‡Present address: Sektion Physik, Universität München, Amalienstr. 54, 8 München 13, West Germany.
[1]A. E. Bisson and R. H. Davis, Phys. Rev. Letters 22, 542 (1969).
[2]J. S. Eck, R. A. LaSalle, and D. Robson, Phys. Rev. 186, 1132 (1969).
[3]R. A. Chatwin, J. S. Eck, D. Robson, and A. Richter, Phys. Rev. C 1, 795 (1970).
[4]A. E. Bisson, K. A. Eberhard, and R. H. Davis, Phys. Rev. C 1, 539 (1970).
[5]R. A. Chatwin, J. S. Eck, A. Richter, and D. Robson, in *Nuclear Reactions Induced by Heavy Ions,* edited by R. Bock and W. R. Hering (North-Holland Publishing Company, Amsterdam, The Netherlands, 1970), p. 76.
[6]J. S. Eck, R. A. Chatwin, K. A. Eberhard, R. A. LaSalle, A. Richter, and D. Robson, Ref. 5, p. 80.
[7]K. A. Eberhard, A. E. Bisson, and R. H. Davis, Ref. 5, p. 89.
[8]K. A. Eberhard, Phys. Letters 33B, 343 (1970).
[9]R. de Swiniarski, C. Glashausser, D. L. Hendrie, J. Sherman, A. D. Bacher, and E. A. McClatchie, Phys. Rev. Letters 23, 317 (1969).
[10]K. W. Kemper, D. S. Haynes, and N. R. Fletcher, to be published.
[11]B. T. Lucas, S. W. Casper, and O. E. Johnson, Phys. Rev. 144, 972 (1966).
[12]W. P. Bourke, Ph.D. dissertation, The Australian National University, 1968 (unpublished).
[13]A. E. Bisson, Ph. D. dissertation, The Florida State University, 1969 (unpublished).
[14]W. J. Wallace, A. E. Bisson, and R. H. Davis, Nucl. Instr. Methods 68, 337 (1969).
[15]J. W. Frickey, Ph.D. dissertation, The Florida State University, 1969 (unpublished).
[16]T. Ericson, Phys. Rev. Letters 5, 430 (1960); Advan. Phys. 9, 425 (1960).
[17]D. M. Brink and R. O. Stephen, Phys. Letters 5, 77 (1963).
[18]T. Ericson and T. Mayer-Kuckuk, Ann. Rev. Nucl. Sci. 16, 183 (1966).
[19]G. Dearnaley, W. R. Gibbs, R. B. Leachman, and P. C. Rogers, Phys. Rev. 139, B1170 (1965).
[20]H. L. Harney and A. Richter, Phys. Rev. C 2, 421 (1970).
[21]E. H. Auerbach, computer program ABACUS-2 (unpublished).
[22]W. J. Thompson, G. E. Crawford, and R. H. Davis, Nucl. Phys. A98, 228 (1967).
[23]W. J. Thompson, to be published.
[24]A. E. Litherland, J. A. Kuckner, H. E. Grove, M. A. Clark, and E. Almquist, Phys. Rev. Letters 7, 98 (1961).
[25]T. Tamura, computer program JUPITOR-1 (unpublished).
[26]W. J. Thompson, private communication.
[27]W. G. Love, private communication.
[28]K. A. Eberhard and D. Robson, Phys. Rev. C 3, 149 (1971).

PHYSICAL REVIEW C VOLUME 4, NUMBER 2 AUGUST 1971

Study of ^{44}Ti by the ^{40}Ca(α,γ)^{44}Ti Reaction

J. J. Simpson
Department of Physics, University of Guelph, Guelph, Ontario, Canada
and
W. R. Dixon and R. S. Storey
Division of Physics, National Research Council, Ottawa, Canada
(Received 6 April 1971)

The ^{40}Ca(α,γ)^{44}Ti reaction has been used to study the nucleus ^{44}Ti. The mass excess of ^{44}Ti has been determined to be $-37\,541\pm10$ keV. Radiative yields and angular distributions of de-excitation γ rays from resonances at 4.22-, 4.26-, and 4.52-MeV α energy, and angular distributions of γ rays between bound levels have been measured using Ge(Li) detectors. Bound states have been found at 1083 (2^+), 1905 (0^+), 2454 (4^+), 2531 (2^+), 2886 (2^+), 3175, 3415 (2, 3), 3645 and 3942 keV, and mixing ratios and branching ratios for the decays of some of these levels are reported. The ground state and first excited 2^+ and 4^+ states can be explained in terms of $(fp)^4$ configurations. Some of the other low-energy states probably require interpretation in terms of particle-hole configurations. Relative reduced $E2$ transition strengths from the 2531-keV (2^+) state are determined and suggest that the 1905- and 2531-keV states may be the beginning of a rotational band.

1. INTRODUCTION

The ^{44}Ti nucleus occupies an important position in the mass-40 region. It fills, in the $0f$-$1p$ shell, the position parallel to ^{20}Ne in the $0d$-$1s$ shell. The analogy between ^{20}Ne and ^{44}Ti is far from complete, however. In published work[1-5] it is found that the second excited states of ^{44}Ti lie at about twice the energy of the first excited state, whereas it is known that ^{20}Ne displays a rotational spectrum.[6]

The present work, which is a continuation of the work published in Ref. 2, is a study of the $^{40}Ca(\alpha, \gamma)^{44}Ti$ reaction. The resonances in this reaction, which are at high excitation ($Q = 5118$ keV), decay by γ emission generally to the ground state and first few excited states. With Ge(Li) detectors it has been possible to determine the decay schemes, not only of the resonances, but of the bound levels to which they decay. Furthermore, by measuring the angular distributions of the γ rays it has been possible to assign spins to a number of bound levels as well as to the resonances. An attempt has also been made to determine the radiative widths of the resonances.

It is found that the first excited state is at 1083 keV and that in the region from 1.9 to 2.9 MeV there are at least four states, three of which have angular distributions and decay schemes consistent with their forming a triplet of states with spins 0^+, 2^+, and 4^+. However, the decay schemes show that comparison with a liquid-drop vibrational spectrum is inappropriate. The results seem to to suggest that the excited 0^+ state is perhaps the start of a rotational-like band.

A few theoretical calculations of the energy spectra of ^{44}Ti have been carried out[2, 7-10] in which the valence nucleons are confined to the *fp* shell, and the ^{40}Ca core remains inert. These calculations explain the first 2^+ and 4^+ states, but are unable to explain the second 0^+ and 2^+ states. Studies of the neighboring ^{42}Ca and ^{43}Sc nuclei,[11, 12] as well as the present work, suggest that excitation from the core may be important. More complete calculations of ^{44}Ti have presumably been deterred by their increasing complexity and by the paucity of experimental details of ^{44}Ti. It is hoped that the present work will help to remove this latter deterrent.

It should also be mentioned that the measurement of the yield of the $^{40}Ca(\alpha, \gamma)^{44}Ti$ reaction is of importance in understanding the astrophysical origin and abundance of the elements.

2. EXPERIMENTAL DETAILS

A. Apparatus

Singly and doubly charged beams of ^4He ions from the 4-MV Van de Graaff accelerator at the National Research Council of Canada have been used to study the $^{40}Ca(\alpha, \gamma)^{44}Ti$ reaction. Targets were made by exposure of 0.025-cm gold backings to vapor released by the reduction of CaO in a tantalum boat. For most of the targets the initial material was $CaCO_3$ enriched to 99.97% in ^{40}Ca. The targets were kept in a dry argon atmosphere while being transferred to the target chamber. Targets of various thicknesses, in the range from 2 to 40 keV for 4.5-MeV α particles, were used. The target backings were directly water cooled. A shroud surrounding the target was kept at liquid-nitrogen temperature in order to avoid a large carbon deposition on the target. A negative potential of 300 V was applied to the shroud to suppress electron emission from the target.

A 12.7×12.7-cm NaI(Tl) crystal was used to measure the yield of γ rays from the reaction as a function of incident ^4He energy. In the first measurements of angular distributions, the NaI(Tl) detector was also used to monitor the yield. A true coaxial 30-cm^3 Ge(Li) detector was used to measure the angular distribution of the γ rays, and a second coaxial Ge(Li) detector of about the same volume was used as the monitor in all experimental runs after the first. The distance from the target to the Ge(Li) detector used to make the angular distribution measurements was about 4 cm. The corrections for the finite size of the detector (attenuation coefficients Q_K) were determined by calculation and by scanning the detector with a collimated γ source. The efficiency of the Ge(Li) detectors was determined for γ-ray energies from about 400 keV to 11 MeV by using standard sources and reactions which provide high-energy γ rays.

The targets were inclined at 45° to the incident beam direction so that the back of the target faced the detector used to determine the angular distribution. This minimizes differences in the γ-ray absorption as a function of the angle of the γ-ray detector, which were in any event low, the experimentally determined difference being only 5% between 45° and 0 or 90° for a 1.33-MeV γ ray. A differential correction for absorption has been applied to the angular distribution of all γ rays with energies below 3.0 MeV.

B. Angular-Distribution Analysis

The intensities of the γ-ray peaks were determined after subtraction of a linear background. In the case of high-energy γ rays, the intensity was obtained from the intensity of the double-escape peak or the double-plus-single-escape peaks.

The angular distributions of the γ rays were fitted to a function of the form[13]

$$W(\theta) = \sum_K B_K(J_1) U_K(J_1J_2) R_K(J_2J_3) P_K(\cos\theta) .$$

The $P_K(\cos\theta)$ are the usual Legendre polynomials. $R_K(J_2J_3)$ depends only on the properties of the observed nuclear transition and contains the dependence of the angular distribution on the multipole mixing ratio of this transition. The term $B_K(J_1)$ depends on the nuclear alignment in the initial state, and in the case of α capture by even nuclei is particularly simple because only the $M=0$ substate is populated. If the observed γ ray is not the primary transition from this capture state but a subsequent member of a deexcitation cascade, additional multiplying terms of the form $U_K(J_1J_2)$ are used for each unobserved transition which precedes it. These factors are required to modify the $B_K(J_1)$ so that the product retains the proper dependence on the nuclear alignment of the state emitting the observed γ ray. Each such term depends on the square of the mixing ratio of the corresponding unobserved transition. The phases of the mixing ratios conform to those of Rose and Brink.[13]

The angular distributions were analyzed by a computer program which calculates the angular distribution for a given choice of spins as a function of up to two mixing ratios δ_1, δ_2. For each choice of mixing ratios it minimizes the χ^2 statistic by least-squares-fitting the normalization of the theoretical angular distribution. The statistic χ^2 is defined by

$$\chi^2 = \sum_i \frac{[Y_i - W_i(\delta_1, \delta_2)]^2}{e_i^2},$$

where Y_i is the experimental value at the ith angle, e_i is the associated experimental error, and $W_i(\delta_1, \delta_2)$ is the theoretical value at that angle. The program then varies each of the mixing ratios in steps of equal arctan δ from -90 to $90°$ and searches for the minimum of χ^2. In cases where the angular distributions have been repeated or where two or more γ rays give information on the same spins and mixing ratios, a simultaneous fit is obtained by adding together the respective χ^2's as a function of δ for these angular distributions.

3. RESULTS

A. General Results

Figure 1 presents a composite yield curve of high-energy γ rays detected in the NaI(Tl) detector as a function of the incident ^{4}He energy. The three energy regions in Fig. 1 together cover a range of ^{4}He energies from about 3.5 to 4.65 MeV. Target thicknesses ranged from about 20 to 40 keV. The yield curve is substantially in agreement with that of Vernotte, Langevin, and Takeutchi,[1] which extended up to a ^{4}He energy of 4.3 MeV. The threshold for the ^{40}Ca$(\alpha, p)^{43}$Sc reaction is at $E_\alpha = 3.89$ MeV, while the threshold for the (α, n) reaction is well above the energy region studied here.

Figure 2 shows a spectrum recorded in a Ge(Li) detector at the $E_\alpha = 4.52$ MeV resonance in the ^{40}Ca$(\alpha, \gamma)^{44}$Ti reaction. The detector was at 55° to the incident beam direction. The strong 1083-keV γ ray is attributed to the first excited state of ^{44}Ti. Its energy is in agreement with a γ ray seen recently in the ^{42}Ca$(^3$He$, n)^{44}$Ti reaction,[14] and also during the bombardment of a ^{32}S target with a ^{14}N beam.[15]

Not all of the peaks in the excitation function shown in Fig. 1 are due to resonances in the ^{40}Ca$(\alpha, \gamma)^{44}$Ti reaction. The association of a peak with this reaction is made if the high-energy γ rays correspond to transitions to known bound levels in ^{44}Ti, if the apparent Q value agrees with the measured value (see Sec. 3 B), and if the change in excitation energy from resonance to resonance corresponds to the center-of-mass-energy change expected for α capture by ^{40}Ca. A further check is provided by measuring the Doppler shifts of the high-energy γ rays. In some cases the resonances in the ^{40}Ca$(\alpha, \gamma)^{44}$Ti reaction are obscured by other peaks or by general background in the excitation curve.

Figure 3 gives the main decay branches of the ^{44}Ti resonances which we have examined. The energies of the resonant states and of the bound levels to which they decay are given with their experimental uncertainties. The spin assignments given in Fig. 3 are based chiefly on angular-distribution analyses which are described below for the $E_\alpha = 4.22$-, 4.26-, and 4.52-MeV resonances. In cases where the angular distributions have been measured, branching ratios have also been obtained using the experimentally measured efficiencies of the Ge(Li) detectors.

It may be useful here to list some of the background γ rays which are observed. Some of these are indicated in Fig. 2 with asterisks. Prominent γ rays are observed at 871 keV from ^{14}N$(\alpha, p\gamma)^{17}$O,

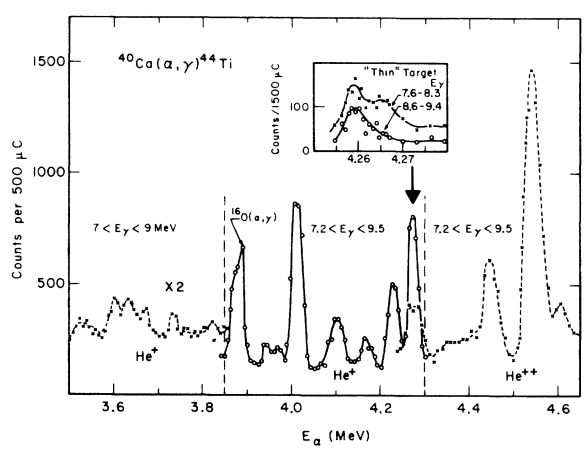

FIG. 1. Composite γ-ray yield curve for the ^{40}Ca(α,γ)-^{44}Ti reaction obtained with ^{4}He$^+$ and ^{4}He^{++} beams and a NaI(Tl) detector. The inset shows the separation of the resonance at $E_\alpha = 4.26$ MeV into two components.

at 1633 keV from $^{17}O(\alpha, n\gamma)^{20}Ne$, and at 1809 keV from $^{23}Na(\alpha, p\gamma)^{26}Mg$. Fluorine has not been a serious contaminant, although its presence is seen. There are several γ rays from the $^{18}O(\alpha, n\gamma)^{21}Ne$ reaction, particularly at 350, 1397, 2790, 2440, and 2796 keV; for $E_\alpha \gtrsim 4.5$ MeV, a 1119-keV γ ray and a 2516-keV γ-ray underlying the 2531-keV γ-ray from ^{44}Ti at forward angles are also present. Carbon contributes to a background of neutrons and neutron-capture γ rays from the $^{13}C(\alpha, n\gamma)^{16}O$ reaction. The $^{12}C(\alpha, \gamma)^{16}O$ reaction has a resonance[16] at $E_\alpha = 4.26$ MeV, resulting in excitation of the 4^+ level at 10.35 MeV in ^{16}O. This level deexcites with γ rays of 3.43 and 6.92 MeV, which fortunately can be distinguished from ^{44}Ti γ rays by the Doppler shift. If the 6.92-MeV γ ray were attributed to the 4.26-MeV resonance in $^{40}Ca(\alpha, \gamma)$-^{44}Ti, one would erroneously "find" a level in ^{44}Ti at 2.1 MeV. This is perhaps the explanation of the 2.1-MeV level reported by Vernotte, Langevin, and Fortier[1] from results obtained with NaI(Tl) detectors.

B. Q Value

Figure 3 shows that several of the ^{44}Ti resonances decay by transitions to the ground state. In particular we have used the resonance at $E_\alpha = 4.257$ MeV to determine the Q value of the $^{40}Ca(\alpha, \gamma)^{44}Ti$ reaction. The energy of the ground-state transition was determined to be 8987 ± 2 keV by calibrating the Ge(Li) detector with the 9168 ± 1-keV γ ray provided by the $^{13}C(p, \gamma)^{14}N$ reaction at the $E_p = 1747.1$-keV resonance.[17] The energy of the incident $^4He^+$ beam was determined from known resonances in the $^{15}N(\alpha, \gamma)^{19}F$ reaction.[18] In this way the Q value for the $^{40}Ca(\alpha, \gamma)^{44}Ti$ reaction was found to be 5118 ± 10 keV. From the accepted masses of ^{40}Ca and ^4He the mass excess of ^{44}Ti is found to be $-37\,541 \pm 10$ keV compared with the value $-37\,658 \pm 12$ keV of the compilation of Mattauch, Thiele, and Wapstra.[19]

This new mass value means that the energy available for the electron-capture decay of ^{44}Ti to ^{44}Sc, Q_{EC}, is 272 ± 15 keV, using the accepted value for the ^{44}Sc mass excess.[19] The dominant electron-capture branch to the 146-keV level in ^{44}Sc thus has a logft of 6.5 instead of less than the value 4.4 previously thought, a value of 47 yr being used for the half-life[20,21] of ^{44}Ti. This branch is therefore not unequivocally an allowed transition, and thus the 146-keV level of ^{44}Sc may not be a 1^+ state as required by the previous logft value. The logft value of the $(1.9 \pm 1.5)\%$ branch to the 68-keV level[22] in ^{44}Sc is about 8.6.

C. $E_\alpha = 4.22$ MeV Resonance

The angular distributions of γ rays of 8954, 7863, 7049, 6501, 5780, and 5310 keV are shown in Fig. 4. There were also γ rays of 6415, 6066, and 5013 keV for which angular distributions are not

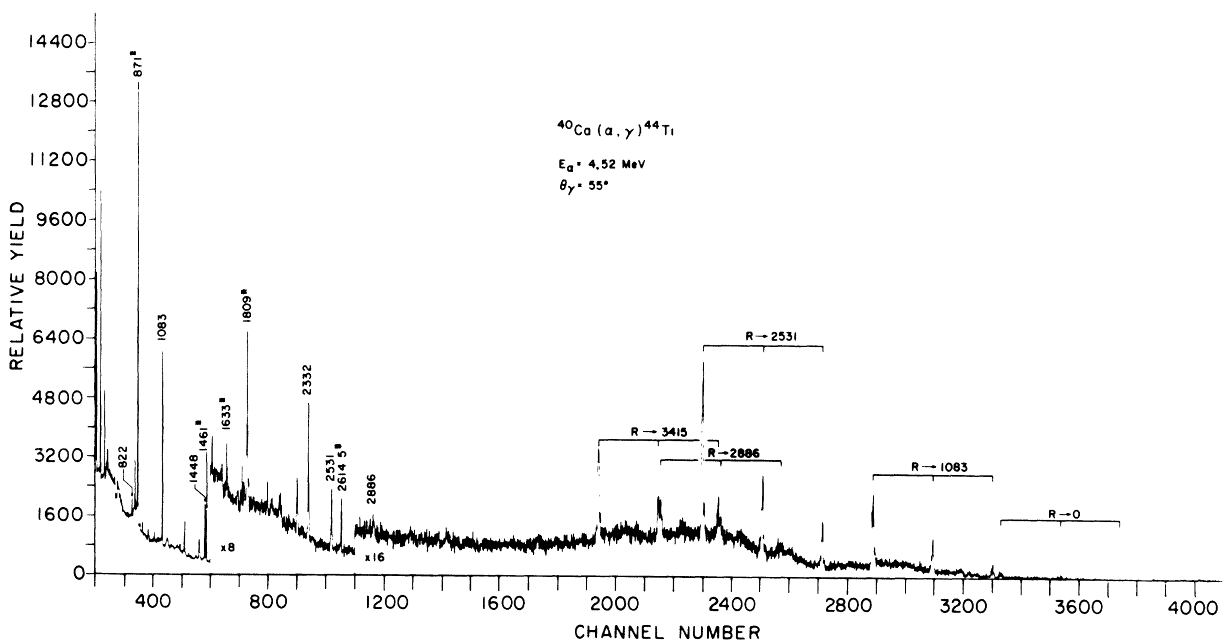

FIG. 2. γ-ray spectrum in a Ge(Li) detector at the $E_\alpha = 4.52$ MeV resonance. Primary transitions are denoted ($R \rightarrow 1083$), for example, and secondary γ rays in ^{44}Ti are labeled with their energies. Energies marked with asterisks are background γ rays.

shown. All of the γ rays showed the expected Doppler shifts.

Our interpretation of this resonance is that there is an overlapping of at least two and more likely three resonances. The evidence for this is as follows. When using a thin target the excitation function was significantly broader than for other single resonances. Secondly, the γ rays of 7863 and 6415 keV are clearly low in energy and correspond to an α-capture state at 8946 ± 3 keV feeding the known levels at 1083 and 2531 keV, whereas the transition to the ground state and to the other levels indicates a state or states at about 8954 keV. The angular distribution of the 8954-keV γ ray is well fitted as a 1 to 0 transition ($\chi^2 = 4.2$ with the number of degrees of freedom $\nu = 4$). Choosing a resonance spin of 2 or 3 resulted in a χ^2 of 15 and 16, respectively, and hence the spin and parity of this member of the resonance is taken as 1^-, the parity assignment arising from the fact that α capture in even nuclei can only populate states of parity $(-)^J$. However, the 6501-keV γ ray corresponds to a transition from a resonance at 8955 keV to a level at 2454 keV. The study of the $E_\alpha = 4.26$ MeV resonance indicates that this level most likely has a spin of 4, and if this is so, this state must be fed from a resonance different from the 1^- resonance feeding the ground state. The weak resonance at 4.47 MeV also suggests that this is the case. The latter resonance is observed to decay to levels at 2454, 3175, 3645, and 3942 keV and no transitions were observed to any of the lower states. Transitions to the same set of states from the 8955-keV resonance are associated with the 6501-, 5780-, 5310-, and 5013-keV γ rays and this suggests that these γ rays may arise from the decay of a common high-spin resonance. Finally the yields of these four γ rays from a thin target increased relative to the other transitions as the incident α energy was increased across the peak in the excitation function. Because of its low yield it has not been possible to decide to which resonance the 6066-keV γ ray feeding a level at 2886 keV most likely belongs.

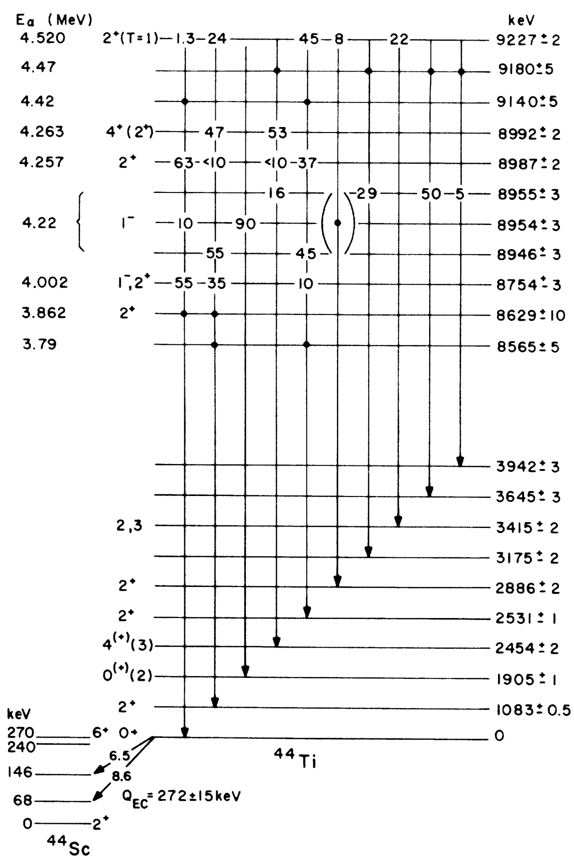

FIG. 3. The main decay branches of resonances examined in the ^{40}Ca(α,γ)^{44}Ti reaction. Resonances for which branching ratios are not given were studied at one angle only. A bracket is used to indicate that no clear choice exists for the resonance at $E_\alpha = 4.22$ MeV feeding the 2886-keV level.

The 7049-keV γ ray is interpreted as a transition from the 1^- resonance to a level at 1905 keV (see Figs. 4 and 5). Figure 5 shows that the primary transition could be equally well fitted with any choice of spin for the 1905-keV level from 0 to 3. However, the choice of spin 3 requires a relatively large mixing ratio, implying an extremely enhanced octupole transition and is very unlikely. A resonant 822-keV γ ray corresponding to a transition from the 1905-keV level to the 1083-keV (2^+) state has also been seen and its angular distribution is shown in Fig. 6 along with that of the 1083-keV γ ray. The strength of a 1905-keV crossover γ ray is less than 5% of the 822-keV γ ray to the 1083-keV level and this makes the choice of spin 1 and 2^+ unlikely for the 1905-keV level. Consequently, 0, 2^- are preferred for the 1905-keV level. The level at 1905 keV has also been studied at the $E_\alpha = 4.52$ MeV resonance, where it is populated in the decay of the 2531-keV level.

The statistical uncertainties were such that it was not possible, from the angular distributions, to decide on the spin of the 8946-keV resonance or of the upper resonance which we have labeled as 8955 keV. Any choice of spin from 0 to 4 would serve for the 8946-keV resonance. As already noted the decay scheme of the 8955-keV resonance suggests that it has a high spin.

Resonant γ rays of 470 and 2092 keV are also seen. The 470-keV γ ray is well separated at 0° from a contaminant γ ray associated with the 477-keV first excited state of ^{7}Li, and is attributed to a transition from the 3645-keV level to the level

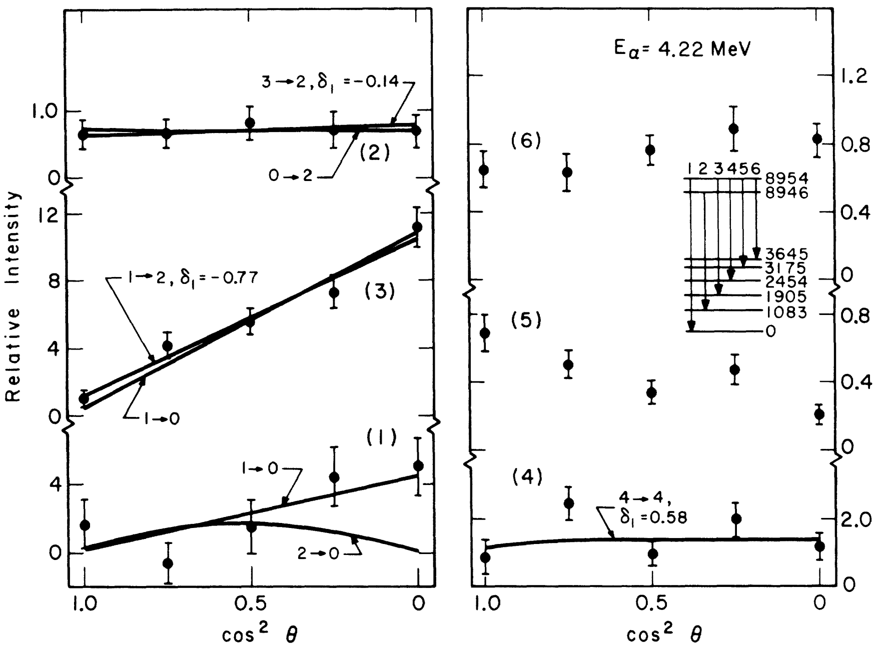

FIG. 4. Angular distributions of some of the primary γ rays from the $E_\alpha = 4.22$ MeV resonance. The number beside each angular distribution corresponds to the number of the transition in the decay scheme also shown.

at 3175 keV. Its yield can account for almost all of the decays of the 3645-keV level within the statistical uncertainties. The 2092-keV γ ray (3175 → 1083) seems to account for all of the decays of the 3175-keV level. These decays seem to suggest that the 3645- and 3175-keV levels have high spins.

The branching ratios (%) for the observed decays of the resonance are given in Table I. Since it was not possible to obtain a clean separation of the excitation function into the individual resonances, branching ratios for a thick target as well as for the individual resonances are given in the table. The decay properties of the bound levels are given in Table II. Mixing ratios, where determined, are given in the tables with errors of 1 standard deviation.

D. E_α = 4.26 MeV Resonance

The 4.26-MeV resonance was observed to be a doublet with a separation of about 6 keV in the incident α energy. A double hump in the thin-target excitation function is clearly present (see the inset in Fig. 1) for a window set to accept transitions from the resonance to the first excited state. At the same time a window set to accept only ground-state transitions shows only a single peak. It was also found that when using a thick target the energies of the γ rays to the ground state and to the first excited state [as measured in a Ge(Li) detector] were separated by only 1078 keV instead of by 1083 keV, indicating a difference in excitation energies of 5 keV if each observed γ ray is due to a transition from a single resonance. A careful determination of the feeding of each resonance to the bound levels was then made with a thin target with the Ge(Li) detector at 45°. The

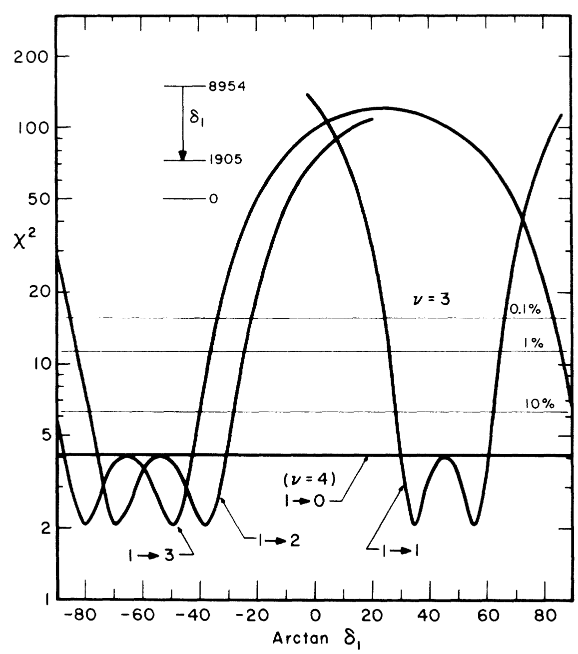

FIG. 5. χ^2 fits for the primary transition ($R \to 1905$) from the $E_\alpha = 4.22$ MeV resonance.

lower resonance, at 4257-keV incident energy, was found to deexcite predominantly to the ground state and to the 2531-keV level. Weaker branches of about 10% were also observed to the 1083- and 2454-keV levels, but because these transitions might have arisen as a result of the beam energy accidentally drifting into the other resonance, these branches are taken as upper limits. The upper resonance, at 4263-keV incident energy, decayed about equally strongly to the 1083- and 2454-keV levels. Decays of the upper resonance to the ground state and to the 2531-keV level are estimated to be less than 5% of the total decays in each case. The upper member of the doublet is about twice as strong as the lower (see Sec. 3 G), so that when a thick target is used, the feeding from the lower resonance to either of the 1083- or 2454-keV levels is less than about 10% of the feeding from the upper resonance. In the analysis of the angular distributions of the primary γ rays as measured with thick targets, it has therefore been assumed that each bound level is fed from only one resonance.

The first γ-ray angular distributions measured at this resonance used the NaI(Tl) detector as a monitor and a target thick enough to include both resonances. After the decay branches of the two

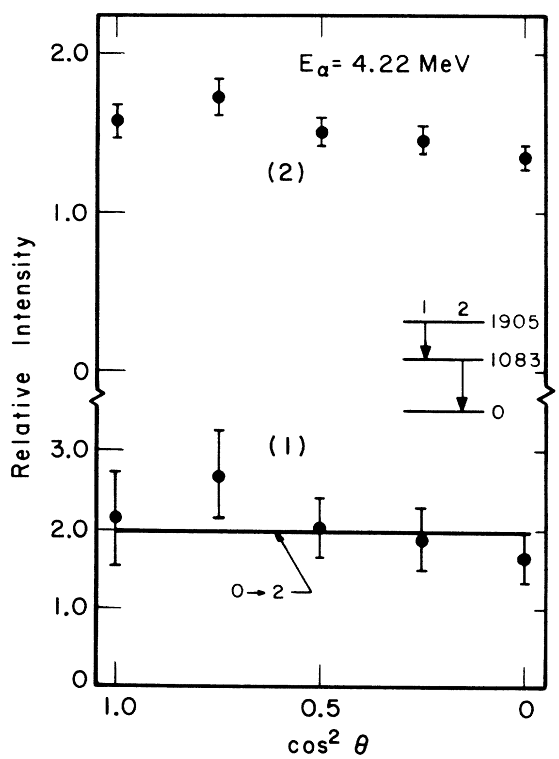

FIG. 6. Angular distributions of the 822- and 1083-keV γ rays at the $E_\alpha = 4.22$ MeV resonance.

resonances had been examined, the angular distributions were repeated with the second Ge(Li) detector used as a monitor, and again with a thick target (~25 keV). The second set of angular distributions was essentially the same as the first and both have been retained in the analysis. Figure 7 shows the angular distributions of the primary γ rays. In this figure the results of each angular distribution of a particular γ ray have been normalized to the same total yield of γ rays integrated over all angles and are displayed using different symbols.

The angular distribution of the 8987-keV transition to the ground state unambiguously labels the lower resonance a 2^+ state ($\chi^2 = 9.4$ with $\nu = 8$). Figure 8 shows χ^2 as a function of δ for the other three primary transitions. The study of the $E_\alpha = 4.52$ MeV resonance (below) assigns the 2531-keV state a spin of 2.

The 7909-keV transition to the 1083-keV state requires that the upper resonance at 4263 keV be a 2^+ or a 4^+ state, with 1^- just allowed at the 1% level. However, the angular distribution of the 1083-keV γ ray shown in Fig. 9 requires a large $P_4(\cos\theta)$ term for a satisfactory fit ($\chi^2 = 1.7$, $\nu = 2$ with a P_4 term, and $\chi^2 = 9.8$, $\nu = 3$ with only a P_2 term) and this, combined with the information on the primary γ ray, eliminates the choice of 1^- for the resonance.

As Fig. 8 shows, almost any spin, with the exception of 0, is permitted for the 2454-keV level by the angular distribution of the 6538-keV γ ray. However, certain combinations of resonance spin and spin of the 2454-keV level are extremely unlikely. In particular, a resonance spin of 4 and level spin of 1 or 2 are ruled out by a large χ^2, and a resonance spin of 2 and level spin of 4 is unlikely because the value of δ_1 and the measured radiative yield $\omega\gamma = 0.6$ eV (see Sec. 3 G) imply a very large octupole admixture.

A further selection of spins has been possible by analyzing the angular distribution of the 1083- and 1371-keV γ rays (Fig. 9). The 1371-keV γ ray deexciting the 2454-keV level has an energy very close to the first excited state of ^{24}Mg. This γ ray was resonant, and an off-resonance run indicated that any ^{24}Mg contamination accounted for less than about 25% of the 1371-keV γ ray. The yield of the 1371-keV γ ray was also consistent with the strength of the primary transition feeding the 2454-keV level. To analyze the angular distribution of the 1083-keV γ ray the contributions to it of the feeding from the 2531-keV level and of the primary γ ray from the 8992-keV resonance were subtracted. The latter contribution was of course the most important, contributing about 45% of the 1083-keV γ ray. This contribution to the 1083-keV

γ ray was calculated using the best mixing ratios determined from the angular distribution of the 7909-keV γ ray (Fig. 8). Thus, for the assumption of a resonance spin of 2, δ_1 was taken to be -1.9, and with a resonance spin of 4, δ_1 was taken to be 0. With these contributions subtracted, the 1083-keV γ ray was fitted as a γ ray following two unobserved cascade γ rays. The ground-state and first-excited-state spins were fixed at 0 and 2, respectively. The mixing ratios δ_1 and δ_2 of the unobserved γ rays were allowed to vary independently.

Figure 10 presents the final results for a simultaneous fit of the angular distributions of the 6538-, 1371- and 1083-keV γ rays. It shows χ^2 as a function of δ_2 for δ_1's determined by the minima in the (δ_1, δ_2) plane which are acceptable at the 0.1% confidence level. The best agreement is with a resonance spin of 4 and a spin of 4 for the 2454-keV level with $\delta_1 = 0.64 \pm 0.11$ and $\delta_2 = (0.07^{+0.20}_{-0.12})$. The combinations of $2 \rightarrow 1$, $2 \rightarrow 2$ are ruled out at the 1% level, and, as mentioned above, the combination $2 \rightarrow 4$ is unlikely because of the large δ_1. (For $2 \rightarrow 4$ the case of $\delta_1 = 0$, $\delta_2 = 0$ has $\chi^2 = 36$ with $\nu = 14$, i.e., at the 0.1% confidence level). The combinations of $2 \rightarrow 3$ and $4 \rightarrow 3$ are, however, also allowed. An appeal to the systematics of nuclei in this mass region suggests that a state of spin 3 so low in energy is unlikely, and hence the combination of resonance 4^+ and 2454-keV level 4^+ seems most likely. The crossover transition from the 2454-keV level to the ground state has not been observed and is <4% of the 1371-keV branch.

The results for the $E_\alpha = 4.257$ and 4.263 MeV resonances are summarized in Tables I and II.

E. $E_\alpha = 4.520$ MeV Resonance

This resonance at an energy of 9227 keV in ^{44}Ti was the strongest studied. An example of a spectrum taken at this resonance is shown in Fig. 2.

TABLE I. Decay of resonances observed in the $^{40}Ca(\alpha, \gamma)^{44}Ti$ reaction. The group of resonances at $E_\alpha = 4.22$ MeV was only partially resolved (see text), and the last column gives branching ratios for the unresolved group.

Incident α energy (MeV)	Resonance energy in ^{44}Ti (keV)	Resonance J^π	Transition energy (keV)	Final state Energy (keV)	J^π	Mixing ratios δ_1	Branching ratios (%)	Branching ratios for group (%)
4.22	8946	?	7863	1083	2^+		55	8 ± 1
			6415	2531	2^+		45	7 ± 1
			6066 [a]	2886	2^+			6 ± 1
	8954	1^-	8954	0	0^+		10	3 ± 1
			7049	1905	0^+		90	24 ± 1
					2	$-4.5 \rightarrow -0.5$		
	8955	?	6501	2454	4 (3)		16	8 ± 1
			5780	3175			29	15 ± 1
			5310	3645			50	26 ± 1
			5013	3942			5	3 ± 1
4.257	8987	2^+	8987	0	0^+		63 ± 2	
			7904	1083	2^+		<10	
			6533	2454	4 (3)		<10	
			6456	2531	2^+	0.29 ± 0.11 or $-(4.0^{+3.0}_{-0.4})$	37 ± 2	
4.263	8992	4^+	7909	1083	2^+	$-(0.02 \pm 0.03)$	47 ± 3	
			6538	2454	4	$+0.64 \pm 0.11$	53 ± 3	
					3	$-(0.09 \pm 0.05)$		
			6461	2531	2^+		<5	
		or 2^+	8992	0	0^+		<5	
			7909	1083	2^+	$-(1.9^{+0.4}_{-0.3})$	47 ± 3	
			6538	2454	4	$-(0.20 \pm 0.07)$	53 ± 3	
					3	$+0.06 \pm 0.06$		
			6461	2531			<5	
4.520	9227	2^+	9227	0	0^+		1.3 ± 0.5	
			8144	1083	2^+	$-(0.02 \pm 0.07)$	24 ± 1	
			6696	2531	2^+	$-(0.02 \pm 0.04)$	45 ± 2	
			6341	2886	2^+		8 ± 2	
			5812	3415	2	$+0.32^{+0.1}_{-0.05}$	22 ± 2	
					3	$+0.09 \pm 0.07$		

[a] It is not certain from which resonance this branch comes.

TABLE II. Decay of bound levels of ^{44}Ti.

Initial level Energy (keV)	Initial level J^π	Final level Energy (keV)	Final level J^π	Transition energy (keV)	Branching ratios (%)	Mixing ratios δ_2
1083	2^+	0	0^+	1083	100	
1905	$0^{(+)}$	1083	2^+	822	100	
	or $2^{(-)}$	1083	2^+	822	100	$0.28 < \delta_2 < \infty$
2454	$4^{(+)}$	1083	2^+	1371	100	$-(0.07^{+0.20}_{-0.12})$
	or 3	1083	2^+	1371	100	$-(0.42^{+0.12}_{-0.09})$
2531	2^+	0	0^+	2531	25^{+8}_{-2}	
		1083	2^+	1448	71	$7.5^{+8.0}_{-2.5}$
		1905	0^+	626	3.7 ± 0.7	
2886	2^+	0	0^+	2886	70 ± 10	
		1083	2^+	1803	30 ± 10	
3175		1083	2^+	2092	~100	
3415	2	1083	2^+	2332	100	$-(1.6^{+1.2}_{-0.6})$
	or 3	1083	2^+	2332	100	$-\infty < \delta_2 < -6$
						or $-(0.4^{+0.10}_{-0.09})$
3645		3175		470	85 ± 15	

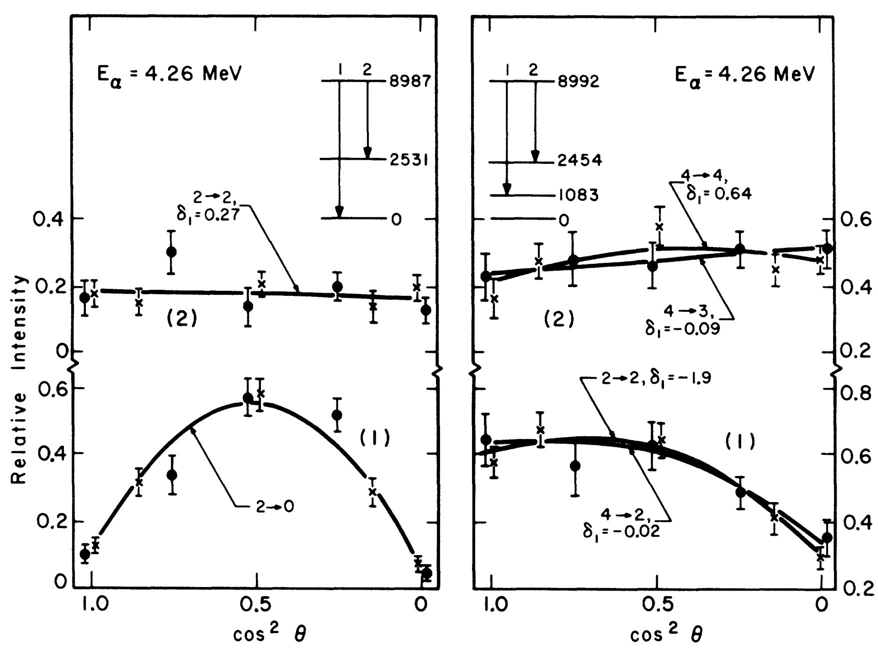

FIG. 7. Angular distributions of primary γ rays from the $E_\alpha = 4.26$ MeV resonance (see caption for Fig. 4).

The angular distributions of primary γ rays from this resonance are shown in Fig. 11. The choice of spin 1 for the resonance is ruled out by the angular distribution of the weak branch to the ground state ($\chi^2 = 24$ with $\nu = 5$) as well as by the fact that the angular distribution of the 1083-keV γ ray required a $P_4(\cos\theta)$ term [with no P_4 term $\chi^2 = 70$ with $\nu = 4$ (see Fig. 13)]. The choice of spin 2 gave a χ^2 of 2 and spin 3 gave a χ^2 of 9.8 with $\nu = 5$. Furthermore the radiative yield $\omega\gamma$ from this resonance is at least 6 eV (see Sec. 3G), and if the resonance were a spin-3 state the transition to the

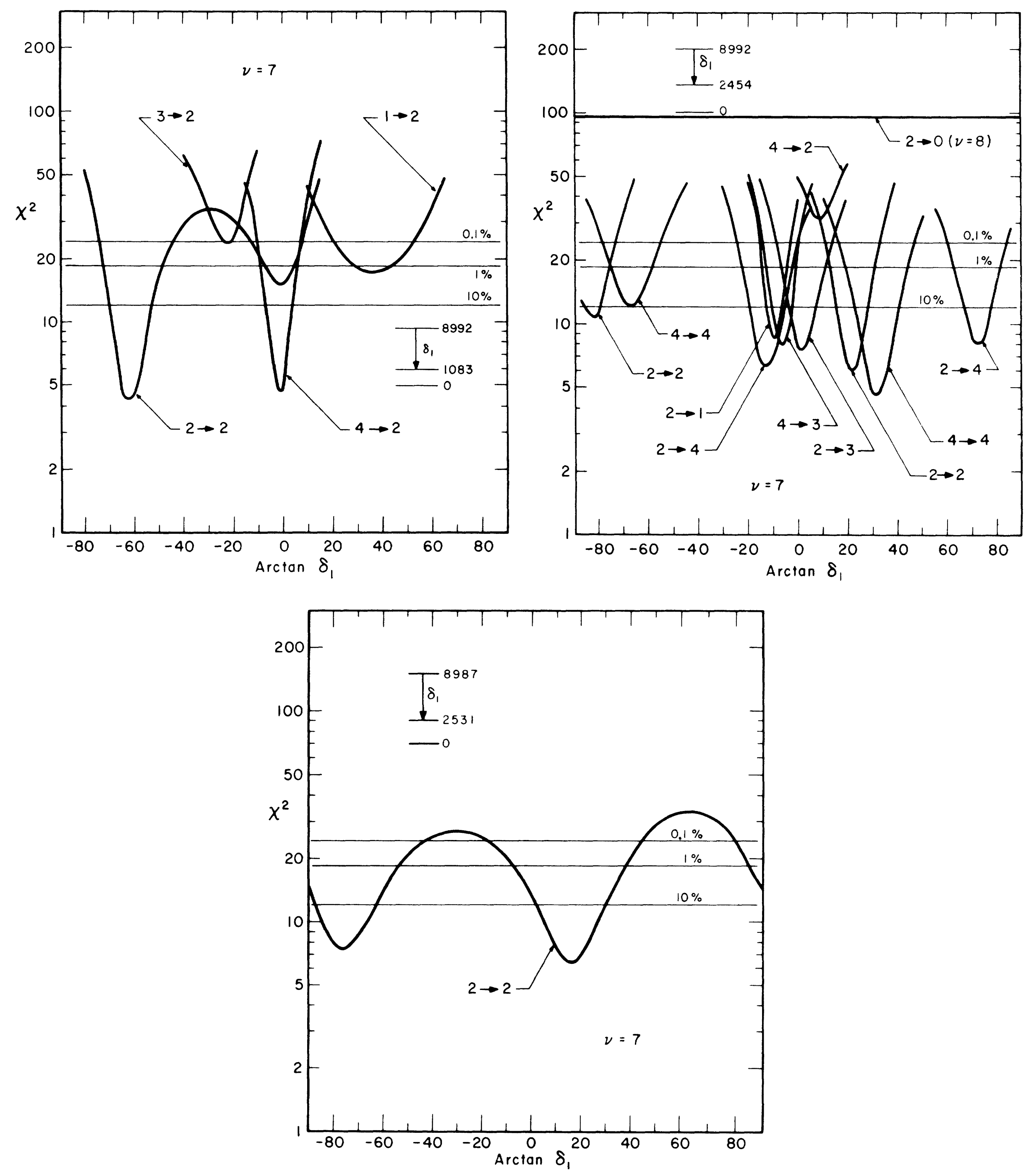

FIG. 8. χ^2 fits for primary γ rays from the $E_\alpha = 4.26$ MeV resonance.

ground state would be enhanced by over 50 W.u. Thus a 2^+ assignment is preferred.

Figure 12 shows the χ^2 fits as a function of δ_1 for the primary 8144-keV γ ray to the 1083-keV state, the 6696-keV γ ray to the 2531-keV state, and the 5812-keV γ ray to a level at 3415 keV. Only the choice of resonance spin 2 gives a satisfactory fit to the angular distribution of the 8144-keV γ ray. The angular distribution of the primary γ ray of 6696-keV feeding the 2531-keV level limits the spin of this level to 2, 3, or 4, but spins 3 and 4 are ruled out by the strength of the 2531-keV crossover decay from this level to the ground state (see Sec. 4). An analysis of the secondary γ rays deexciting this level also favors the spin-2 assignment (see below).

The 5812-keV γ ray has been postulated as a primary γ ray to a level at 3415 keV. The angular distribution of the primary γ ray allows any spin from 1 to 4 for the 3415-keV level. A γ ray of 2332 keV corresponding to a decay from this level to the 1083-keV level has been observed. It should be remarked that the 3415-keV level has not yet been identified at another resonance.

The 6341-keV γ ray has been postulated as a primary γ ray to a level at 2886 keV. This γ ray shows the full Doppler shift. A resonant γ ray of 2886 keV has been seen, and another branch from this level to the 1083-keV state seems to be observable at 90°, where it lies very close to a contaminant line of 1809 keV from the ^{23}Na(α,p)^{26}Mg reaction. The angular distribution of the primary γ ray can be fitted with any choice of spin for the 2886-keV level from 1 to 4. The large errors on

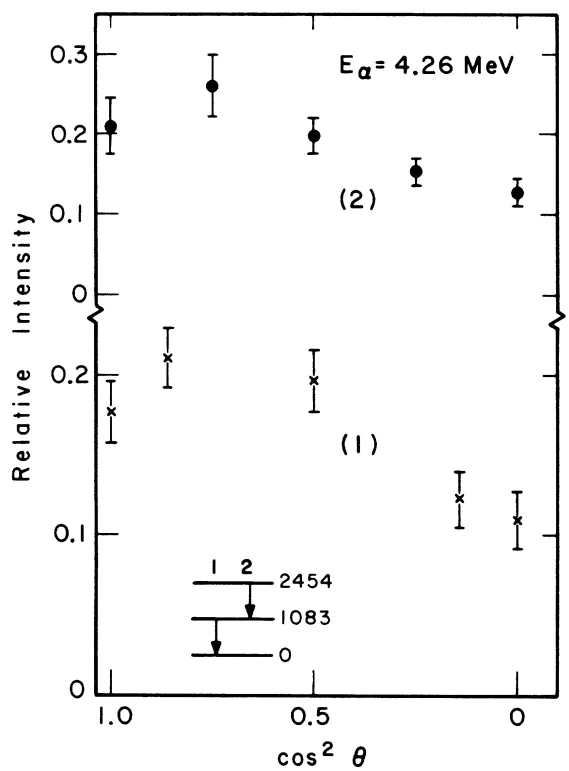

FIG. 9. Angular distributions of the 1371- and 1083-keV γ rays at the $E_\alpha = 4.26$ MeV resonance.

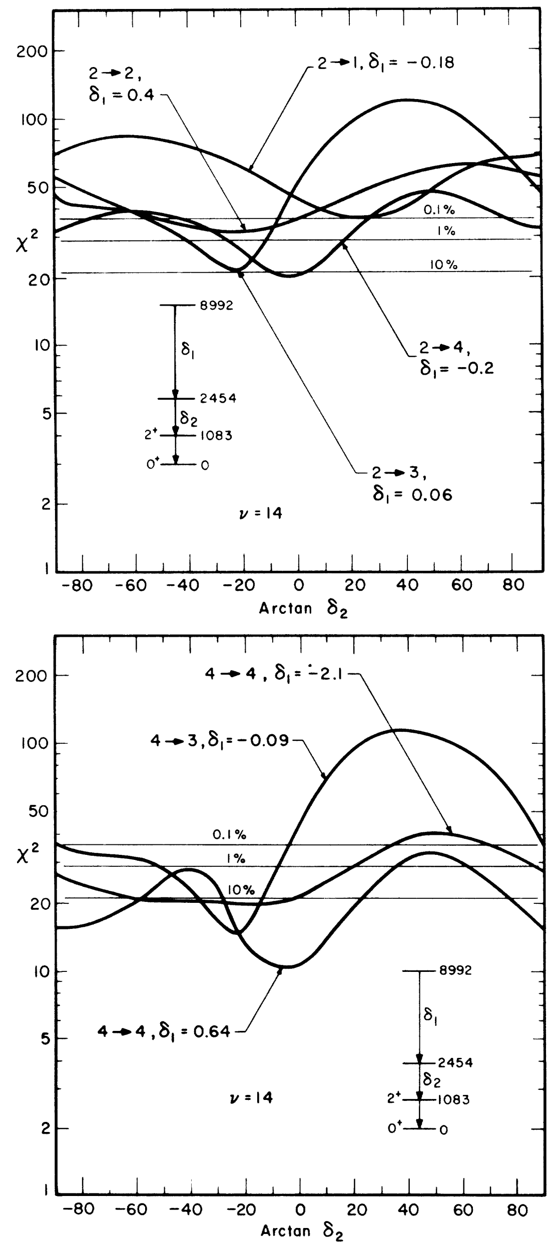

FIG. 10. A simultaneous χ^2 fit for the γ rays in the cascade 8992→2454→1083→0 as a function of the mixing ratio δ_2 of the 1371-keV γ ray. Values of the primary mixing ratio δ_1 are determined by the minima in the (δ_1,δ_2) plane which are acceptable at the 0.1% confidence level.

the angular distribution are due in part to having to subtract the single-escape peak of the 5812-keV γ ray. Spins of 3 and 4 for the 2886-keV level are ruled out by the crossover transition to the ground state.

Figure 13 shows the angular distributions of the secondary γ rays observed at this resonance. Of particular interest is the 2531-keV level which decays to the ground state (25%), to the first excited state (71%), and to the state at 1905 keV (3.7%). To obtain the angular distribution of the 2531-keV γ ray, a contaminant line of 2516 keV from the $^{18}O(\alpha, n\gamma)^{21}Ne$ reaction resonant at 4.52 MeV [23] and feeding a state at 2866 keV in ^{21}Ne was subtracted and this considerably increased the errors on the angular distribution. The amount of the 2516-keV contribution was estimated from the observed yield of another branch from the 2866-keV level of 1119 keV,[24] taking into account the Doppler shift of the 2516-keV γ ray and assuming an angular distribution corresponding to the emission of s-wave neutrons.

Figure 14 shows the χ^2 plots for simultaneous fits to the angular distributions of the primary and secondary γ rays. The simultaneous fit of the angular distributions of the 6696-keV γ ray, the 2531-keV γ ray, and the 1448-keV γ ray to the 1083-keV level confirms the spin-2 assignment of the 2531-keV level. Spin 2 is favored for the 2886-keV level, whereas the 3415-keV level is about equally well fitted with either choice of 2 or 3 for the spin. No crossover to the ground state has been detected from the 3415-keV level (<3%).

The 626-keV γ ray seen at this resonance is interpreted as a transition from the 2531-keV level to the 1905-keV level. The angular distribution for this γ ray shown in Fig. 13 is well fitted either with spin 0 or 2 for the 1905-keV level, and less well fitted with spin 1. (Spin 1 can be rejected at the 5% confidence level.) The angular distribution of the 822-keV γ ray (1905 → 1083 keV) which is also resonant at this α energy is essentially isotropic. No transition from the 1905-keV level to the ground state is seen.

Since ^{44}Ti is a self-conjugate nucleus, the predominance of $M1$ transitions and the relative inhibition of $E2$ transitions from this resonance suggest that this resonance may have $T = 1$.

The results for the $E_\alpha = 4.520$-MeV resonance are summarized in Tables I and II. Some preliminary lifetime measurements of the bound states in ^{44}Ti have been made using this resonance and their indications towards the correct spin and parity assignments will be given in Sec. 4.

F. Other Resonances

Other resonances which we have looked at include those at $E_\alpha = 3.79$, 4.002, 4.42, and 4.47 MeV, with the main (≳5%) γ-ray decay branches being shown in Fig. 3. Vernotte, Langevin, and Takeutchi[1] have found that the resonance at $E_\alpha = 4.002$ MeV is a doublet, and they have assigned spins of 2^+ and 1^- to it. This is consistent with our results. Figure 1 also shows a resonance at $E_\alpha = 3.86$ MeV which partially overlaps a reso-

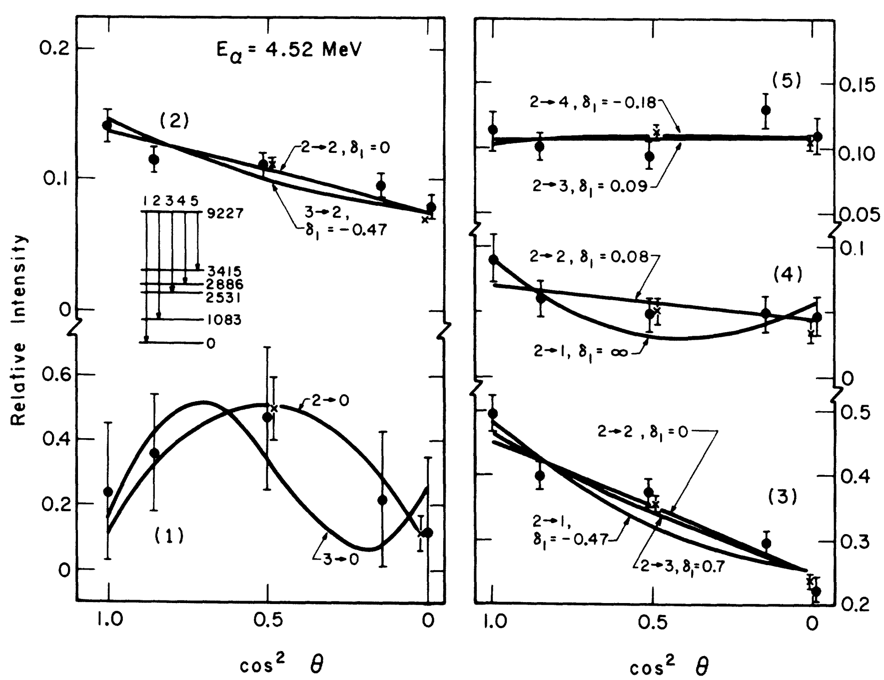

FIG. 11. Angular distributions of primary γ rays from the $E_\alpha = 4.52$ MeV resonance (see caption for Fig. 4).

nance in α capture by ^{16}O. A spin of 2^+ has been determined by Vernotte, Langevin, and Takeutchi[1] for this resonance. The resonance at $E_\alpha = 4.42$ MeV is largely obscured by a resonance in the ^{13}C(α, n)^{16}O reaction.[23]

Only a cursory examination has been made of resonances between $E_\alpha = 4.5$ and 5.0 MeV. There appear to be many weak resonances present, but no very strong ones. It is hoped to study this region more carefully in the future.

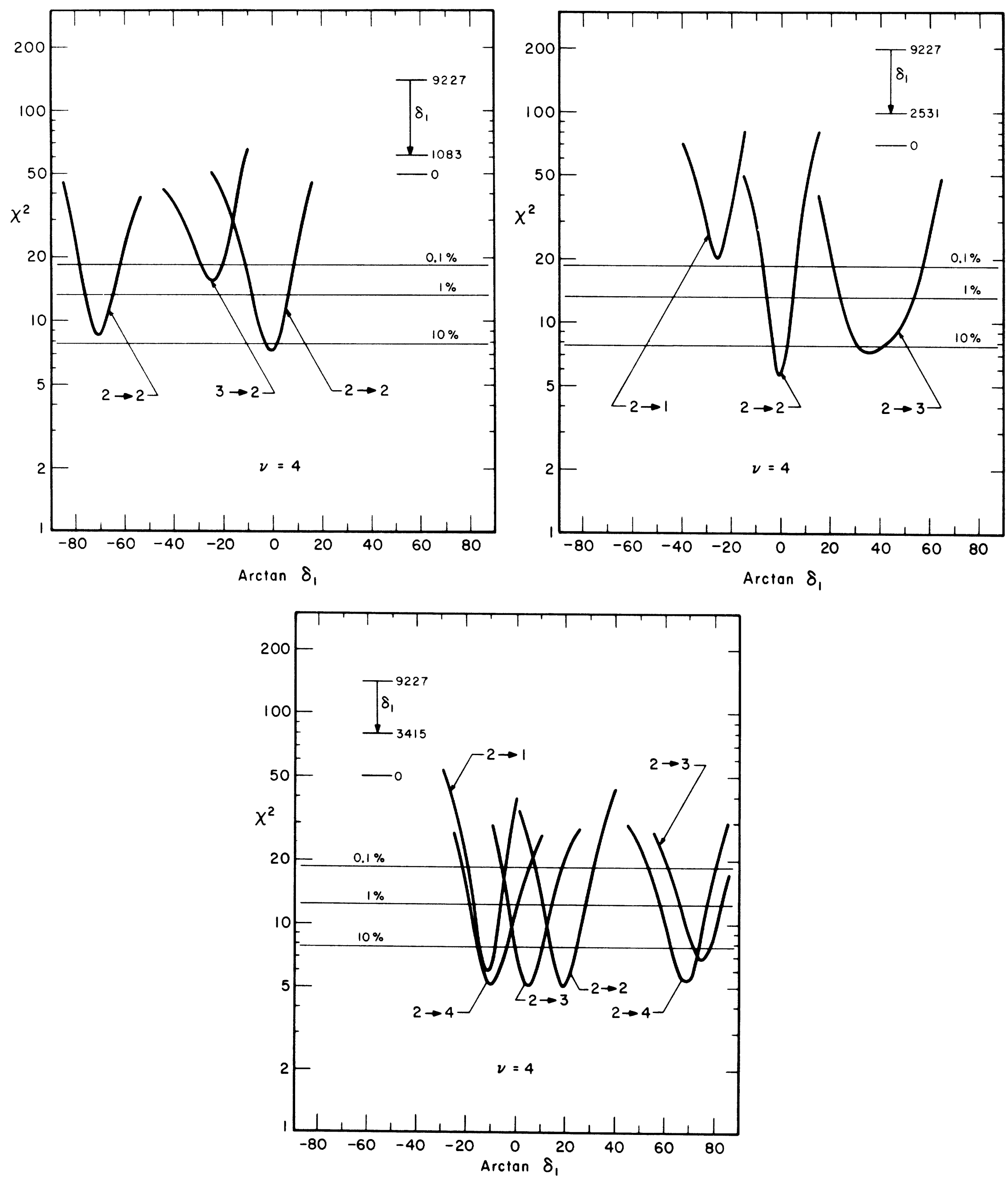

FIG. 12. χ^2 fits for three of the primary γ rays at the $E_\alpha = 4.52$ MeV resonance.

G. Radiative Yields

For a number of the runs, the radiative yield of the resonance was calculated from the relation

$$\omega\gamma = \frac{M_T}{M_\alpha + M_T}\,\frac{2S}{\rho}\,\frac{1}{\lambda^2_{\mathrm{c.m.}}}\,Y\,,$$

where S is the α-particle stopping power in laboratory units of energy per g/cm^2, $M_T/(M_\alpha+M_T)$ is a factor which effectively corrects the stopping powers to the center-of-mass system,[25] ρ is the number of ^{40}Ca nuclei per gram of target material, $\lambda_{\mathrm{c.m.}}$ is the wavelength for the incident α particle in the center-of-mass system, and Y is the thick-target yield of primary γ rays (photons per α particle). The total charge delivered to the target was measured with a calibrated current integrator (with suppression of electron emission), and the photon yield was found by calibrating the detector *in situ* with a standard ^{60}Co source inserted in place of the target. There is some uncertainty arising from a lack of accurate knowledge of the composition of the target; we have assumed pure calcium which gives a minimum value for the calculated $\omega\gamma$. The $\omega\gamma$ values determined in this way are given in Table III.

In the case of α particles incident on ^{40}Ca the partial width Γ_γ for γ-ray emission is related to $\omega\gamma$ by

$$\omega\gamma = (2J+1)\left(\frac{\Gamma_\alpha\Gamma_\gamma}{\Gamma}\right)_{\mathrm{c.m.}},$$

where Γ_α is the partial width for α-particle emission, Γ is the total width ($\Gamma = \Gamma_\alpha + \Gamma_p + \Gamma_\gamma + \cdots$), and J is the spin of the compound-resonant state. The γ-ray partial widths Γ_γ given in Table III are determined from the $\omega\gamma$ values assuming that Γ_p and Γ_γ are both small compared to Γ_α. Hence these Γ_γ's are lower limits.

4. DISCUSSION

Figure 15 shows the decay scheme of the bound levels of ^{44}Ti. In determining the spins of the resonances and consequently the spins of the lower states, it has been assumed that the ground state and the first excited state have spins 0^+ and 2^+, respectively. Below is a brief summary of the evidence on the other levels.

1905 keV. This level has been studied at the $E_\alpha = 4.22$ MeV resonance, where it is populated by a primary transition, and at the $E_\alpha = 4.52$ MeV resonance, where it is fed from the decay of the 2531-keV level. The angular distribution of the γ rays feeding this level and of the 822-keV γ ray deexciting this level are consistent with it being a state of spin 0. The failure to observe a crossover γ ray to the ground state makes the assignment of 1 or 2^+ to the level unlikely, although 2^- cannot be discriminated against on this basis. Systematics of energy levels in this mass region would, however, seem to rule out 2^-, and favor a 0^+ assignment.

2454 keV. From the angular distributions this

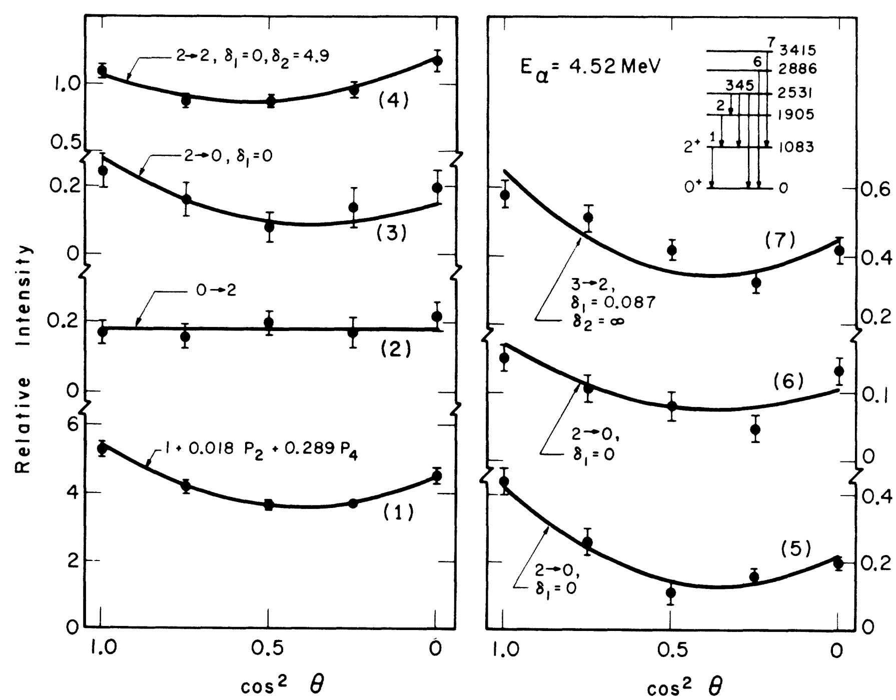

FIG. 13. Angular distributions of secondary γ rays at the $E_\alpha = 4.52$ MeV resonance (see caption for Fig. 4).

state is either a state of spin 4 or 3, with 4 favored. Systematics of energy levels favor a 4^+ assignment.

2531 keV. The angular distributions assign a spin of 2 to this level. We have also obtained a preliminary estimate of the mean lifetime of this level of 1.5 psec using the Doppler-shift-attenuation method. This would mean that this level would decay by very enhanced $M2$ transitions if it had negative parity, and hence it is assigned a spin and parity 2^+.

A recent publication by Longequeue, Longequeue,

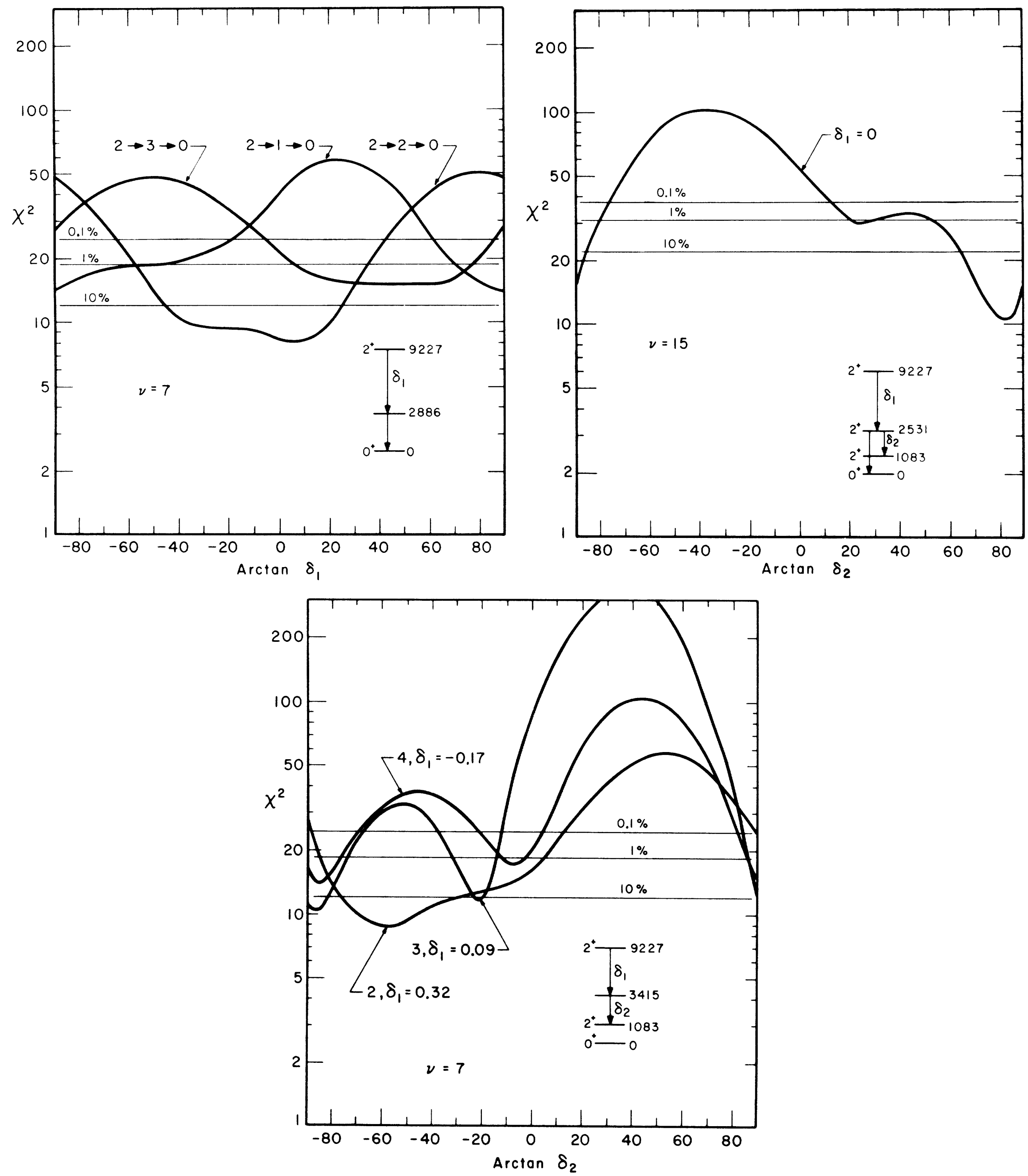

FIG. 14. A simultaneous χ^2 fit for primary and secondary γ rays at the $E_\alpha = 4.52$ MeV resonance. The γ rays fitted are those shown in each decay-scheme diagram.

and Vignon[5] on the ^{46}Ti(p, t)^{44}Ti reaction shows a state excited at 2.50 MeV. This indicates that at least one of the states, either the 2454- or 2531-keV state, has positive parity and even spin. A state(s) at 2.50 MeV has also been seen in the ^{40}Ca(^{16}O, ^{12}C)^{44}Ti reaction.[3]

2886 keV. The angular-distribution analysis favors a spin of 2 for this state. A preliminary lifetime for this state is 0.5 psec indicating a positive parity for the state. A state at 2.95 MeV has been seen by Longequeue, Longequeue, and Vignon[5] which seems to confirm the 2^+ assignment. A state at 2.9 MeV has been seen in the ^{40}Ca(^{6}Li, d)-^{44}Ti and ^{40}Ca(^{7}Li, t)^{44}Ti reactions.[4]

3175 keV. This state decays predominantly to the 1083-keV level. No other decay modes have been detected. Longequeue, Longequeue, and Vignon[5] report a level at about 3.20 MeV which suggests that if this is the same state, it has even spin and parity.

3415 keV. The angular-distribution analysis favors spins 2 or 3 for this level. No transition to the ground state has been observed. A state near 3.40 MeV is seen in the ^{46}Ti(p, t)^{44}Ti reaction,[5] in the ^{40}Ca(^{16}O, ^{12}C)^{44}Ti reaction[3] and in the ^{40}Ca(^{6}Li, d)^{44}Ti reaction,[4] but due to the low-energy resolution in these experiments compared with the expected level spacing, it is not clear if all of these represent the same state.

3645 keV. This state appears to decay almost entirely to the state at 3175 keV, suggesting high spin, perhaps $J \geq 5$. The (p, t) work does not appear to excite a state at this energy.

3942 keV. Little is known about this level at present. The transfer reactions[3-5] also excite levels near 4.0 MeV.

The present indications of levels at 1083 and 1905 keV and the results of references[1-3,5] are in disagreement with the work of Gol'dberg *et al.*[4] which places the first excited state at 1.4 MeV.

The low-energy states of ^{44}Ti display more similarity to a vibrational than a rotational spectrum. There appears to be a two-phonon triplet at about twice the energy of the first excited state. Furthermore the transition from the second 2^+ state to the first is consistent with a pure $E2$ transition and as Table IV shows, the reduced transition strength for the crossover transition, $B(E2;\ 2_2^+ \rightarrow 0_1^+)$, is small compared to $B(E2;\ 2_2^+ \rightarrow 2_1^+)$. However, the table shows that the liquid-drop vibrational model is seriously amiss for the transition from the second 2^+ state to the second 0^+ state. Such a transition is identically zero in first order, whereas experimentally $B(E2;\ 2_2^+ \rightarrow 0_2^+)$ is four times greater than $B(E2;\ 2_2^+ \rightarrow 2_1^+)$. Such a feature could hardly be achieved by an anharmonic admixture in the vibrational states which would leave the liquid-drop model still approximately valid.

The absence of a ground-state rotational band in the lower fp shell has been explained by Bhatt and Parikh[26] as resulting from the fact that the $f_{7/2}$ spherical orbital is lower than the $p_{3/2}$ orbital, whereas the formation of a state of large deformation by the residual quadrupole-quadrupole force requires more of the p than the f orbital. This contrasts with the case of ^{20}Ne where the order of the spherical single-particle orbitals favors an intrinsic state of large deformation.

A shell-model calculation restricted to four particles in the fp shell has been made of $T=0$ and $T=1$ states for $A=44$ using the program of French *et al.*[27] The calculated levels for the mass-44 nuclei are shown in Ref. 2. It is found that the $T=0$ states display approximately correctly the energy

TABLE III. Radiative yields $\omega\gamma$ for α-capture resonances. The partial width Γ_γ is calculated using the preferred J^π for the resonance and assuming $\Gamma_\alpha \approx \Gamma$. Both $\omega\gamma$ and Γ_γ are lower limits.

Resonant α energy (MeV)	J^π	$\omega\gamma$ (eV)	Γ_γ (eV)
4.22	1^-, ?, ?	0.5	
4.257	2^+	0.3	0.06
4.263	4^+	0.6	0.07
4.520	2^+	6	1.2

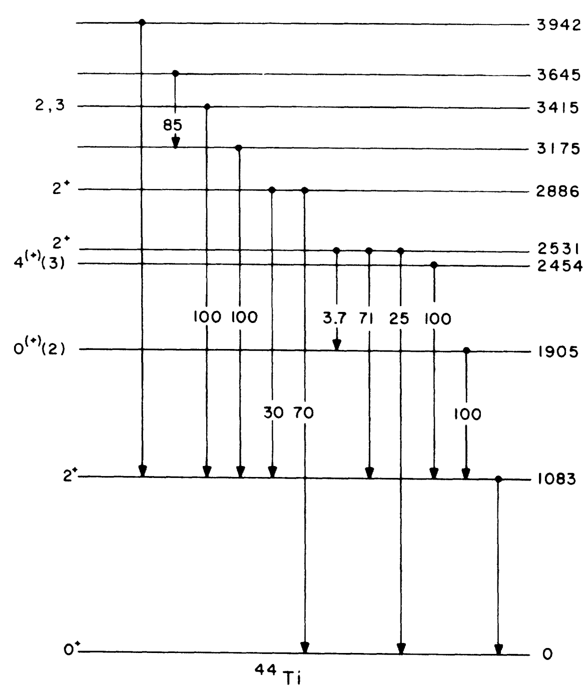

FIG. 15. Bound levels of ^{44}Ti showing γ-ray branching ratios and preferred spins.

TABLE IV. Decay of the 2531-keV (2_2^+) state. The last column gives reduced transition strengths using a mean lifetime of 1.5 psec obtained in a preliminary measurement.

E_γ (keV)	Final state Energy (keV)	J_i^π	Branching ratio	$B(E2;\,2_2^+\to J_f^\pi)$ / $B(E2;\,2_2^+\to 0_1^+)$	$E2$ transition strength (W.u.)
626	1905	0_2^+	3.7	160	23
1448	1083	2_1^+	71	46 [a]	6.5 [a]
2531	0	0_1^+	25	1	0.14

[a] A δ_2 of 7.5 has been used.

separation between the ground state, the 2^+ state and the 4^+ state in ^{44}Ti. Already at 1.9 MeV however, there are extra levels which are not explained by the calculations and presumably have different configurations than pure *fp*.

The similarity in spacing and position of the second 0^+ and 2^+ states in the three nuclei ^{42}Ca, ^{44}Ca, and ^{44}Ti may suggest a similar origin for these states. A comparison of absolute transition strengths is not possible until further lifetime measurements are made in ^{44}Ca and ^{44}Ti, but on the basis of present information, the decay of the 2_2^+ state appears to be similar in the three nuclei. The ground-state transition $2_2^+\to 0_1^+$ is certainly weak compared with the $2_2^+\to 2_1^+$ transition in all three nuclei. There is an interesting difference, however, in the $E2/M1$ mixing ratio for this transition, which is at least partly a consequence of the self-conjugate nature of ^{44}Ti: In ^{44}Ti we find $\delta = 7.5^{+8.5}_{-2.5}$, whereas in ^{42}Ca and ^{44}Ca the values[28] are $\delta = 0.09 \pm 0.08$ and $\delta = 0.15^{+0.09}_{-0.04}$, respectively. It should perhaps be noted that the comparative transition[29] in ^{46}Ti has $|\delta| = 0.6$.

The second 0^+ and 2^+ states in ^{42}Ca have been quite well explained by Flowers and Skouras[11] as arising from the promotion of two protons from the *sd* into the *fp* shell, creating deformed intrinsic states. Flowers and Skouras have been able to reproduce the energy spectrum of ^{42}Ca up to about 3 MeV as well as producing reasonably good agreement with the experimental $B(E2)$ values.[28] It may well be then that 6p-2h configurations are important in ^{44}Ca and ^{44}Ti. It is interesting that although the $2_2^+\to 0_2^+$ transition has not yet been observed in ^{42}Ca, Flowers and Skouras[11] calculate the ratio of $B(E2;\,2_2{}^+\to 0_2{}^+)$ to $B(E2;\,2_2{}^+\to 0_1{}^+)$ to be about 60 (method B for an effective charge of 1.0). In ^{44}Ti we observe this ratio to be about 160.

Core excitations in which a "quartet," an α-particle-like structure, is elevated from the *sd* shell to the *fp* shell, may also be important in ^{44}Ti. Arima, Gillet, and Ginocchio[30] have recently calculated the positions of the quartet-excited 0^+ states in even-even self-conjugate nuclei. Using the presently obtained mass of ^{44}Ti, the 0_2^+ state should come at 2.0 MeV, very close to the experimental value of 1905 keV. A rotational-like band would be expected to be based on this 0^+ state, and it is tempting to associate the 2531-keV state with the 2^+ member of such a band in view of the strongly enhanced transition connecting it to the 1905-keV (0_2^+) state.

The spectrum of ^{44}Sc below 1 MeV also has very many more levels than can be explained by a shell-model calculation[2] of particles in the *fp* shell. Furthermore the presently measured mass of ^{44}Ti requires the log*ft* value for the electron-capture branch to the 146-keV state of ^{44}Sc to be 6.5. Thus, this state is not necessarily a 1^+ state as required by the earlier estimate of log*ft*. The γ-decay properties of the 146-keV state of ^{44}Sc are also curious in that this state is observed to decay almost solely to the first excited state at 68 keV, with only a 0.1% branch to the 2^+ ground state.

In conclusion, ^{44}Ti does not appear to display a rotational band built on the ground state as does ^{20}Ne, but rather has a resemblance to a vibrational-type spectrum. The decay modes of the second 2^+ state at 2531 keV suggest another possible interpretation, that the 0^+ state at 1905 keV is from a predominantly deformed intrinsic state and with the 2531-keV (2^+) state forms the beginning of a rotational band. The shell model restricted to the *fp* shell can account for only a few of the low-lying excited states, in particular the 1083-keV (2^+) and 2454-keV (4^+) states. Finally, the revised mass of ^{44}Ti has made uncertain some of the properties of low-lying levels in ^{44}Sc.

ACKNOWLEDGMENTS

We should like especially to thank Professor A. E. Litherland, who suggested this work, for his interest and helpful advice. We are deeply grateful to Dr. S. S. M. Wong for the use of his shell-model program, to D. W. O. Rogers and P. B. Dworkin for making available their angular-distribution programs, and to J. D. Stinson for making the targets. Useful discussions with Dr. J. Law and Dr. S. T. Lam are gratefully acknowledged.

One of us (J.J.S.) acknowledges the partial financial support of the National Research Council and the Research Advisory Board of the University of Guelph.

[1]J. Vernotte, M. Langevin, and F. Takeutchi, Compt. Rend. B265, 859 (1967); J. Vernotte, M. Langevin, and S. Fortier, *ibid*. B266, 972 (1968).

[2]J. J. Simpson, W. R. Dixon, and R. S. Storey, Phys. Letters 30B, 478 (1969).

[3]A. M. Friedman, H. T. Fortune, G. C. Morrison, and R. H. Siemssen, in *Nuclear Reactions Induced by Heavy Ions* (North-Holland Publishing Company, Amsterdam, The Netherlands, 1970), p. 171.

[4]V. Z. Gol'dberg, V. V. Davydov, A. A. Ogloblin, S. B. Sakuta, and V. I. Chuev, Izv. Akad. Nauk SSSR Ser. Fiz. 33, 586 (1969) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 33, 542 (1969)].

[5]N. Longequeue, J. P. Longequeue, and B. Vignon, Phys. Letters 32B, 596 (1970).

[6]A. E. Litherland, J. A. Kuehner, H. E. Gove, M. A. Clark, and E. Almqvist, Phys. Rev. Letters 7, 98 (1961).

[7]J. D. McCullen, B. F. Bayman, and L. Zamick, Phys. Rev. 134, B515 (1964); Princeton University Technical Report No. NYO-9891, 1964 (unpublished).

[8]K. H. Bhatt and J. B. McGrory, in *Contributions, International Conference on Properties of Nuclear States, Montrêal, Canada, 1969* (Les Presses de l'Université de Montrêal, Montrêal, Canada, 1969), p. 223.

[9]S. B. Khadkikar and B. Banerjee, Nucl. Phys. A129, 220 (1969).

[10]J. A. Shah and M. Danos, Phys. Rev. 183, 899 (1969).

[11]B. H. Flowers and L. D. Skouras, Nucl. Phys. A116, 529 (1968); A136, 353 (1969).

[12]I. P. Johnstone, Nucl. Phys. A110, 429 (1968); Can. J. Phys. 48, 1208 (1970).

[13]H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).

[14]W. Davies, N. Anyas-Weiss, and S. T. Lam, private communication.

[15]Attributed to the ^{32}S(^{14}N, $pn\gamma$)^{44}Ti reaction [W. Davies, J. J. Simpson, S. T. Lam, and A. E. Litherland, private communication].

[16]J. D. Larson and R. H. Spear, Nucl. Phys. 56, 497 (1964).

[17]The energy value of 9168 ± 1 keV is calculated from the known masses of ^{13}C and ^{14}N, and has been corrected by 3.2 keV for nuclear recoil from the γ emission. This energy corresponds to observation at 90° to the incident proton beam. This γ-ray standard is listed incorrectly by J. B. Marion and F. C. Young, *Nuclear Reaction Analysis, Graphs and Tables* (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968), p.144.

[18]J. H. Aitken, A. E. Litherland, W. R. Dixon, and R. S. Storey, Phys. Letters 30B, 473 (1969).

[19]J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 1 (1965).

[20]J. Wing, M. A. Wahlgren, C. M. Stevens, and K. A. Orlandini, J. Inorg. Nucl. Chem. 27, 487 (1965).

[21]P. E. Moreland and D. Heymann, J. Inorg. Nucl. Chem. 27, 493 (1965).

[22]R. A. Ristinen and A. W. Sunyar, Phys. Rev. 153, 1209 (1967).

[23]F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).

[24]J. G. Pronko, C. Rolfs, and H. J. Maier, Phys. Rev. 186, 1174 (1969).

[25]K. A. Snover, Ph.D. thesis, Stanford University, 1969 (unpublished).

[26]K. H. Bhatt and J. C. Parikh, Phys. Letters 24B, 613 (1967).

[27]J. B. French, E. C. Halbert, J. B. McGrory, and S. S. M. Wong, in *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum Press, Inc., New York, 1969), Vol. 3.

[28]N. Lawley, N. Dawson, G. D. Jones, I. G. Main, P. J. Mulhern, R. D. Symes, and M. F. Thomas, Nucl. Phys. A159, 385 (1970); A149, 95 (1970).

[29]J. N. Mo, P. J. Twin, and J. C. Willmott, Nucl. Phys. 89, 686 (1966).

[30]A. Arima, V. Gillet, and J. Ginocchio, Phys. Rev. Letters 25, 1043 (1970).