Angular Correlations in Ti^{48}

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The angular correlations of the (0.99, 1.32) Mev and (2.23, 0.99) Mev gamma-ray cascades in Ti^{48} have been measured and are consistent with spin assignments to the ground, 0.99-, 2.31-, and 3.22-Mev states of 0, 2, 4, and 4, respectively. Taken with these results, the measured values of the two polarization-direction correlations for the (0.99, 1.32) Mev cascade rule out most spin assignments for the first three levels which require a mixed 1.32-Mev transition, and show that these levels must all have even parity. The mean lifetime of the 0.99-Mev level was found to be $<2\times10^{-11}$ sec.

INTRODUCTION

THE currently accepted level scheme for Ti^{48} (Fig. 6), which is based on a number of investigations[1–3] of the decay schemes of Sc^{48} and V^{48}, can be regarded as well established. Reported angular correlation measurements[4–8] are consistent with spin assignments of 0, 2, 4, and 6 to the ground, 0.99-, 2.31-, and 3.35-Mev levels, but do not eliminate the possibility of other spin sequences involving mixed transitions. Though this ambiguity could be largely eliminated by direction-polarization correlation measurements, and the existence of such measurements has been reported,[7] no such data appear to have been published. The measurements reported here were undertaken to determine the spin of the 3.22-Mev level, and to confirm the ground, 0.99-Mev, 2.31-Mev spin sequence by polarization-direction correlation measurements, carried out with a polarimeter able to resolve the 0.99- and 1.32-Mev gamma rays.

PRELIMINARY MEASUREMENTS

Sources of V^{48} were prepared in the Harwell cyclotron by spallation of iron with 160-Mev protons. The preparation of the targets and their chemical treatment, which included separation of cobalt, iron, manganese, and chromium activities, was carried out by Dr. C. E. Mellish of the Isotopes Division. The gamma-ray spectrum of the purified V^{48}, observed with an NaI scintillation spectrometer, is shown in Fig. 1. In this plot, the ordinate is the attenuation required in front of a fixed single-channel kicksorter to bring the appropriate group of pulses into the fixed channel. Only the expected 0.511, 0.99, 1.32, and 2.23-Mev lines are present. Measurements with two scintillation spectrometers in coincidence confirmed the existence of the (2.23, 0.99) Mev coincidences observed by Casson *et al.*[3] The intermediate state in all the correlation measurements described below is the 0.99-Mev level. Temmer and Heydenburg[9] have measured the mean life of this level by Coulomb excitation techniques, finding the value 2.1×10^{-12} second. An attempt was made to measure this lifetime independently by centroid shift techniques, comparing gamma-gamma coincidences from V^{48} with those from Na^{24}. The slow channels of a parallel coincidence unit were set so that one rejected all pulses from the 0.99-Mev gamma ray of Ti^{48}, and the ratio of the efficiencies for the two gamma rays of Mg^{24} was approximately the same for both channels. In this way the centroid of the composite coincidence curve for Na^{24} was made to coincide approximately with the centroid of a curve for prompt events.[10] The value obtained for the mean lifetime of the 0.99-Mev level was $(0.6\pm1.4)\times10^{-11}$ second, inconclusive in itself, but consistent with the Coulomb excitation results. This lifetime is small enough to make perturbation of the angular correlations very improbable, but for safety all correlation measurements

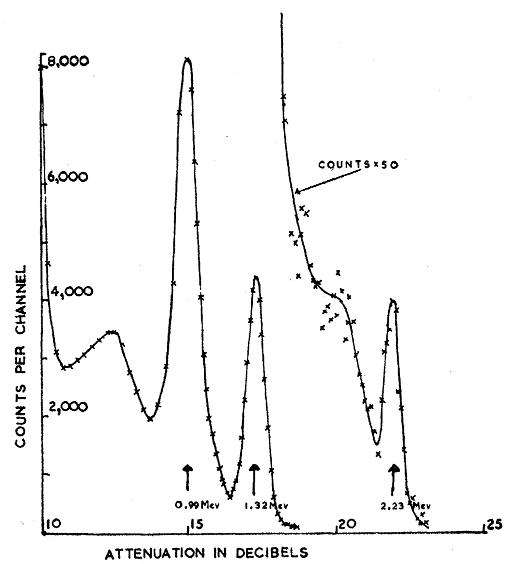

FIG. 1. Gamma-ray spectrum of purified V^{48}.

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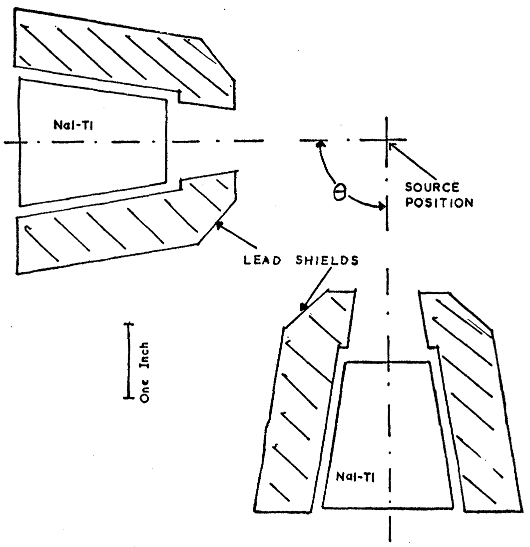

FIG. 2. Geometrical arrangement of angular correlation equipment.

were made using solutions of vanadyl chloride in hydrochloric acid.

ANGULAR CORRELATION MEASUREMENTS

A scale drawing of the detector geometry used for angular correlation measurements is shown in Fig. 2. In this arrangement, the cones of acceptance are defined by the shapes of the detecting crystals themselves, and the lead shields serve primarily to absorb scattered radiation. One detector is placed with its axis vertical since, although this is undesirable for the angular correlation measurements, it allows a much more convenient arrangement[11] of the direction-polarization correlation experiments.

NaI(Tl) phosphors and E.M.I. 6260 photomultipliers are used as detectors, working into a parallel-type coincidence unit. This has single-channel kicksorters in each slow branch, and a fast resolving time $2\tau=2\times10^{-8}$ second. Rate-controlled gain stabilizers[12] in the slow channels hold the slow gains steady enough to allow runs lasting several days. Coincidences are recorded automatically for 50-minute intervals at angles in the sequence 90°, 105°, 120°, . . ., 165°, 180°, 180°, 165°, . . ., with counts of the accidental-coincidence rate inserted after every third normal count.

The data are analyzed in groups, each containing the complete set of angles from 90° to 180° or its reverse. The coincidence count for each angle is corrected for accidentals and source decay, and is then divided by the product of the two single-channel counting rates, also corrected for source decay. The ratio of this quantity to the mean of all similar quantities over the group is next calculated, and finally the mean and standard deviation of these ratios over all the groups (usually ~10) is determined. An expression of the form $A_0+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ is fitted to the data so obtained by least-squares procedures.

It has been found that a source containing a positron spectrum in coincidence with gamma radiation may give an anomalously high coincidence rate at $\theta=180°$, even though both the slow channels are biased well above the annihilation photopeak. This arises from summation in one crystal of an annihilation quantum and a coincident gamma ray, which can produce a pulse falling into the corresponding slow channel. The second annihilation quantum detected in the second crystal automatically gives a fast-coincidence output. Accidental summation in this crystal with an unrelated gamma ray may then produce a pulse falling into the second slow channel, and therefore an output signal. When this effect can arise, the 180° point is excluded from the data for the least-squares fitting.

1.32-, 0.99-MEV CASCADE

The observed angular correlation for this cascade, corrected for finite angular resolution, is

$$W(\theta)=(1.000\pm0.003)+(0.104\pm0.007)P_2(\cos\theta)-(0.001\pm0.010)P_4(\cos\theta),$$

which is consistent with other observations,[4–6] and fits the spin sequence $4(E2)2(E2)0$. It can also be fitted by the sequences $3(M1+E2)2(E2)0$ and $2(M1+E2)2(E2)0$, if the mixture ratio of the 1.32-Mev transition is chosen suitably, but these possibilities are excluded by the polarization correlation measurements described below. Figure 3 shows the experimental angular correlations for this cascade and for the (2.23, 0.99) Mev cascade. The full lines represent the

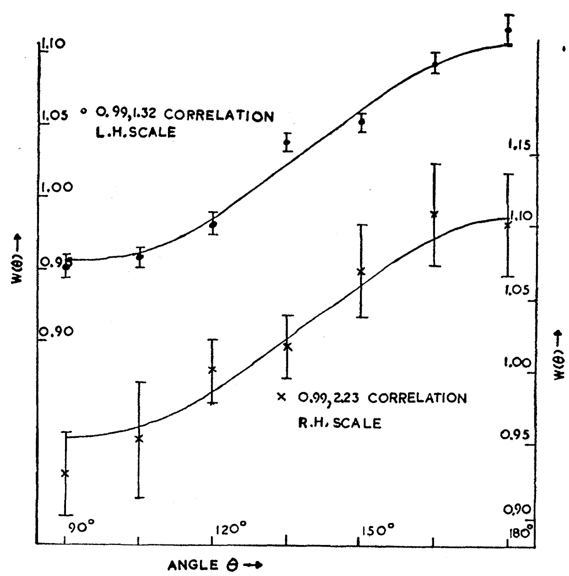

FIG. 3. Directional correlations of the (1.32, 0.99) and (2.23, 0.99) Mev gamma-ray cascades.

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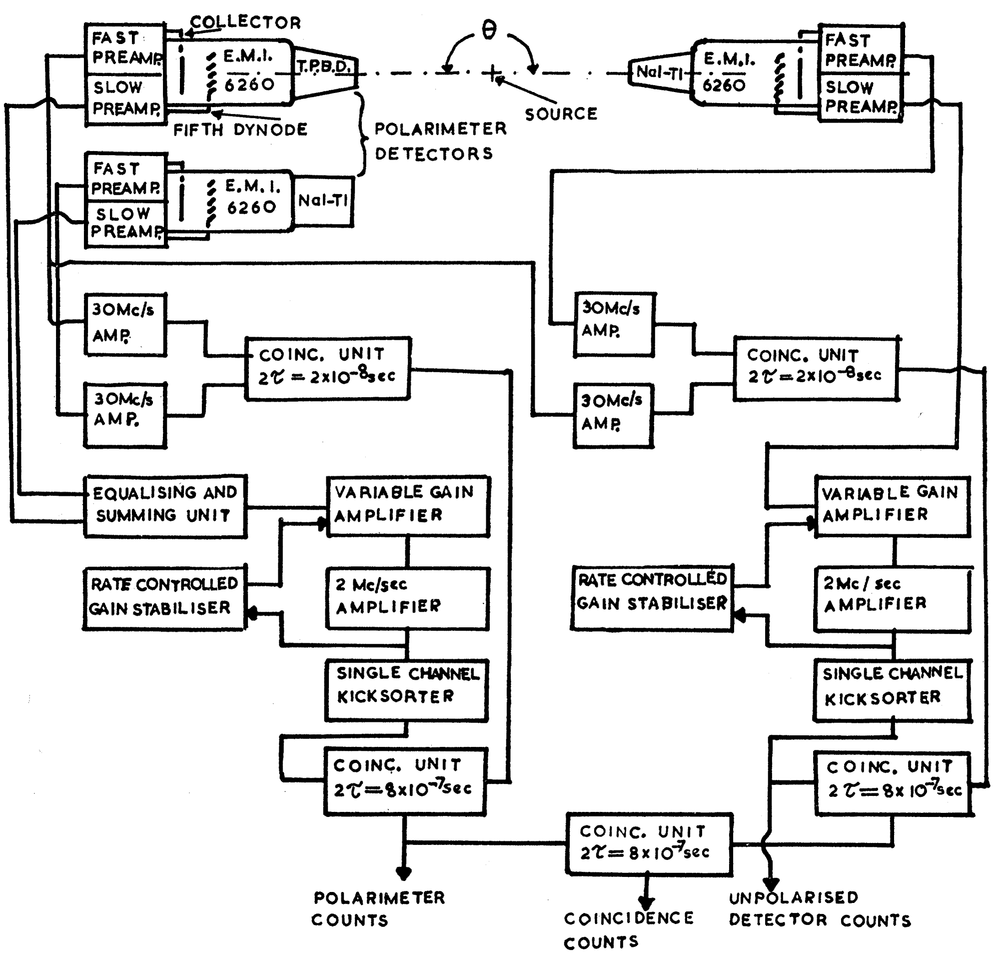

FIG. 4. Block diagram of electronics for direction-polarization correlation measurements.

theoretical 4, 2, 0 correlation, modified by the experimental angular resolution.

2.23-, 0.99-MEV CASCADE

Because of the low abundance of the 2.23-Mev gamma ray ($\sim 2\%$) and the presence of positrons in coincidence with the main cascade, it is necessary in interpreting the experimental data to consider the effects of crystal summing. Summation of the 0.99- and 1.32-Mev radiations to produce a pulse which falls in the slow channel selecting the 2.23-Mev radiation can be ignored, since the other channel is biased high enough to reject annihilation radiation. Summation of the 1.32- and 0.511-Mev radiations accounts for about 10% of the events detected in the 2.23-Mev channel, and such events are coincident with the 0.99-Mev radiation. The correlation of such triple-coincidence events will be just that of the (0.99 1.32) Mev cascade. Since the observed (2.23, 0.99) Mev correlation is indistinguishable from this, it is unnecessary to know the exact fraction of the observed coincidences arising from summation events. Background coincidences amounted to less than 1% of the observed coincidence rate. The least-squares fit to the (2.23, 0.99) Mev correlation, corrected for resolution, is

$$W(\theta) = (1.000\pm0.014) + (0.122\pm0.030)P_2(\cos\theta) - (0.011\pm0.045)P_4(\cos\theta).$$

This fits a 4, 2, 0 spin sequence, which is the most likely assignment, though a 3, 2, 0 sequence with the 2.23-Mev radiation mixed, is again a possibility.

DIRECTION-POLARIZATION CORRELATION MEASUREMENTS

In the past, direction-polarization correlation measurements have usually been interpreted in terms of pure transitions, when they determine relative parities. This interpretation fails when mixed radiations can be present. Under these conditions there is no longer a unique anisotropy of the angular correlation for each spin sequence, and a very accurate measurement of the coefficient A_4 is required if the spin sequence is to be determined from the angular correlation alone. This coefficient is very sensitive to any asymmetry

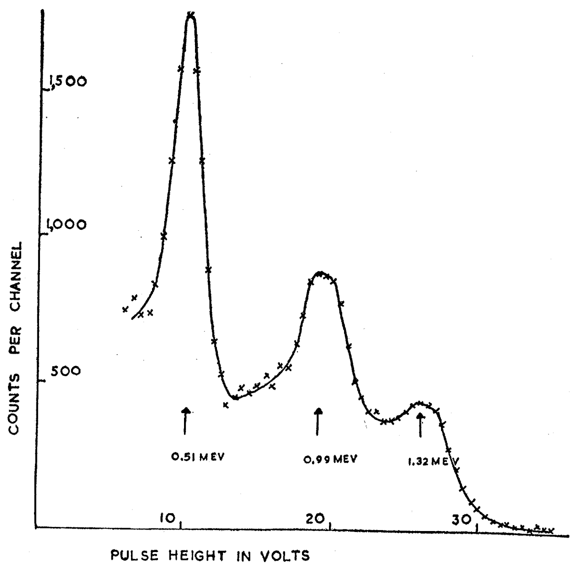

FIG. 5. Spectrum of V^{48} source observed in polarimeter.

in the experimental arrangement, and to scattering effects. The two types of correlation measurement taken in conjunction, however, can greatly reduce this ambiguity, as Steffen has shown for the Cd^{114} levels.[13] That this will be a general phenomenon can be seen from the form of the correlation for a cascade containing a (dipole+quadrupole) mixture, when the polarization effects are included for the mixed radiation only.[14] This is

$$W(\theta,\phi)=1+\delta^2+(a_2+b_2\delta+c_2\delta^2)P_2(\cos\theta)$$
$$+c_4\delta^2P_4(\cos\theta)+\{(\mp\tfrac{1}{2}a_2\pm\tfrac{1}{6}b_2\delta\mp\tfrac{1}{2}c_2\delta^2)P_2{}^2(\cos\theta)$$
$$\pm(1/12)c_4\delta^2P_4{}^2(\cos\theta)\}\cos2\phi.$$

In the region where the terms linear in δ dominate, this expression is such that if the directional anisotropy increases in absolute magnitude with increasing δ, the polarization-direction anisotropy near $\theta=90°$ diminishes, and conversely. The effect of this is that the experimental values of the two correlations will usually determine widely different values of δ for all spin sequences but the correct one.

To make full use of this fact, it is desirable to be able to measure separately the polarization effects of the two gamma rays concerned in a cascade. For this purpose a "total absorption" polarimeter, of which the method of operation and mechanical layout have been described elsewhere,[11] has been used. Figure 4 is a block diagram of the electronic circuits used with this apparatus. Since the gain stabilizer in the polarimeter channel receives a pulse spectrum dominated by the Compton distribution from the scattering detector, it tends to stabilize the output pulse level from this detector alone. This can be tolerated since these pulses account on average for about two-thirds of the height of the summed pulses in the high-energy peak. The polarimeter spectrum obtained from V^{48} is shown in Fig. 5. Pulses from the 0.99- and 1.32-Mev radiations are sufficiently resolved for this experiment, and those from annihilation radiation can be completely eliminated. For the (0.99, 1.32) Mev cascade at $\theta=105°$, the measured polarization ratios for the 0.99- and 1.32-Mev radiations are $N_\perp/N_{\parallel}=1.090\pm0.016$ and 1.070 ± 0.023, respectively. The first result shows that the 0.99-Mev level has even parity. For the spin sequences 2, 2, 0 and 3, 2, 0, the observed angular correlation would require admixtures of at least 3% of quadrupole radiation in the 1.32-Mev transition, which would imply an $(E2,M1)$ mixture. The predicted values of $N_\perp/N_{\parallel}$ for the 1.32-Mev radiation, for the two mixture ratios which are consistent with each assignment, are then 1.26 and 0.99, and 0.90 and 0.79, none of which fits the observations. For the $4+(E2)2+(E2)0+$ assignment, the predicted value is 1.084, which, with the value 1.11 for the 0.99-Mev ratio, is in reasonable agreement with the experimental values.

CONCLUSIONS

Figure 6 shows an energy-level diagram for Ti^{48}, with spin and parity assignments. The spins 0+, 2+, and 4+ for the ground, 0.99-Mev, and 2.31-Mev levels have been established uniquely by a combination of angular and direction-polarization correlation measurements. This strengthens the assignment of a spin 6 to the 3.35-Mev level on the basis of angular correlation measurements[7,8] with sources of Sc^{48}. The spin of the 3.22-Mev level is most probably 4, though a spin of 3 with a value of δ for the 2.23-Mev radiation lying between -0.2 and -0.3 would also fit the experimental

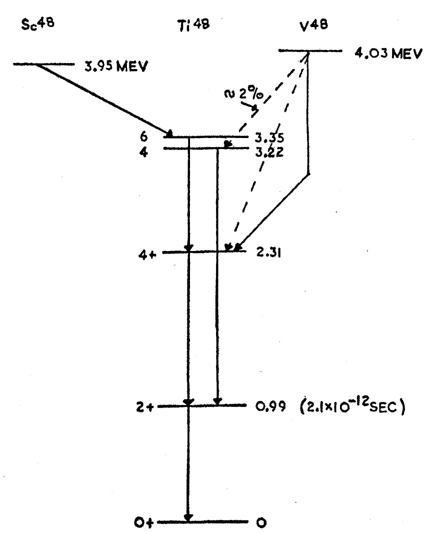

FIG. 6. Energy level scheme for Ti^{48}.

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results. A sequence of levels with characters 0+, 2+, 4+, and 6+ is to be expected from the calculations of Edmonds and Flowers[15] on the independent-particle model, assuming *jj* coupling, but the 2+, 4+, and 6+ levels should then form a fairly close triplet. The ratio of the observed energies of the 2+ and 4+ levels, 2.34, and the ratio between the observed transition probability from the 0.99-Mev level[9] and the value given by the single-particle model, agree closely with the values found for even-even nuclei having $36 \leq N \leq 88$, which Scharff-Goldhaber and Weneser[16] interpret in terms of a weak-coupling version of the Bohr-Mottelson model. The spin-6 state might then be interpreted as a member of a higher multiplet with an excitation in the zero coupling limit of $3\hbar w$ relative to the ground state. If the spin-4 state at 3.22 Mev is also regarded as a member of this multiplet, it should decay preferentially to the 2+ and 4+ members of the two-phonon triplet. The triple-coincidence data of Casson *et al.*[3] show that such transitions are $\lesssim 7$ times as strong as the competing 2.23-Mev transition.

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Gamma Radiation in RaD and RaE Decay*

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By using chromatographically separated, carrier-free sources, the electromagnetic spectra of RaD and RaE have been investigated from 4 to 60 kev with an argon-methane gas proportional spectrometer. No gamma rays or *L* x-rays were detected in the decay of RaE. Aside from the principal 46.5-kev transition, no gamma rays (<0.2% of the 46.5-kev photons) were observed in the decay of freshly-purified RaD. However, when equilibrium mixtures of RaDEF, from spent radon seeds less than 2 years old, were examined through aluminum absorbers of thickness sufficient to eliminate pile-up peaks (20 to 26 kev) from the *L* x-rays (10 to 16 kev), a broad peak at about 31 kev appeared; it was established conclusively that in reality this is external beta-bremsstrahlung of RaE, whose low-energy region has been attenuated selectively so as to give the appearance of a gamma-ray peak.

A chromatographic column separation of millicurie quantities of carrier-free RaD and RaE from each other, as well as from RaF and macro amounts of gold and mercury impurities, is described. The time required for separation is less than 2 hours.

I. INTRODUCTION

THE work published from 1926 to the present[1–21] on gamma radiations from the decay of RaD(Pb^{210}) reveals a persistent controversy concerning the existence of gamma rays of energy lower than the 46.5-kev transition which accounts at least for 87.5% of RaD

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