit an energy dependence typical of quasirotational behavior. The same energy dependence on J as measured in ^{43}Ti is observed in ^{43}Sc; however, for ^{43}Sc the relation $E=f(J)$ is extended to larger spin values either known or suggested.[7,9] They follow nicely the trend of the states with lower J values.

Collective motion is confirmed for some of the positive-parity states in ^{43}Sc by the measured mean lifetimes τ of Refs. 9 and 8. The resultant experimental reduced transition probabilities

$B(E2)$ are calculated from τ by

$$B(E2)=\frac{816}{\tau(1+\alpha)E_\gamma^5}\,e^2\,\mathrm{fm}^4\,, \quad (1)$$

where τ is in psec, the energy E_γ is in MeV, and $\tau(1+\alpha)$ equals the partial mean life of the particular γ-ray transition, τ_{partial}. Here α is either the conversion coefficient (136-keV γ ray) or is derived from the measured intensity ratios of the different γ rays emitted from the level of interest. τ, τ_{partial}, and the derived $B(E2)$ values are shown in Table II. The Weisskopf single-particle reduced transition probability $B(E2)_{\text{W.u.}}$ is obtained from

$$B(E2)_{\text{W.u.}}=\frac{1}{4\pi}(\tfrac{3}{5})^2(1.2A^{1/3})^4\;e^2\,\mathrm{fm}^4 \quad (2)$$

and is 8.95 $e^2\,\mathrm{fm}^4$ for $A=43$. As seen in Table II, the enhancement factors h, where

$$h=\frac{B(E2)}{B(E2)_{\text{W.u.}}} \quad (3)$$

are all greater than 15 for the positive-parity states. For comparison Table II also presents the $B(E2)$ values of some negative-parity states. Of these, the $\frac{19}{2}^- \to \frac{15}{2}^-$ transition, with $h=2.6$, does not show the $E2$ enhancement expected for collective nuclear motion.

As in the ^{43}Ti–^{43}Sc nuclei, the measured energy shifts and the Coulomb displacement energies ΔE_C between corresponding states depend strongly on the parity of the states in another pair of mirror nuclei ^{19}Ne and ^{19}F (Ref. 3). In these latter nuclei the one-hole–many-particle states have the nucleon configuration $p^{-1}\times(sd)^4$, and hence they have negative parity. The levels all show fairly constant energy shifts and ΔE_C values (see Table I) which are larger by 120–160 keV than those in states of natural parity with the configuration $(sd)^3$. The latter states display energy shifts and ΔE_C values which are distinctly more spin dependent than the one-hole–many-particle states. So it appears that a measurement of Coulomb displacement energies, and in particular the observance of large ΔE_C values in (sd)- and f-shell nuclei, single out one-hole–many-particle states—states with negative parity in ^{19}Ne and ^{19}F and with positive parity in ^{43}Ti and ^{43}Sc. This conclusion supports the positive-parity assignment of states in ^{43}Ti at 1022.4, 1483.5, and 2062.4 keV with spins of $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$, respectively.

B. $B(M2)$ value of the $3/2^+ \to 7/2^-$ transition in ^{43}Ti

The reduced transition probability $B(M2)$ for the transitions $\frac{3}{2}^+ \to \frac{7}{2}^-$ in ^{43}Ti and ^{43}Sc and $\frac{7}{2}^- \to \frac{3}{2}^+$ in ^{39}Ca (Ref. 16) and ^{39}K (Ref. 17) are derived from the measured mean life τ by the equation

$$B(M2;J_i\to J_f)=\frac{0.0741}{\tau(1+\alpha)E_\gamma^5}\,\mu_N^2\,\mathrm{fm}^2\,, \quad (4)$$

where the measured mean lifetime τ is in μsec, the energy E_γ is in MeV, and α is the conversion coefficient. In comparing $\frac{3}{2}^+ \to \frac{7}{2}^-$ transitions with $\frac{7}{2}^- \to \frac{3}{2}^+$ transition it is important to remember that

$$(2J_< +1)B(M2;J_<\to J_>)=(2J_> +1)B(M2;J_>\to J_<)\,, \quad (5)$$

where $J_>$ is the larger and $J_<$ the smaller of the

TABLE II. Some $B(E2)$ values in ^{43}Sc.

E_i (keV)	J_i^π	J_f^π	E_γ (keV)	τ_{meas} (psec)	Relative intensity	τ_{partial} (psec)	$B(E2)$[a] (e^2 fm^4)	$h=\frac{B(E2)}{B(E2)_{\text{W.u.}}}$
2553	$\frac{11}{2}^+$	$\frac{9}{2}^+$	620.8	0.74[b]	1748[c]	1.24		
		$\frac{7}{2}^+$	1215.7		1188[c]	1.83	167.9	18.8
1932	$\frac{9}{2}^+$	$\frac{7}{2}^+$	595.1	3.4[b]	3454[c]	12.9		
		$\frac{5}{2}^+$	1051.8		9682[c]	4.6	137.8	15.4
1337	$\frac{7}{2}^+$	$\frac{5}{2}^+$	456.8	1.2[d]	2250[c]	3.71		
		$\frac{3}{2}^+$	1185.1		4714[c]	1.77	197.2	22.0
3123.3	$\frac{19}{2}^-$	$\frac{15}{2}^-$	136.0	6.90×10^5 [e]	100%	7.56×10^5	23.4	2.6
2987.3	$\frac{15}{2}^-$	$\frac{11}{2}^-$	1157.7	8.1[f]	100%	8.1	48.4	5.4
1830.0	$\frac{11}{2}^-$	$\frac{7}{2}^-$	1830.0	0.32[d]	100%	0.32	124.2	13.9

[a] Transitions with $E2/M1$ admixtures are excluded.
[b] Reference 8.
[c] Reference 9.
[d] Reference 14.
[e] Reference 1.
[f] Reference 15.

TABLE III. $B(M2)$ and magnetic moment values in the mirror nuclei ^{43}Ti - ^{43}Sc and ^{39}Ca - ^{39}K.

Nucleus	Transition	E_γ (keV)	τ_{meas}	$B(M2; J_> \to J_<)$ μ_N^2 fm^2	(W.u.)	μ (μ_N) of $\frac{3}{2}^+$
^{43}Ti	$\frac{3}{2}^+ \to \frac{7}{2}^-$	313.0	(18.2 ± .8) μsec[a]	0.68	0.0334	(1.103)[b]
^{43}Sc	$\frac{3}{2}^+ \to \frac{7}{2}^-$	152.0	(628 ± 10) μsec[c]	.695	0.0345	0.348[d]
^{39}Ca	$\frac{7}{2}^- \to \frac{3}{2}^+$	2796	(90 ± 24) psec[e]	4.82	0.253	1.0216[f]
^{39}K	$\frac{7}{2}^- \to \frac{3}{2}^+$	2813	(63 ±10) psec[g]	6.68	0.351	0.391[h]

[a] Present work.
[b] This value is calculated, see Refs. 4 and 18.
[c] Reference 5.
[d] Reference 19.
[e] Reference 16.
[f] Reference 20.
[g] Reference 17.
[h] Reference 21.

values of total angular momentum involved in the transition. Hence the reduced transition probabilities of the $M2$ transition in the mirror nuclei ^{43}Ti–^{43}Sc and ^{39}Ca–^{39}K are compared by using the $B(M2;J_> \to J_<)$ values. They are presented in Table III; column 5 gives the values in units of μ_N^2 fm^2, column 6 in Weisskopf units, $B(M2)_{\text{W.u.}}$, where

$$B(M2)_{\text{W.u.}} = \frac{10}{\pi}\left(\tfrac{3}{5}\right)^2(1.2A^{1/3})^2\,\mu_N^2\,\text{fm}^2 \qquad (6)$$

and are $19.0\mu_N^2$ fm^2 for $A=39$ and $20.3\mu_N^2$ fm^2 for $A=43$. In contrast to the $B(E2)$ values obtained for the positive-parity states in ^{43}Sc and ^{43}Ti the $B(M2)$ values for the $\frac{3}{2}^+ \to \frac{7}{2}^-$ transition in both ^{43}Sc and ^{43}Ti are small in comparison to the Weisskopf single-particle strength. This observation indicates that in contrast to the $E2$ transitions, only a small fraction of the active nucleons are able to participate in the $M2$ transition. In fact the $B(M2)$ values for ^{43}Sc and ^{43}Ti are even a factor of 10 smaller than those of ^{39}Ca (Ref. 16) and ^{39}K (Ref. 17) (see Table III). This result, known for some time for ^{43}Sc, is surprising since the magnetic moments of the $\frac{3}{2}^+$ states in ^{43}Sc and in ^{39}K are very similar, with $\mu = 0.348\mu_N$ in ^{43}Sc (Ref. 19) and $\mu = 0.391\mu_N$ in ^{39}K (Ref. 21). This suggests a $d_{3/2}$ proton hole for both $\frac{3}{2}^+$ states; hence $B(M2)$ values are expected which are of the same order of magnitude in ^{43}Sc and ^{39}K. Recently, however, Lawson and Müller-Arnke[4] have shown that the observed discrepancy can be understood if it is assumed that the $\frac{3}{2}^+$ state in ^{43}Sc does not have a pure $d_{3/2}^{-1}(f_{7/2})^4$ configuration but contains instead a 10–15% $(s_{1/2})^{-1}(f_{7/2})^4$ admixture. This $(s_{1/2})^{-1}(f_{7/2})^4$ admixture strongly influences the magnetic moment of the $\frac{3}{2}^+$ ^{43}Sc state but does not contribute to the $M2$ strength of the $\frac{3}{2}^+ \to \frac{7}{2}^-$ transition. Hence the $\frac{3}{2}^+$ states in the nuclei ^{39}K and ^{43}Sc can well have similar magnetic moments and at the same time exhibit $B(M2)$ values differing by a factor of 10. A comparison with the nuclei ^{39}Ca and ^{43}Ti is of interest. Using the same $(s_{1/2})^{-1}(f_{7/2})^4$ admixture for the $\frac{3}{2}^+$ state in ^{43}Ti a magnetic moment of $1.103\mu_N$ is calculated,[4,18] very close to that measured in ^{39}Ca (see Table III), while again the two measured $B(M2)$ values differ by a factor of about 10. Unfortunately the magnetic moment of the $\frac{3}{2}^+$ ^{43}Ti state is not yet measured.

The authors of Ref. 4 have also shown that the measured lifetimes of the $\frac{7}{2}^- \to \frac{3}{2}^+$ transition in ^{39}Ca and ^{39}K, together with the wave function given for the $\frac{7}{2}^-$ states by Kurath and Lawson,[22] lead to the following reduced $M2$ matrix element for the single proton and single neutron transtions $\frac{7}{2}^- \to \frac{3}{2}^+$

$$X = \langle \pi_{7/2} || M2 || \pi_{3/2} \rangle = 10.8\mu_N\,\text{fm}\,,$$

$$Y = \langle \nu_{7/2} || M2 || \nu_{3/2} \rangle = -10.4\,\mu_N\,\text{fm}\,.$$

The ratio X/Y together with the measured mean life of the $\frac{3}{2}^+ \to \frac{7}{2}^-$ transtion in ^{43}Sc allows us to calculate the τ value of the corresponding transition in ^{43}Ti. That is, the expression

$$\frac{B(M2)_{\text{Sc}}}{B(M2)_{\text{Ti}}} = \left(\frac{X}{Y}\right)^2$$

leads to $\tau(\text{Ti}) = 19.2$ μsec, very close to the measured value of 18.2 μsec. On the other hand, the single-particle values of these matrix elements are

$$X_{\text{s.p.}} = 10.9\,\mu_N\,\text{fm}\,,$$

$$Y_{\text{s.p.}} = -8.5\,\mu_N\,\text{fm}\,,$$

which lead to $\tau = 29.4$ μsec, a value incompatible with the measured value. Thus our result is consistent with the assumption that for both pairs of mirror nuclei ($A=39$ and 43) an unquenched proton $M2$ matrix element, together with a neutron $M2$ matrix element which is about 20% larger than that of the single-particle estimate, is involved in the $\frac{7}{2}^- \to \frac{3}{2}^+$ and $\frac{3}{2}^+ \to \frac{7}{2}^-$ transitions.

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