The Disintegration Scheme of V^{48}†

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The disintegration scheme involved in the decay of 16-day V^{48} to Ti^{48} has been established by scintillation studies, and spins and parities have been assigned to the levels. The angular correlation of the well-known cascade gamma-ray pair with energies of 0.99 and 1.32 Mev has been measured. The corresponding levels are found to have spins 0–2–4. The positron spectrum has been measured with a magnetic beta-ray spectrometer and shows evidence for positron emission to a level in Ti^{48}, 22.2 Mev above the ground state. The positron group involved in the decay to the 2.31-Mev level of Ti^{48} is found to have an end point of 0.69 Mev.

INTRODUCTION

THE general features of the decay of 16-day V^{48} are well known. The disintegration by K-capture and positron emission to an excited state of Ti^{48} is followed by the emission of two cascade γ-rays of energies 1.32 and 0.99 Mev.[1–3] In addition, a third γ-ray of energy 2.22 Mev is present in 1–5 percent of the disintegrations.[4–6] The recent scintillation spectrometer work of Miller[5] and Ticho *et al.*[6] exclude the assignment of this γ-ray as the cross-over transition. Miller has found that the de-excitation of Ti^{48} following the β-decay of Sc^{48} is accompanied by the 1.32- and 0.99-Mev γ-rays only. The 2.22-Mev γ-ray, if present at all in the Sc^{48} decay, is estimated to have an intensity not more than 10^{-3} of the intensity of the 1.32-Mev γ-ray. In the V^{48} decay, on the other hand, the intensity of the 2.22-Mev radiation is found to be approximately 2 percent of the 1.32-Mev γ-ray. This view is supported by the careful energy measurements of Ticho *et al.* They find that the high energy γ-ray is about 90 kev less in energy than the sum of the 0.99- and 1.32-Mev energies. Moreover, as has been pointed out by Miller, no possible spin assignment of the excited levels can account for a cross-over having the lifetime ($<10^{-7}$ sec) and intensity of the 2.22-Mev γ-ray.

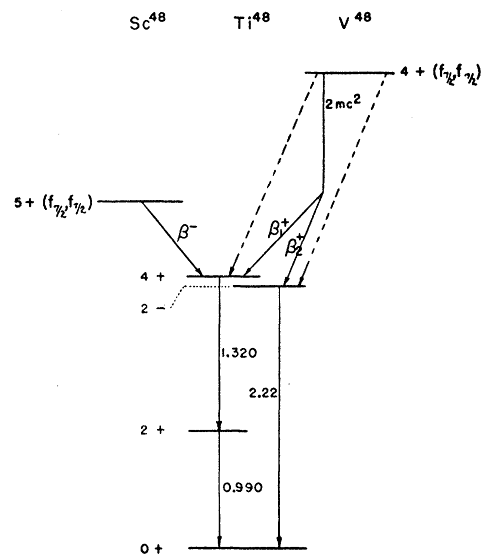

FIG. 1. Disintegration scheme of V^{48}.

In this paper, the results of further experiments which clarify the decay scheme of V^{48} are presented. The level system, shown in Fig. 1, has been verified by coincidence scintillation spectrometry. The directional correlation of the cascade γ-rays has been measured and fairly definite spin assignments made for the corresponding levels. Finally, the positron and negatron spectrum have been re-investigated with a magnetic beta-ray spectrometer, in order to obtain more information concerning the level at 2.22 Mev.

EQUIPMENT

The same apparatus is used for coincidence spectrometry measurements and angular correlation studies. For coincidence studies the source is placed midway between two $\frac{3}{4}$-in. cubical NaI(Tl) crystals $\frac{1}{2}$ in. off the line joining their centers. The crystals are mounted in air-tight Lucite holders filled with vacuum-dehydrated mineral oil. The crystal containers are mounted on selected RCA 5819 photomultiplier tubes. Light-tight aluminum housings enclose the photomultiplier tubes. The distance between the two counters can be varied from 2.5 in. to 8 in. No "sum" lines are observed under these conditions. Lead shielding between the counters minimizes crystal-to-crystal scattering.

The electronic circuits are for the most part conventional. The high voltage for the 5819's is furnished by an electronically stabilized supply, the output of which is continually monitored with a potentiometer. The voltage applied to the tubes is maintained constant to within ±0.1 percent for the duration of a run. Thermal drifts are minimized by maintaining the room temperature constant to within two degrees. Cathode follower preamplifiers are mounted adjacent to the 5819 tube sockets to allow the use of leads less than 5 cm long. The pulses from the cathode followers are amplified by Atomic Instruments Model 204-B linear

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1 W. C. Peacock and M. Deutsch, Phys. Rev. **69**, 306 (1946).
2 Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).
3 Robinson, Ter-Pogossian, and Cook, Phys. Rev. **75**, 1099 (1949).
4 R. G. Fluharty and M. Deutsch, Phys. Rev. **76**, 182 (1949).
5 Maurice M. Miller, Phys. Rev. **88**, 516 (1952).
6 Ticho, Green, and Richardson, Phys. Rev. **86**, 422 (1952).

amplifiers which are operated with 0.2 μsec rise times. Pulses out of the two amplifiers are fed into fast single channel differential pulse-height selectors which are modifications of the circuit described by Roulston.[7] This circuit has a dead-time of about 1 μsec and is especially useful in coincidence work in which high singles counting rates are encountered. The usual disadvantages of a circuit containing no elaborate pulse shaping devices, "window amplifiers" etc., are present. However, the attendant variation of effective slit width with pulse-height setting and slit width instability in time is more than offset by the speed of the circuit, since large slit widths are generally used. The outputs of the two single channel discriminators are mixed in a coincidence circuit which uses a delay line pulse shaper to obtain a resolving time of 0.15 μsec. Delayed coincidence studies are accomplished by inserting a variable delay line in either channel.

For angular correlation measurements, one of the counters can be positioned on a circle at angles from 85° to 275° with respect to the second (fixed) counter. The source, in this case, is placed on the axis of rotation. The instrument is designed to allow accurate repositioning at any angle and possesses practically no geometrical asymmetry. Asymmetries in counting rates due to stray magnetic fields are minimized by the use of Mumetal shields. The source-to-crystal distance can be varied continuously from 1.5 in. to 4.5 in. For the $\frac{3}{4}$-in. crystals used, these limits correspond to angular resolutions of 9° and 25° as determined from annihilation radiation coincidence measurements.

Since only pulse heights in desired ranges are accepted in each channel the correlation between two selected γ-rays may be studied with little or no interference from scattering or other undesired γ-rays. Lead shields are placed between the counters only in certain special instances in which multiple scattering may be a problem.

The beta-ray experiments were carried out with a small 180° shaped field spectrometer having a resolution of about 1.5 percent and a transmission of about 1.5 percent. Although the basic radius of curvature of the instrument is only 7.5 cm, scattering effects are kept to a minimum by the focusing action and by the large dimensions of the vacuum chamber.

SOURCES

The V^{48} used in these experiments was produced by $Sc^{45}(\alpha, n)V^{48}$ in the Indiana University cyclotron. The Sc was removed by repeated *HF* precipitation and centrifugation. Impurities such as Cu and Ga were removed by *HS* precipitation and ether extraction. Sources reasonably free of carrier were finally obtained by electrodeposition from a dilute and slightly basic solution. While no V carrier was added, a small amount of foreign material, probably iron, plated out with the V^{48}. Sources for the coincidence spectrometry were prepared by placing one small drop of vanadium chloride in a cylindrical Lucite cup. Over-all source dimensions were of the order of 2 mm for most measurements. The beta-ray spectrometer sources were made in the conventional manner.

[7] K. I. Roulston, Nucleonics 7, 27 (1950).

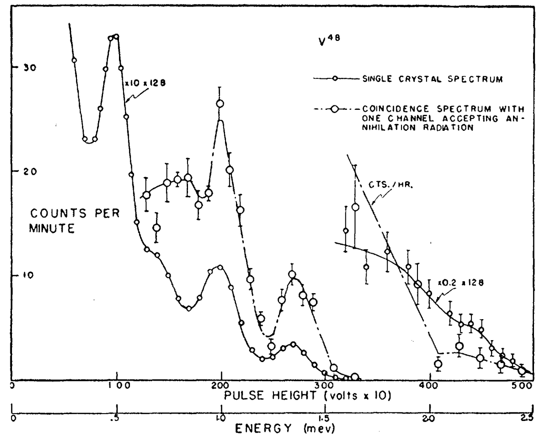

FIG. 2. Single channel and coincidence spectra of the γ-rays of V^{48}. The prominent peaks are due to γ-rays at 0.511 Mev (annihilation radiation), 0.99 Mev, and 1.32 Mev. The curves at the right are an expanded plot in the region of the 2.22-Mev γ-ray. The energy scale is obtained by calibration with Cs^{137}.

COINCIDENCE SPECTROMETRY

The single crystal spectrum and a coincidence spectrum are shown in Fig. 2. Prominent photoelectron peaks in the single crystal spectrum correspond to the 0.511-Mev annihilation radiation and the well-known γ-rays of energies 0.99 and 1.32 Mev. In addition, a weak line corresponding to the high energy γ-ray is found at 2.2 Mev. By rough estimate (the usual corrections applied) the 2.22-Mev γ-ray is found to have about 2 percent the intensity of the 1.32-Mev γ-ray. The coincidence spectrum shown in Fig. 2 was obtained by setting one channel to accept the annihilation photopeak while scanning the remainder of the spectrum with the other channel. The curve represents the coincidence rate between the two channels, corrected for chance coincidences, *versus* discriminator setting of the variable channel. The energy scale was obtained by calibration with the Cs^{137} photoelectron peak. The true-to-chance coincidence ratio ranged from 10 for the 0.99-Mev peak to 2 for the 2.22-Mev peak. The coincidence spectrum clearly shows that all three γ-rays are in coincidence with the annihilation radiation and hence with the positrons.

The results of other coincidence measurements are as follows. With the fixed channel adjusted to accept the 0.99 peak, coincidence spectrum peaks were observed at 0.99 and 1.32 Mev, but none at 2.22 Mev. When the fixed channel was set on the 2.22-Mev peak, no coincidences above chance were recorded at 0.99 or 1.32 Mev. In all of the experiments the coincidences were found to be prompt with respect to the 1.5×10^{-7} sec resolving time of the coincidence circuit. These results verify the cascading of the 0.99- and the 1.32-Mev γ-rays and show that the 2.22-Mev γ-ray is not coupled with either of the other two. These facts are consistent only with the decay scheme of Fig. 1. The coincidences observed when both channels accepted the 0.99-Mev peak are due to coincidences between the photoelectrons from the 0.99-Mev γ-ray and the Compton electrons from the 1.32-Mev γ-ray.

DIRECTIONAL CORRELATION

With the apparatus described, it becomes possible in certain cases to extend $\gamma-\gamma$ directional correlation studies to positron emitting elements. The strong angular correlation of the annihilation radiation ordinarily present is not troublesome in this case since the γ-rays involved, 0.99 and 1.32 Mev, give rise to photoelectron peaks which are well beyond the annihilation radiation peak. The amplifier gains were adjusted so that the pulse heights due to the γ-rays were approximately the same in each channel. Figure 3 shows a typical singles spectrum as obtained in either channel with a 1.5-volt slit. In order to enhance the true-to-chance coincidence ratio, coincidence counts were taken with slits wide enough (13.5 volts) to accept the photoelectrons of both γ-rays and with the discriminators set high enough to exclude annihilation radiation. Coincidence counting rates in the three runs taken ranged from 15 to 30 counts per minute with corresponding true-to-chance ratios from 12 to 5. Total counts of about 5000 were recorded in each run at the intermediate settings and approximately 10,000 counts at 90° and 180°. An angular resolution of 20° was used. Correction for this effect was less than the expected statistical fluctuation. The results are shown in Fig. 4. The measured asymmetry coefficient $[n(180)-n(90)]/n(90)$ is 0.171 ± 0.02. The solid curve in Fig. 4 is a plot of the theoretical correlation function to be expected

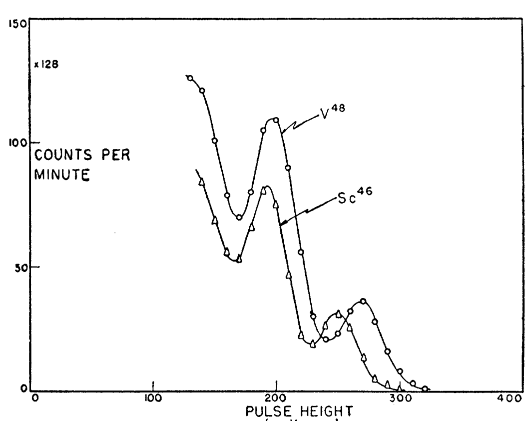

FIG. 3. Single channel spectra of the 0.89- and 1.12-Mev γ-rays of Sc^{46} and the 0.99- and 1.32-Mev γ-rays of V^{48} obtained with the same spectrometer conditions. The discriminator slit width was 1.5 volts.

for spin assignments 0–2–4. As a check on the performance of the equipment, the well-known[8] correlation of Co^{60} was determined with the 13.5-volt slits. The expected correlation was found, the asymmetry coefficient being 0.147 ± 0.02. In addition, the contribution of the annihilation radiation was checked by repeating the experiment with Cu^{64}, with the discriminator settings and slit width the same as for the case of V^{48}. For sources of Cu^{64} comparable in intensity with the V^{48} sources, no effect was found. It seems reasonable to conclude that the spins of the levels involved in the cascade γ-rays emission are 0–2–4.

MAGNETIC SPECTROMETER MEASUREMENTS

It seemed advisable, in view of the coincidence spectrometry results, to re-investigate the positron and electron spectra of V^{48}. A careful search was made for internal conversion lines in the region 70 to 120 kev. Since no lines were found, it is quite probable that there is no transition from the 2.31-Mev level to the

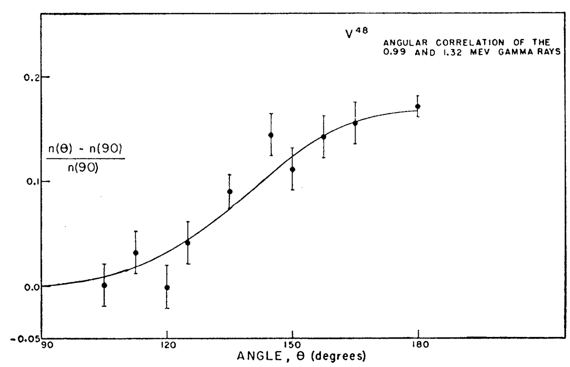

FIG. 4. The directional correlation of the 0.99 and 1.32-Mev γ-rays of V^{48}. The solid curve represents the theoretical correlation function $W(\theta)=1+0.125\cos^2\theta+0.042\cos^4\theta$.

2.22-Mev level. Sources were too weak to study the photoelectrons of the 2.22-Mev γ-ray.

Figure 5 shows a Fermi plot of the positron spectrum taken with a source 0.3 mg/cm² thick. In addition to the main group having an end point at 0.69 ± 0.01 Mev, there is evidence for a second group with an end point at approximately 0.82 Mev and 5 percent intensity. While the presence of this group seems fairly definite, it must be emphasized that the estimated intensity and end point may be quite in error. The small uncertainties in the background generally present in positron measurements are in this instance not negligible. Although careful background measurements were made at each point, errors are still large and accurate determination of the intensity and endpoint cannot be made until much stronger sources are available. It should be pointed out that every point was followed through nearly two half-lives and found to decay with a 16-day half-life. The departure from the straight line in the

[8] E. L. Brady and M. Deutsch, Phys. Rev. **78**, 558 (1950).

neighborhood of 250 kev is somewhat surprising with the source thickness used, and it is possible that the spectrum possesses a shape other than allowed. This matter requires further study.

DISCUSSION

The foregoing results are summarized in the decay scheme presented in Fig. 1. The data pertinent to the discussion of the beta-rays and positrons involved in the decay to Ti^{48} are listed in Table I.

The values of the spins and parities (0+, 2+, 4+) of the levels involved in the angular correlation make possible a quite consistent assignment of the remaining levels. An upper limit of 3 is already available to the spin of the 2.22-Mev level since the transition from this level is prompt with respect to 10^{-7} sec. According to the shell model the ground states of Sc^{48} and V^{48} are characterized by $(f_{7/2}f_{7/2})$ for the odd neutron and odd proton. Nordheim's[9] rules for such nuclei call for high spin and even parity for these levels. Therefore, a beta-ray or positron transition to the first excited state of Ti^{48} would involve no parity change, and the spins of the ground states of Sc^{48} and V^{48} must be at least 4 to account for the absence of these transitions. On the other hand, the transitions β^- and β_1^+ are characterized as allowed by their ft-values and the parity changes involved, so that the ground-state spins of Sc^{48} and V^{48} cannot be greater than 5. With the spins of these states thus limited to 4+ or 5+, the occurrence of the 2.22-Mev level in the V^{48} decay, and its absence in the Sc^{48} decay, can only be explained by assigning 5+ to the Sc^{48} ground state and 4+ to V^{48}. As a consequence of this, the spin and parity of the 2.22-Mev level must be 2− if it is to be populated in a measurable amount.

TABLE I. Data concerning the beta-rays and positrons involved in the decay to Ti^{48}.

	Intensity	Energy Mev	log ft	K/β^+
$\beta^-(Sc^{48})$	100%	0.64	5.4	
$\beta_1^+(V^{48})$	95%	0.69	6.1	0.7
$\beta_2^+(V^{48})$	~5%	~0.80	>7.4	>0.7(?)

The fact that no γ-transition was found between the 2.31- and 2.22-Mev level is in accord with these assignments. Furthermore, this transition is not expected since the 2.22-Mev γ-ray is not seen in the Sc^{48} decay. It is possible that the transition from the 2.22-Mev level to the first excited state exists. Its existence would be difficult to detect in the presence of the much stronger 1.32-Mev γ-ray. The intensity measurements, although subject to large errors, suggest that the 2.22-Mev γ-ray is not intense enough to account for all of the positrons, β_2^+. Furthermore, the coincidence studies (Fig. 2) suggest that K_2/β_2^+ is as large, or larger than K_1/β_1^+. A quantitative estimate of these ratios is not possible because of the large multiple scattering corrections. If the transition from the 2.22-Mev level to the 0.99-Mev level does occur, it does so in less than 3 percent of the disintegrations.

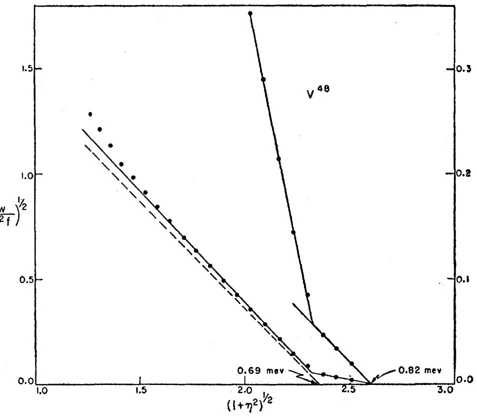

FIG. 5. Fermi plot of the beta-rays of V^{48} taken with a 180° shaped field spectrometer. The curve at the right is an expanded plot of the end-point region. The dotted line represents the Fermi plot of the main group of positrons.

Recently, it has been proposed[10,11] that the decay of Sc^{48} to Ti^{48} involves the excitation of a level one Mev above the 2.31-Mev level. It is certain from this work that such a level does not exist in the decay of V^{48} to Ti^{48}. This would mean that the photopeak of the 0.99-Mev γ-ray shown in Fig. 3 is actually due to two γ-rays. A comparison with the Sc^{46} photopeak is shown in Fig. 3. The curves were obtained under identical conditions. When account is taken of the small difference in energies of the higher energy γ-rays of Sc^{46} and V^{48}, the intensity ratios in the two cases are the same. It must be concluded that the 0.99 and 1.32 γ-rays of the V^{48} decay are of equal intensity if the γ-rays of Sc^{46} are of equal intensity as is generally established.

The authors wish to thank Dr. Milo B. Sampson and the cyclotron staff for the bombardments and Mr. Arthur Lessor for his assistance with the chemistry.

[9] L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).

[10] D. Kurath, Phys. Rev. **87**, 528 (1952).

[11] Hammermesh, Hummel, Goodman, and Engelkemeir, Phys. Rev. **87**, 528 (1952).