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Low-Intensity Branches in the Ti^{45} Decay*

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The decay of Ti^{45} ($\sim$100% electron capture and β^+ to the Sc^{45} ground state) has been reinvestigated with the Argonne toroidal-field beta spectrometers and with lithium-drifted germanium gamma detectors. New low-intensity branches to levels in Sc^{45} at 725.1±0.8 [149±35], 1238±1.5 [16±6], and 1411.3±0.9 [112±30] keV have been found. *Numbers in brackets are the intensities for 10^5 decays.* The 12.4-keV level in Sc^{45} previously seen in the β decay of Ca^{45} is also populated in the Ti^{45} decay; its energy is $12.40_{-0.01}^{+.02}$ keV and its intensity is [12±3]. The intensity of the first-forbidden unique decay ($\frac{7}{2}-$ to $\frac{3}{2}+$) to the 12.4-keV state is not known because of the unknown amount of gamma branching to the 12.4-keV state from higher levels in Sc^{45}, but from the observed 12.4-keV intensity, $\log f_1t > 8.1$. No evidence was found for beta decay to the 376-keV level [<60] or to the 540-keV level [<9]. Log*ft* values for beta decays to the three states at 725, 1238, and 1411 keV are 6.3, 6.8 and 5.6, respectively. In general, to the other states, log*ft* values are greater than 7, with the exception of the 1660-keV state for which our gamma intensity limit yields $\log ft > 5.7$. The available data are consistent with spin and parity assignments of ($\frac{3}{2}^+$) for the 12.4-keV state and ($\frac{3}{2}^-$) for the 376-keV state. The end point of the positron spectrum, 1044±5 keV, indicates a total decay energy, $Ti^{45} \rightarrow Sc^{45}$, of 2066±5 keV, 20 to 40 keV higher than earlier measurements and in better agreement with reaction data, 2062±4 keV. Our half-life measurement of 3.08±0.01 h agrees with previous measurements.

INTRODUCTION

Both Ca^{45} and Ti^{45} decay predominantly by beta emission to the ground state of Sc^{45}. Recently a low-lying state with $l=2$ was suggested in (d,He^3) work by Yntema and Satchler,[1] and was confirmed in higher resolution (p,α) experiments of Yntema and Erskine.[2] Holland, Lynch, and Nystén[3] observed the gamma ray of 13±1 keV following (p,p') excitation, the measured lifetime of the state being 0.44 sec. These observations, along with similar data[1,3] in other odd mass scandium isotopes, suggested that this state is the $d_{3/2}$ single-proton "hole" state.

Beta transitions to this state from both Ca^{45} and Ti^{45} are first forbidden unique $(\frac{7}{2}^-) \rightarrow (\frac{3}{2}^+)$ for which $\log f_1t$ values normally[4] are 8.5. We have reported the intensity of this beta transition in the Ca^{45} case[5] where the intensity of the conversion electrons from the 12.4-keV state provides a direct measure of the beta decay to the 12.4-keV state (conversion coefficient expected to be $\sim$260). The observed value of $\log f_1t = 9.28_{-0.18}^{+0.06}$ indicated a relatively slow beta transition to the 12.4-keV state from Ca^{45}.

Cohen and Lawson[6] have discussed this retardation, pointing out that the shell model configurations $(\pi d_{3/2})^4$, $(\nu d_{3/2})^4$, $(\nu f_{7/2})^5$ for Ca^{45} and $(\pi d_{3/2})^3$, $(\nu d_{3/2})^4$, $(\pi f_{7/2})^2$, $(\nu f_{7/2})^4$ for the 12.4-keV state admit no beta transition with only single-particle transitions. They use the measured f_1t value to obtain the amount of configuration $(\pi d_{3/2})^2$, $(\nu d_{3/2})^4$, $(\pi f_{7/2})^2$, $(\nu f_{7/2})^5$ mixed into the ground state of Ca^{45} by way of which the beta decay may proceed by single particle transition.

For the beta decay from Ti^{45} to the 12.4-keV state the shell model configuration $(\pi d_{3/2})^4$, $(\nu d_{3/2})^4$, $(\pi f_{7/2})^2$ $(\nu f_{7/2})^3$ suggests no retardation of the beta decay, and we undertook to measure the intensity of this transition in the same way; namely, to measure the intensity of the 12.4-keV conversion electrons relative to the total beta spectrum. However, the larger decay energy in the case of Ti^{45} complicates the picture. For Ca^{45} with beta decay energy of 258 keV, the only known states in Sc^{45} which can be populated are the 12.4-keV state and the ground state. In contrast Ti^{45} has 2.066 MeV available in decay energy and can populate several of the excited states in Sc^{45} (see Fig. 1). Thus, in order to learn about the intensity of the weak beta decay to the 12.4-keV state, detailed knowledge must be obtained of the population in beta decay and of gamma ray branching of the higher excited states in Sc^{45} to the 12.4-keV first excited state.

We can summarize the situation as it now stands by noting that the Ti^{45} decay to excited states in Sc^{45} is intense enough and the gamma branching to the 12.4-keV state uncertain enough to render only a lower limit on the f_1t value for this transition. The main purpose of the present work is then to present the evidence for the low intensity features of the decay of Ti^{45}, none of which have been reported before. (See note added to Table I.)

It has been known for many years that the main decay of Ti^{45} proceeds to the ground state.[7,8] Weak gammas

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* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

[1] J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964).

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[3] R. E. Holland, F. J. Lynch, and *K-E.* Nystén, Phys. Rev. Letters **13**, 241 (1964).

[4] P. Lipnik and J. W. Sunier, Nucl. Phys. **56**, 241 (1964), see also Ref. 28.

[5] M. S. Freedman, F. T. Porter, and F. Wagner, Jr., Phys. Rev. **140**, B563 (1965).

[6] S. Cohen and R. D. Lawson, Phys. Letters **17**, 299, (1965).

[7] H. E. Kubitschek, Phys. Rev. **79**, 23 (1951); and H. E. Kubitschek, A. Longacre, and M. Goldhaber, Phys. Rev. **77**, 724A (1950).

[8] M. Ter-Pogossian, C. S. Cook, F. T. Porter, K. H. Morganstern, and J. Hudis, Phys. Rev. **80**, 360 (1950).

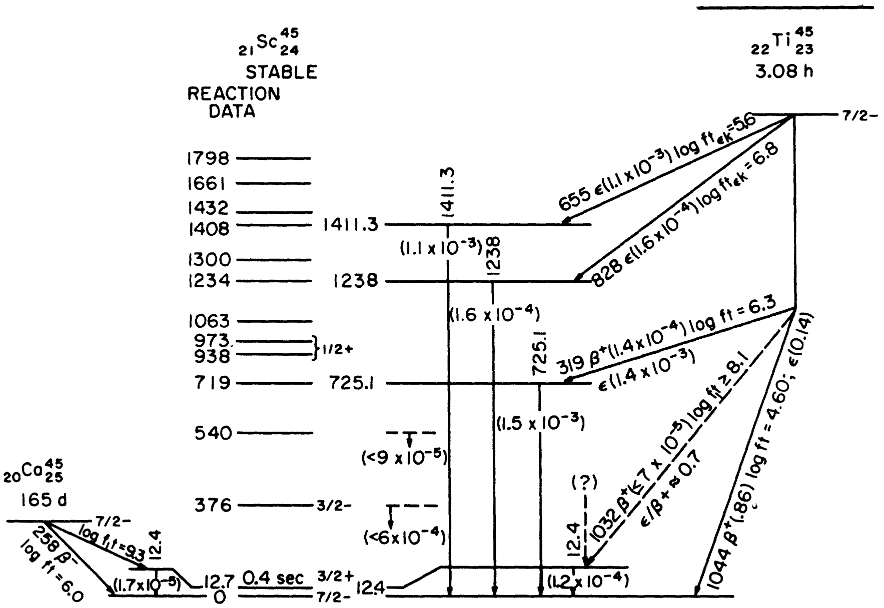

FIG. 1. Decay scheme of Ti^{45}. Energy levels and decay energies are in keV. The numbers in parentheses are the intensities per decay. The energies of the levels under "reaction data" are taken from Refs. 2, 23, 24, and 25. No certain gamma branching is known to the 12.4-keV levels in Ti^{45} decay, but the upper limits on possible gamma branches to this level make specification of the beta decay intensity to the 12.4 level uncertain. All capture (ε) to positron ratios are theoretical. See Table I for gamma de-excitation limits not indicated here for some of the higher energy states.

of 0.45 MeV [8] and 0.8 MeV [7] were reported in the early work. Ishii and Takahashi[9] reported evidence for 376-keV gamma at ~0.3% per decay and possibly a 541-keV gamma at $\lesssim 0.1\%$ from coincidence studies with annihilation radiation. Ramaswamy, Skeel, and Jastram,[10] also using coincidences with annihilation radiation, reported a gamma of 270 keV with an intensity of ~2%. Later Ramaswamy[11] showed that this 270-keV gamma was the result of scattering of the 511-keV quanta and set a limit of <0.1% per decay for any gamma ray up to 600 keV. This last statement is consistent with our results.

TABLE I.[a] Intensity of transitions in Sc^{45} following beta decay of Ti^{45}, and upper limits for the intensity of transitions from other levels known from nuclear reaction studies.

Energy (keV)[b]	γ Intensity 10^{-5}/decay	e^- Intensity 10^{-5}/decay	*K* conversion coefficient
$12.4_{-0.01}^{+0.02}$	(0.05)[c]	12±3	
725.1±0.8	149±35	0.030 ±0.004	$(2.0\pm0.6)\times10^{-4}$
1411.3±0.9	112±30	0.0053±0.0007	$(4.7\pm1.4)\times10^{-5}$
1238 ±1.5	16±6		
725 −12.4	<5	<0.004	
1411 −12.4	<4	<0.001	
375.5±2.0[d]	<60[e]	<0.02	
540 ±3	<9	<0.008	
938 ±4	<8		
973 ±4	<5		
1064 ±4	<6		
1300 ±5	<6		
1432 ±5	<7		
1661 +5	<40		

[a] *Note added in proof.* The work of D. Gföller and A. Flammersfeld [Z. Physik, **187**, 490 (1965)] has come to our attention; gamma rays were observed using NaI and Ge(Li) detectors. No electron spectroscopy was done. They report gamma rays of 718(400±40), 1238(50±20), 1408-(270±30), and 1665(80±10) keV. Numbers in parentheses are intensities in units 10^{-5}/decay. Our results are in agreement qualitatively with these, but we find intensities (see Table I above) which are about a factor of 2.5 smaller.

[b] Where uncertainties are more than 2 keV the energies are taken from Refs. 2, 23, 24, and 25.

[c] Assume *K* conversion coefficient ~260 from extrapolation in M. E. Rose *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

[d] Energy from Ref. 24.

[e] Limit on 364-keV gamma since this state de-excites ~90% to 12.4-keV level.

We have used the Argonne toroidal-field beta spectrometers and lithium-drifted germanium detectors to measure the energy and intensities of the very low intensity transitions in Sc^{45} following the beta decay of Ti^{45}.

SOURCE PREPARATION: HALF-LIFE

Ti^{45} was produced by (*d*,2*n*) on scandium metal foil in the Argonne 60-inch cyclotron. From solution in concentrated HCl, the titanium was extracted (no carrier added) into 20% *n*-heptanol in petroleum ether followed by four scrubbings with equal volumes of concentrated HCl. Each such extraction has been shown to reduce the Sc/Ti ratio by ~100 down to tracer levels.[12] The Ti fraction was passed through a Dowex-1 anion exchange column which retains possible contaminants (e.g., Zr, Ta) which partially extract with Ti. No Sc^{46} was observed in the final Ti fraction; Zr^{89} with initial decay rate 10^{-4} to 10^{-3} relative to Ti^{45} appeared in the samples but offered no difficulty because of its much longer half-life.

The decay of a portion of the Ti fraction from one of the two irradiations was followed with a gas proportional

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[9] C. Ishii and K. Takahashi, J. Phys. Soc. Japan **15**, 736 (1960).

[10] M. K. Ramaswamy, W. L. Skeel, and P. S. Jastram, Bull. Am. Phys. Soc. **5**, 423 (1960).

[11] M. K. Ramaswamy, Current Sci. (India) **32**, 13 (1963).

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

counter with continuous automatic printout for ten half-lives before deviation from exponential decay could be detected. Our value for the half-life of Ti^{45} is 184.8±0.5 min (3.08±0.01 h). A weighted average of values given in Nuclear Data Sheets[13] is 3.09 h with a comparable error.

The sources for the beta spectrometer were of two types. For the low energy conversion electrons of the 12.4-keV transition, the Argonne isotope separator was used in order to keep source thickness from reagent solids to a minimum. The ion beam was decelerated to ~600 V to prevent penetration into the aluminum backing and was focused to ~3 mm diameter. For the high-energy transition, whose conversion lines are 10^{-3} as intense as the 12.4-keV K line, we could not afford the intensity loss of the isotope separator and used a "liquid drop" source deposited directly on a mica backing (gold coated). The "liquid drop" source was very thick, several mg/cm². This source was also used for the Ge(Li) detector survey.

BETA SPECTROMETRY

For these very weak conversion lines, the Argonne toroidal field beta spectrometers[14] were operated in tandem. In this mode of operation, the focal plane of one unit is the source plane for the second unit. The advantages in the case of strong positron sources are a reduction in the electron background (from annihilation in the source region) and better resolution for a given source size which gives a better peak to continuum ratio. For sources 3 mm diameter and detector aperture of 5 mm the resolution was 0.2% with a transmission of 11% for the Cs^{137} calibration source.

Figure 2 shows the K conversion electrons from the 12.4-keV transition. The continuum is Compton electrons generated in the source region and counter background which has not been subtracted. The detector was a 2-mm-thick × 18-mm-diam anthracene disk on a selected 9536 S (EMI) photomultiplier, both at −30°C. The efficiency for these ~8 keV electrons was ~90%.

The width of the line (0.3%) is larger than expected for a source of 3 mm diameter. (The size of the isotope separator deposit was measured by autoradiograph.) At this atomic number, electron energy, and resolution, the natural width[15] of the K shell could be expected to broaden the line by at most 10% and in a symmetrical way. The asymmetry suggests source thickness. Ninety percent of the 600-V ions penetrate[16] less than 2 μg/cm². The "background ion" current at mass 45 in the separator just before the run was $\sim 5\times 10^{-9}$ A, and this did not change appreciably when the Ti fraction was introduced into the separator. Collection time of 1 h yields on a 3-mm-diam spot only about 10^{-1} μg/cm². Thus if the broadening is the result of source thickness we can account for only ~2 μg/cm².

At this resolution the first inelastically scattered satellite line,[17] which lies ~20 eV below the unscattered line for a number of metals, would have to have an intensity of at least $\frac{1}{2}$ the unscattered peak to account for our results. The infinitely thick sources of Sokolowski[17] showed ratios of this order. Although 2 μg/cm² is much less than the range in aluminum, the specific energy loss for 8-keV electrons is ~20–25 eV/(μg/cm²) which may indicate that 2 μg/cm² could produce the broadening observed.

The electron energy $7.89_{-0.010}^{+0.020}$ keV and K binding energy of 4.493 keV yields $12.40_{-0.010}^{+0.02}$ keV. This can be compared to our value for the same transition reported[5] in the decay of Ca^{45}, $12.47_{-0.03}^{+0.14}$ keV. The errors quoted here reflect no specific statistical criterion but rather reflect the experimenters' feeling about systematic uncertainties such as source thickness. We feel that our present measurement has considerably more weight than the first and quote the transition energy from the present experiments.

As indicated above, the 12.4-keV transition is believed to be one of the group of retarded $M2$ transitions from the $d_{3/2}$ proton hole states observed in the odd-mass scandium isotopes. We know of no multipolarity (or possible $M2/E3$ mixing) measurements for any of these transitions to support the assignment of $(\frac{3}{2}+)$ made from nuclear reaction and lifetime studies. Therefore a measurement of the K/L and L subshell conversion coefficient ratios would be of interest; although, the uncertain extrapolation of presently available theoretical conversion coefficients for this case might cloud the analysis.

A search was made for the L conversion lines of the 12.4-keV transition. A bump of about $\frac{1}{5}$ the intensity of the K line was found at an energy ~20 eV lower than would be calculated for L_1 even from the recently revised binding energy (0.483 keV).[18] No indication of $L_{2,3}$ was found. Extrapolation of Rose's tables to $Z=21$ and 12.4 keV yields K/L values for $M2$ transitions ~12 and $L_1/(L_2+L_3)\sim 6$. Because our results are sufficiently vague, no conclusion from K/L or L subshell ratios can be made about the multipolarity, and this interesting question and also the question of the L_I binding energy must await still stronger and sufficiently thin sources.

The positron spectrum from the isotope separator

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[13] *Nuclear Data Sheets*, Compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 60-2-28.

[14] M. S. Freedman, F. Wagner, Jr., F. T. Porter, J. Terandy, and P. P. Day, Nucl. Instr. Methods **8**, 255 (1960); Bull. Am. Phys. Soc. **8**, 526 (1963); more extensive reports to be published.

[15] G. T. Ewan and R. L. Grahm, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Ch. XV, Sec. IIIB.

[16] I. Bergstrom, F. Brown, J. A. Davies, J. S. Geiger, R. L. Graham, and R. Kelley, Nucl. Instr. Methods **21**, 249 (1963).

[17] E. Sokolowski, Arkiv. Fysik **15**, 1 (1959).

[18] A. Fahlman, D. Hamrin, R. Nordberg, C. Nordling, and K. Siegbahn, Phys. Rev. Letters **14**, 127 (1965).

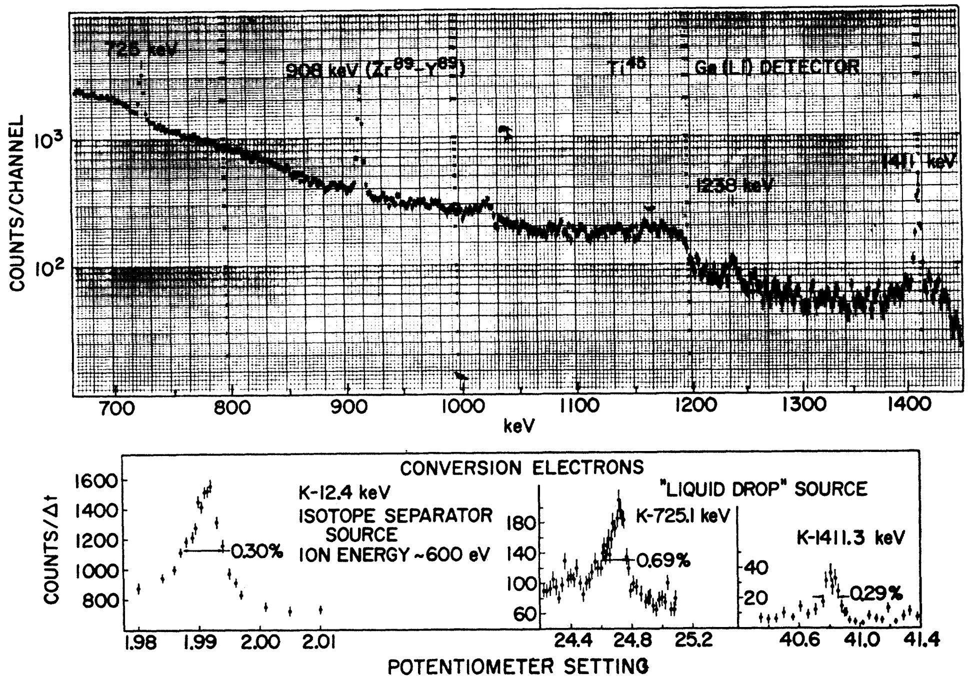

FIG. 2. Gamma rays and conversion electrons following the decay of Ti^{45}. The conversion line data have not been corrected for differences in source strength or for decay. Potentiometer setting is proportional to electron momentum.

source was obtained by reversing the current in the spectrometers. The end point, obtained from a Kurie plot of data between 860–1010 keV, was $E_0 = 1044 \pm 5$ keV. Previous values[7,8] were lower by 20–40 keV. Our present end point gives 2066±5 keV for the decay energy $Ti^{45} \rightarrow Sc^{45}$ in better agreement with (p,n) threshold measurement[19] yielding $Q(\beta+) = 2062 \pm 4$ (using neutron-proton mass difference = 782 keV).

Figure 2 shows the K conversion electrons from the 725- and 1411-keV transitions in Sc^{45}. The thick source results in strongly energy-dependent line width. High-energy edge extrapolations were used for fiducial points in obtaining the line energies. Branching to the 12.4-keV state from these levels would be indicated by peaks at 24.44 and 40.52 potentiometer units in Fig. 2. We did not look for the conversion of the 1238-keV transition, ~6 times weaker than the 1411-keV transition. Electron line intensities are obtained by comparing the line areas with the $\beta+$ spectrum area (on momentum plots) which yields conversion electrons per $\beta+$. The theoretical K-capture/positron ratios of Zweifel[10] and small corrections[21] for electron capture from L and M shells give conversion electrons per decay. The intensity information is collected in Table I.

GAMMA SPECTROSCOPY

Lithium-drifted germanium detectors,[22] one 22 mm another 14 mm in diameter, drifted to a depth of ~6 mm, were used to view samples of Ti^{45}. The 725- and 1411-keV gammas were obvious in the early surveys; the 1238-keV full-energy peak, while less obvious, appears to have the correct half-life, has a Compton edge at the correct energy, and has an energy which agrees quite well with the energy of a level in Sc^{45} known from reaction studies. Figure 2 shows a portion of the spectrum taken on the 14-mm diam detector with the same sample which was used in the beta spectrometer to observe the high-energy conversion lines. The positrons were stopped by $\frac{3}{16}$-in. plastic (Lucite) absorbers on each side of the source disk. The data were collected over a period of 12 h in the following way. The sample was strong enough so that at a distance of 20 cm from the detector the over-all rate was not taxing the electronics as evidenced by no distortion of the peaks. After 4 h the distance was decreased to just compensate for the decay of the sample. Three of these 4-h runs were examined individually to verify that the peaks of interest were following the Ti^{45} half-life. The data of Fig. 2 are then just the sum of those three runs.

This particular sample had the largest amount of Zr^{89} which was observed in any of the samples. Since the 908-keV gamma ray follows essentially all the decays of Zr^{89}, (30% $\beta+$, 70% electron capture) one

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[19] R. M. Brugger, T. W. Bonner, and J. B. Marion, Phys. Rev. **100**, 84 (1955).

[20] P. F. Zweifel, Phys. Rev. **107**, 329 (1957).

[21] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

[22] Produced at Argonne National Laboratory under the direction of Harry Mann.

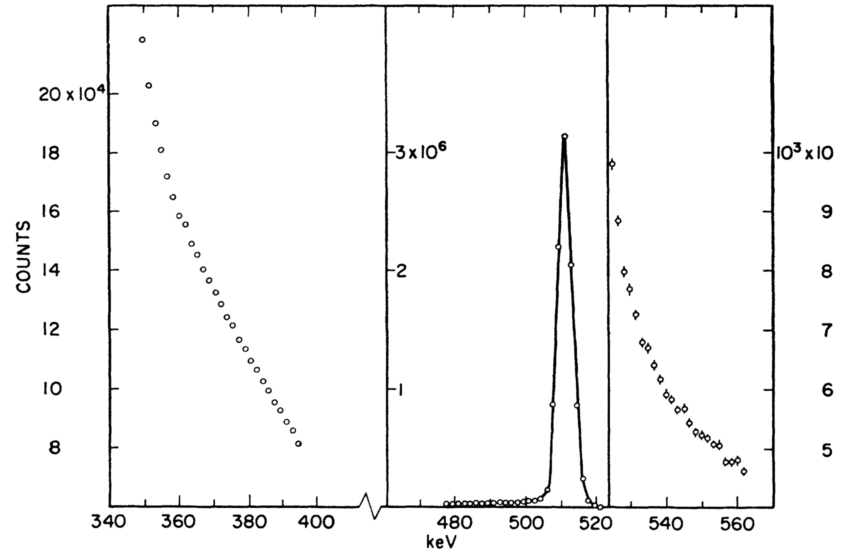

FIG. 3. Portions of the germanium detector spectrum showing where 364-keV (from the 376-keV level), 540-, and (540−12.5)-keV gammas might be expected. These are continuations of the spectrum exhibited on the top part of Fig. 2. Note the changes in ordinate scale in different sections of the drawings. The 511-keV annihilation radiation is the only obvious feature of the whole gamma spectrum of Ti^{45}.

calculates that only 10^{-3} of the 511-keV peak results from Zr^{89} positrons over the 12-h period, quite negligible for our purposes. The 908-keV peak clearly had a longer life time than Ti^{45} (Zr^{89}—79 h). The conversion electrons were examined carefully after the Ti^{45} had decayed. The *K-L* energy difference proved the transition takes place in yttrium; our energy 908.4±0.4 keV for the transition is probably the best determination available and is $\sim\frac{1}{2}\%$ lower than the accepted value.[23]

The energy span in the germanium detector runs was 250 to 1450 keV. The relative efficiency of the full energy peak as a function of energy was obtained by comparing the response with that of a 3×3-in. NaI detector. The sources used were Hg^{230}, Na^{22}, Cs^{137}, Sc^{46} and Co^{60}.

The areas under the peaks on the Ti^{45} germanium data are compared to the 511-keV peak area and, after correcting for relative efficiency, and capture to positron ratio in Ti^{45} decay, result in gamma abundances per decay (see Table I). A measure of the over-all uncertainties in the intensities may be gained by noting that the internal conversion coefficients (ICC) obtained from our procedures for the 1411- and 725-keV transitions probably should fall somewhere between $M1$ and $E2$. For the 725-keV transition the measured K ICC is about midway between $M1$ and $E2$ while the 1411-keV K ICC falls above both $M1$ and $E2$ values (they are almost the same at this energy) by about 25%. We conclude that 25% is the order of the uncertainty in the intensities of these weak transitions.

Since there are a number of well-defined levels in Sc^{45} known from nuclear reaction data, it is of interest to set limits on the intensity of gamma transitions from these levels because these in turn lead to *ft* value limits which may aid in making spin and parity assignments for the levels in Sc^{45}. This has not been done in an exhaustive way, but we have given the limits for the transition to the ground and/or the 12.5-keV state. The sensitivity of these limits depends on the gamma energy and in a rough way any gamma of comparable energy not specifically noted will have about the same limit. Figure 3 shows the spectrum in the regions near 376 and 541 keV. Recent work by Blaugrund, Holland, and Lynch[24] indicates that the 376-keV level de-excites to the 12.4-keV level with a probability of 92% with only 8% to the ground state; thus, the more obvious signature for the population of the 376-keV state in the beta decay is the 364-keV gamma ray. It is clear in the case of the 725- and 1411-keV levels that these de-excite to the ground state since the transitions are too intense to cascade through the 12.4-keV transition. The same can be said for the 1238-keV transition but with less certainty.

Early surveys indicated not much chance to see anything beyond the 1411-keV full-energy peak hence the available 800 channels on the pulse-height analyzer were used over the range 250–1450 keV. With more counts on the final runs, however, there developed the suggestion that the 1411-keV full-energy peak is superimposed on the Compton distribution of still another gamma ray, whose energy is approximately 1660 keV. From the magnitude of the Compton rise and from a limit on the 2-annihilation-quanta escape peak (at ~640 keV) we place an upper limit on the intensity of a 1660-keV transition.

When limits are given in Table I for the transitions to the ground state they include the possibility of

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[23] *Nuclear Data Sheets*, Compiled by K. Way *et al.* (Printing and Publishing Office, National Academy, of Sciences–National Research Council Washington 25, D. C.) NRC (60-3-78).

[24] A. E. Blaugrund, R. E. Holland, and F. Lynch, private communication. The 375.5±2-keV level has been excited with Cl ions on Sc targets. The gamma rays are observed with a Ge(Li) detector.

branching to the 12.4-keV state except in the case of the 725- and the 1411-keV transitions where the limits on branching to the 12.4-keV state are given separately. The level energies where the uncertainties are 3 keV or more are taken from the work of Windham *et al.*[25] (p,p'), from Bjerregaard *et al.*,[26] (p,p') and (d,α), from Buechner and Mazari[27] (p,p'), and from Yntema and Erskine,[1] (p,α).

THE QUESTION OF BETA DECAY TO THE 12.4-keV STATE

It is clear from Table I that the question of the intensity of the beta decay to the 12.4-keV state from Ti^{45} cannot be answered because of the unknown amount of γ branching the 12.4-keV state. The large upper limit on the (376−12.4)-keV γ from the germanium data is 5 times the intensity of the 12.4-keV transition. For this transition, the electron intensity limit results in a lower transition intensity if one assumes theoretical $M1$ conversion coefficient $(\sim 6\times 10^{-4})$, namely 30×10^{-5}/decay, still 2.5 times larger than the 12.4-keV intensity. Another approach is to assume a $(\frac{3}{2}^-)$ assignment for the 376-keV level (see summary below) in which case the beta transition is second-forbidden nonunique. Logft values of 11 to 12 are to be expected[28] for transitions of this type; this in turn implies a beta-transition intensity of $\sim 3\times 10^{-8}$/decay to the 376-keV state which is low enough to insure an insignificant contribution to the 12.4-keV state population. Even with this argument there remains enough *possible* feed from other weakly populated levels to account several times over for the intensity of the 12.4-keV transition.

If all the 12.4-keV intensity is attributed to beta decay, then $\log f_1t = 8.1$, a value which is quite probable for a first-forbidden unique transition. The interest in this beta transition lies in the theoretical speculation that indeed it may be retarded, even though the decay can proceed by a single-particle transition (see introduction). Lawson[29] calculates using a deformed core model[30] that the $\log f_1t$ value may be 9.0 (negative deformation) to 9.4 (positive deformation). Experimentally, this could be the case only if ~90% of the 12.4-keV level population is *via* transitions from the higher excited states in Sc^{45}. An experiment which could reveal gammas at an intensity level of 10^{-6}/decay would be required to illuminate this problem.

SUMMARY: LEVELS IN Sc^{45}

In this section we gather together the evidence from Ti^{45} beta decay and from nuclear reaction studies to comment on the levels in Sc^{45}. From the $\log ft = 4.60$ for the main beta-decay branch, the spin of Ti^{45} is $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ with the same parity as the ground state of Sc^{45} (measured spin $\frac{7}{2}$). Shell-model arguments strongly support $(\frac{7}{2}^-)$ for both Ti^{45} and Sc^{45} ground states. We shall assume in what follows that these are correct assignments.

12.4-keV level. Probably $(\frac{3}{2}^+)$, the single proton hole state (see Introduction). The Ti^{45} decay information is certainly consistent with this assignment (see previous section).

375.5-keV level. Probably $(\frac{3}{2}^-)$. Schwartz and Alford[31] observing the reaction $Ca^{44}(He^3,d)Sc^{45}$ note that the angular distribution of outgoing deuterons indicates $l=1$. The Coulomb excitation with chlorine ions and the observed[22] gamma branching of the 376 level with 8% to the ground state support $\frac{3}{2}^-$ rather than $\frac{1}{2}^-$. Alkhazov *et al.*[32] have also observed this state in Coulomb excitation (nitrogen ions) and have measured the angular distribution of the "376"-keV gamma ray. At the time of their analysis they did not know about the 12.4-keV state or the fact that the 376-keV level decays predominantly to the 12.4-keV state and thus their analysis was based on the assumption of $(\frac{7}{2}^-) \rightarrow (J) \rightarrow (\frac{7}{2}^-)$ as the spin sequence in the excitation and de-excitation. They concluded that $\frac{5}{2}^-$ or $\frac{7}{2}^-$ was possible for the 376 level. Using their measured value of the correlation coefficient our analysis shows that their result is consistent with the sequence $(\frac{7}{2}^-) \rightarrow (\frac{3}{2}^-) \rightarrow (\frac{3}{2}^+)$ if the transition from the 376-keV level to the 12.4-keV level is either almost pure $E1$ (0 to 5% M_2) or 70 to 90% M_2 (30 to 10% $E1$). In the analysis we have neglected the fact that the 364-keV peak has 8% mixture of 376-keV transition in it; the NaI detectors used[32] could not resolve these transitions. Finally the beta-decay $\log ft > 7.2$ is not impossible but is unlikely for the allowed transition required by $(\frac{5}{2}^-)$ or $(\frac{7}{2}^-)$ assignment; the $(\frac{3}{2}^-)$ is preferred.

The levels at 541, 938, 972, 1063, 1300, and 1433 keV. Little evidence for any choices for these states. The (d,He^3) experiment of Yntema and Satchler[1] showed $l=0$ for a broad peak at an excitation energy of 930±50 keV. Thus either the 938- or the 972-keV state may be $(\frac{1}{2}^+)$. The 541-keV state is *not* produced strongly[31] in $Ca^{44}(He^3,d)$ (<0.1 mb cross section). The beta decay information gives $\log ft$ values >7 probably ruling out $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ with *negative* parity for any of this group.

The levels at 725, 1238, and 1411 keV. Here the beta-decay information gives no unique answers but serves

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to limit the possibilities. All $\log ft$ values are in the allowed distribution.[28] The $\log ft=6.8$ for the decay to the 1238 state is high enough so that positive parity cannot be ruled out. Assignments of $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ with negative parity are the most probable for any of this group.

The levels above 1433 keV. While our limit is $<4\times10^{-4}$/decay for the 1660-keV transition, the low energy available for capture decay ($\sim$400 keV) still leaves the $\log ft$ value well into the allowed range; so that the present evidence cannot rule out $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ with negative parity for the states between 1433 and 2066 keV (the available decay energy).

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Polarization in the Elastic Scattering of Protons from Carbon and Nitrogen*

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The polarization of protons elastically scattered from nitrogen and carbon has been measured using double-scattering techniques. The polarization was determined for nitrogen at a scattering angle of $48°_{\mathrm{c.m.}}$ in the proton-energy interval 12.6 to 13.6 MeV. The polarization resulting from elastic proton scattering with nitrogen targets had a constant value of -0.60 ± 0.10 in the incident proton-energy interval 8.2 to 11.8 MeV. The polarization from carbon, however, varied markedly with energy at most scattering angles. [Example: $P(50°_{\mathrm{lab}}, 12.9\text{ MeV})=-0.8$, $P(50°, 13.2)=-0.4$, and $P(50°, 13.5)=-0.7$.] At numerous angles between 20° and 140°, polarization measurements from carbon covered the range of energies from 12.8 to 13.4 MeV. The angular distributions of polarization (and cross section) are in general quite sensitive to small changes in energy; the 12.95- and 13.25-MeV angular distributions even differ in shape significantly for $\theta>90°$. The energy-averaged (12.8- to 13.4-MeV) angular distribution for the polarization of protons scattered from carbon was compared with optical-model calculations.

I. INTRODUCTION

DESPITE the basically unsolved status of the problem of nuclear forces, various theories have been quite successful in the phenomenological description of nuclear reactions. Of these, perhaps the most striking quantitative success has been achieved with the optical model of nuclear interactions. The use of the optical model has been particularly successful in describing nucleon-nucleus elastic scattering,[1] especially from medium and heavy nuclei. It has also provided a helpful tool in understanding more complex nuclear reactions.[2] There are many aspects of the nucleon-nucleus interaction, however, which the optical model is not expected to describe. Some of these (such as the detailed energy dependence of various processes) are still largely unexplained or unexplored.

While the optical model has been systematically used to analyze scattering from nuclei throughout the periodic table, from the heaviest nuclei to deuterium, there exists some question regarding its meaningful applicability to light nuclei. Despite this, a considerable amount of experimental data for proton scattering from carbon has been subjected to optical-model analyses[3,4] with a fair degree of success.

In the present investigation, protons were elastically

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FIG. 2. Gamma rays and conversion electrons following the decay of Ti^{45}. The conversion line data have not been corrected for differences in source strength or for decay. Potentiometer setting is proportional to electron momentum.