Excited Levels in Ti^{48}†

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Excited levels of Ti^{48} have been investigated by means of the radioactive decays of V^{48} and of Sc^{48}. The intensity of a 2.29-Mev gamma-transition in Ti^{48} relative to the total number of V^{48} and Sc^{48} disintegrations is found to be different for the two decays. This evidence that the 2.29-Mev transition in Ti^{48} is not a cross-over is further substantiated by delayed-coincidence measurements and lifetime considerations.

EXCITED levels in Ti^{48} have been investigated by observing the positron and orbital electron capture decay of 16-day V^{48} and also the 44-hour negatron decay of Sc^{48}.

The single crystal scintillation spectrum of V^{48} is shown in Fig. 1. The data were taken with a conventional scintillation spectrometer utilizing a NaI (Tl) crystal and an RCA 5819 photomultiplier. Photopeaks are observed at 0.51, 0.99, 1.32, and 2.29 Mev on the basis of a calibration with the Cs^{137} 0.661-Mev radiation and the Sc^{46} 1.12-Mev radiation. A similar spectrum is obtained by observing the decay of Sc^{48} in the same geometry. In this case photopeaks are observed at 0.51, 0.99, and 1.32 Mev but not at 2.29 Mev. The 0.51-Mev peak is due, in each case, to the annihilation radiation observed when positrons are stopped in the Pb absorber surrounding the source. The annihilation radiation observed in the spectrum of Sc^{48} is due to the positron decay of Sc^{44} which is fed by a 52-hour isomeric transition. The Sc^{44} was produced along with the Sc^{48} in the deuteron bombardment of calcium.

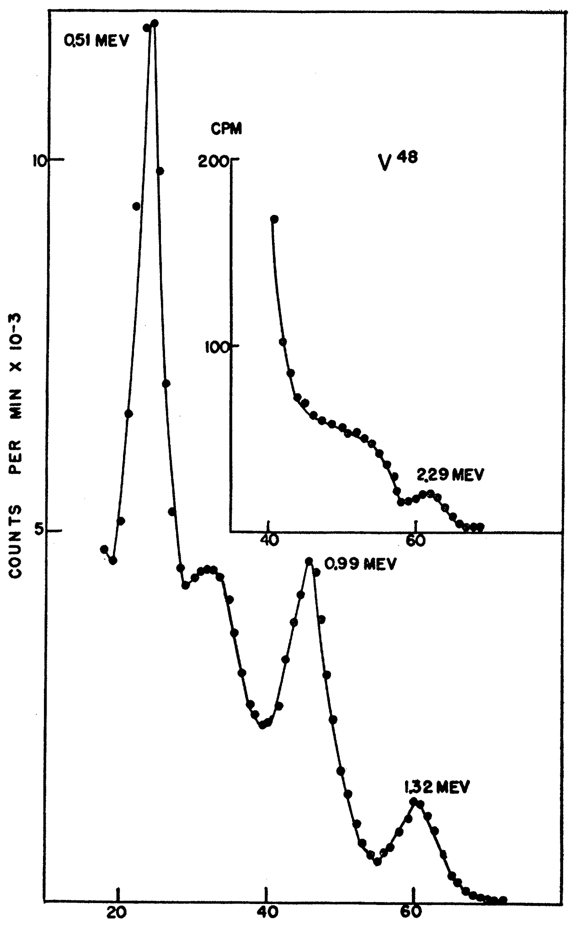

FIG. 1. Scintillation spectrum of V^{48}. Inset shows photopeak and Compton distribution of a 2.29-Mev gamma-ray taken with reduced gain.

In each of the decays the lines at 1.32 and 0.99 Mev are of approximately equal intensity. In the V^{48} decay the intensity of the 2.29-Mev radiation (inset of Fig. 1) is found to be 1.7±0.5 percent of the 1.32-Mev radiation. This intensity comparison takes into account the variation of the photoelectric cross section with energy and the contribution to the photopeak intensity due to multiply-scattered Compton gamma-rays which are absorbed completely within the crystal. This intensity ratio compares favorably with the value of one percent obtained by quite different means.[1] Since the search for the corresponding 2.29-Mev gamma-ray in the Sc^{48} decay revealed no discernible line, its intensity is estimated to be no more than 10^{-3} of the intensity of the 1.32-Mev gamma-ray.

Coincidence spectrometer measurements utilizing two single crystal spectrometers[2] showed the 1.32 and 0.99-Mev gamma-rays of V^{48} to be in coincidence with each other and the annihilation radiation. This is in accord with the decay scheme of V^{48} as proposed by Peacock and Deutsch.[3] In addition, coincidences were observed between the annihilation radiation and the 2.29-Mev gamma-ray. All coincidences were found to be "prompt" (with respect to the 10^{-7} second resolving time of the coincidence circuit) by means of the delayed coincidence technique. Co^{60} gamma-coincidences also showed the "prompt" delayed coincidence spectrum.

These results suggest that the high energy gamma-ray does not arise from a cross-over transition. Assuming

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[1] R. G. Fluharty and M. Deutsch, Phys. Rev. **76**, 182 (1949).
[2] The spectrometer is described by Miller, Pruett, and Wilkinson, Phys. Rev. **84**, 849 (1951).
[3] W. C. Peacock and M. Deutsch, Phys. Rev. **69**, 306 (1946).

the ground state of the even-even nucleus Ti^{48} is characterized by spin 0, the Weisskopf[4] formula shows that the level giving rise to the 2.29-Mev transition cannot have a spin greater than 3 due to its short lifetime ($<10^{-7}$ seconds). With this limitation, however, no possible spin assignment of the excited levels can yield a cross-over whose intensity relative to the cascade gamma-process is comparable with that measured for the 2.29-Mev gamma-ray. The absence of the 2.29-Mev gamma-ray in the Sc^{48} decay further supports this view. A possible alternative assumption is that the second excited level in Ti^{48} is split into two separate levels differing slightly in energy but differing substantially in spin. The level of lower spin would be characterized by a spin of 3 or less and a higher relative population in the decay of V^{48} as compared with the decay of Sc^{48}. Such a splitting of the second excited state of an even-even nucleus has been previously postulated by Spiers[5] to explain the observed angular correlation in the decay of Pd^{106}.

The author is indebted to Professor R. G. Wilkinson for his suggestion of the problem.

Note added in proof:—A study of the relative intensities of the 1.32-Mev and the 0.99-Mev gamma-rays emitted following the Sc^{48} decay has been reported by Hamermesh, Hummel, Goodman, and Engelkemeier [Phys. Rev. **87**, 528 (1952)].

[4] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[5] J. A. Spiers, Phys. Rev. **78**, 75 (1950).

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Angular Correlations of the Radiations from Deuteron Stripping Reactions*

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The general problem of the angular correlation of the radiations from excited states of nuclei produced in stripping reactions is discussed using the theory of Butler. The $(d,p\gamma)$ correlation is given explicitly.

I.

The angular distribution of the single particles produced in deuteron stripping reactions[1] has proven to be a powerful tool for obtaining detailed information about the quantum states of the nuclei formed in these reactions. The method has had its greatest success in determining parities; for determining spins, however, it is less useful, and in fact, fails whenever the target nucleus has nonzero spin or the orbital angular momentum transfer is nonzero. If the residual nucleus is left in an excited state, further information on the spin of this state may be inferred from observation of the radiations emitted when the state decays. The specific experiment that seems most practical is to measure the angular correlation of the subsequent radiation in coincidence with stripped particles of a selected energy (in order to specify the energy of the emitting state). The correlations to be expected are found to be quite simple if one uses Butler's theory for the stripping process, and a brief report of the results has been given earlier.[2] Because of the current interest in this type of experiment, a detailed treatment seems to be of some value and is given below.

* This document is based on work performed for the AEC at the Oak Ridge National Laboratory.

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[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).

[2] Biedenharn, Boyer, and Charpie, Phys. Rev. **86**, 619 (1952); it has come to the authors' attention that W. Cheston and L. Gallaher of Washington University (St. Louis) have independently arrived at similar results. *Note added in proof:*—Professor Spiers has informed us of similar work by G. R. Satchelor and himself to be published in the Proc. Phys. Soc. (London).

II.

In order to calculate the angular distribution of radiations emerging from an excited state of a nucleus formed in stripping, it is sufficient to have the density matrix of the state in question and then apply standard techniques.[3] The required density matrix is implicit in the work of Butler and can be written down immediately if one has evaluated the integrals in his Eqs. (19) and (21) and thereby obtained an explicit form for the wave function that describes the stripping process.

Consider the process whereby an unpolarized deuteron beam, with momentum $\mathbf{K}_d$, bombards a target nucleus of spin j to form a residual nucleus of spin J and a beam of protons which emerges with momentum $\mathbf{K}_p$. (The momenta $\mathbf{K}_d$ and $\mathbf{K}_p$ are measured in the laboratory system.) Then Butler's Eqs. (19) and (21), upon performing the indicated steps, yield the asymptotic wave function

$$\begin{aligned}\psi\sim\left(\chi_p{}^{\mu_p}\frac{e^{iK_pr_p}}{K_pr_p}\right)\cdot v_J{}^M(K_p)\sum_{l_n,s} i^{l_n}\cdot N(l_n,s;K_p,r_0)\\ \cdot Q_{l_n}(\mathbf{K}_d,\mathbf{K}_p)\cdot[Y_{l_n}{}^{M-m-\mu_d+\mu_p}(\mathbf{K}_d-\mathbf{K}_p)]^*\\ \cdot(\tfrac{1}{2}\tfrac{1}{2}\mu_p\mu_d-\mu_p|\tfrac{1}{2}\tfrac{1}{2}1\mu_d)\\ \cdot(\tfrac{1}{2}j\mu_d-\mu_pm|\tfrac{1}{2}js\mu_d-\mu_p+m)\\ \cdot(sl_nm+\mu_d-\mu_p\,M-m-\mu_d+\mu_p|sl_nJM).\quad(1)\end{aligned}$$

We use the notation of reference 1 for convenience,

[3] See for example, U. Fano, National Bureau of Standards Circular No. 1214, or the forthcoming review paper of Biedenharn and Rose on angular correlations.