nuclei. The decline of the anisotropy may well be associated with the rapidly increasing probability of symmetric fission with neutron energy.

The preponderance of heavy fragments in the forward direction likewise is susceptible of improved observation. Thus this experiment could be performed with U^{238} at 2.5-Mev neutron energy. In this region it is known that the ratio of the height of the higher-energy peak to valley minimum in the ionization spectrum is at least 3.3 whereas in the case of Np^{237} it was only about 2.

The progress of this experiment was possible only through the assistance of many of our associates. In particular we thank L. K. Schlacks for evaporating the fissile layers, R. W. Davis for untiring help in setting up the apparatus at the Cockcroft Walton machine and operating the accelerator, Group P-4 for the generous allotment of time on this accelerator, R. K. Zeigler for computational aid, and J. Waugh for graphical assistance.

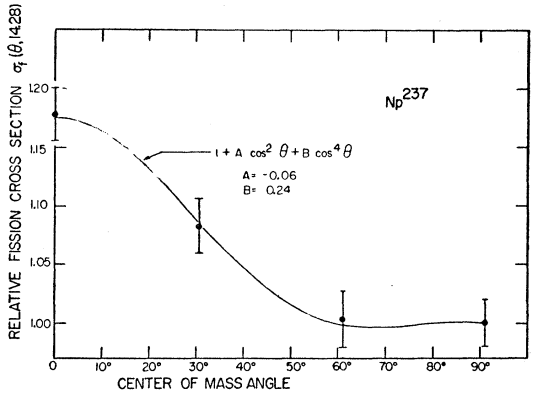

FIG. 11. Relative differential fission cross section of Np^{237} at $E_n = 14.3$ Mev.

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Isobaric Triplet $Cr^{48}-V^{48}-Ti^{48}$*†‡

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Cr^{48} has been produced by the nuclear reaction $Ti^{46}(\alpha,2n)Cr^{48}$. The gamma spectra of this nuclide have been investigated and peaks found at 118 kev and 307 kev. The two gamma rays are in coincidence and have the same intensity. The gamma rays of the daughter nuclide V^{48} have been shown to appear in the gamma spectra as Cr^{48} decays. The half-life of Cr^{48} has been determined as 24±1 hours. The energy of the Cr^{48} orbital electron capture has been shown to be approximately 1.30 Mev with a very low log ft value. A decay scheme for the isobaric triplet $Cr^{48}-V^{48}-Ti^{48}$ is proposed. Using the proposed decay schemes as a basis, the masses of Cr^{48} and V^{48} have been calculated to be 47.96934±22 and 47.96749±7, respectively.

INTRODUCTION

CHROMIUM-48 has been reported as an orbital electron capturing activity produced in the spallation of iron with 340-Mev protons.[1] Its half-life was reported to be 23 or 24 hours. No gamma radiations were reported for this nuclide. Cr^{48} is an even-even nucleus with an associated 0+ ground state[2] whereas V^{48}, the product nucleus, is known to have a ground state of 4+ or 5+.[3] The decay of Cr^{48} may therefore be expected to be complex with the emission of gamma rays.

This work was undertaken in an effort to produce Cr^{48} and to study its decay scheme and the decay scheme of its daughter V^{48}. Because of the great number of radionuclides produced in a spallation reaction, it was decided to attempt to produce Cr^{48} by alpha bombardment of titanium. The nuclear reaction expected was $Ti^{46}(\alpha,2n)Cr^{48}$. The bombardment of enriched Ti^{46} was indicated since normal titanium contains only 8 percent Ti^{46}.

EXPERIMENTAL

Enriched Ti^{46} as TiO_2 was bombarded by 50-Mev alpha particles in the 60-inch cyclotron at the University of California for a period of 4 hours. The total beam current for the bombardment was 12.4 microampere hours.

The TiO_2 together with 10 mg of chromium as Cr_2O_3 and 10 mg of vanadium as V_2O_5 was fused with anhydrous sodium carbonate for a period of 30 minutes. The melt was extracted with hot water and filtered. A few drops of 6N NaOH was added to the filtrate

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† This paper is taken from a portion of a thesis submitted by J. R. Wilkinson to the Graduate Faculty of Florida State University in partial fulfillment of the requirements for the Ph. D. degree.

‡ A paper on the decay of Cr^{48} was presented before the New York Meeting of the American Physical Society, 1955 [van Lieshout, Greenberg, and Wu, Bull. Am. Phys. Soc. **30**, No. 1, 32 (1955)].

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[2] M. G. Mayer, Phys. Rev. **78**, 16 (1950).
[3] Casson, Goodman, and Krohn, Phys. Rev. **92**, 1517 (1953).

and $Fe(NO_3)_3$ added. The $Fe(OH)_3$ was filtered and the filtrate again scavanged as before. The filtrate from the second scavenging was acidified with HCl and evaporated to a small volume. The solution was taken up in 1:10 HCl, cooled to below 10°C in an ice bath, and three ml of cold, 6 percent solution of cupferron added to precipitate the vanadium. The solution was filtered and the filtrate evaporated to a small volume. 25 ml of concentrated HNO_3 was added and the solution again evaporated to a small volume to destroy the excess cupferron. The solution was made basic with NaOH and a few mg of Na_2O_2 added to insure the complete oxidation of the chromium. The solution was neutralized with HCl, made faintly basic with NH_4OH, then faintly acid with acetic acid, and the chromium precipitated as $BaCrO_4$. The precipitate was centrifuged, washed with H_2O, and dissolved in HCl. The $BaCrO_4$ was reprecipitated by addition of NH_4OH and was again centrifuged, washed, and dissolved as before. This step was repeated five more times to purify the $BaCrO_4$. The final precipitate was mounted on thin polystyrene film and the gamma ray spectra of the chromium were investigated by scintillation techniques employing a differential and integral discriminator similar to the one previously described by Fairstein.[4]

RESULTS

The gamma-ray spectra of Cr^{48} taken as a function of time show peaks at 118-kev and 307-kev. The apparent gamma ray at 425 kev is due to the sum line of the 118-kev and 307-kev gamma rays. The 118-kev, 307-kev gamma rays and the 425-kev sum line all decay with a 23-hour half-life. No annihilation radiation was observed in the first gamma spectra of Cr^{48} taken 2 hours after the separation of vanadium. The absence of any annihilation radiation confirms the observation of Rudstam, Stevenson, and Folger[1] that Cr^{48} decays by means of orbital electron capture without positron emission.

Spectra of Cr^{48} taken at intervals of 12 to 24 hours show the growth of gamma rays at 0.99 Mev and 1.32 Mev. Gamma rays of 0.99 Mev and 1.32 Mev have previously been identified with the decay of V^{48}.[5–7] The observation of these gamma rays growing into the spectra with a 16-day half-life as the Cr^{48} gamma rays decay is a positive identification of the nuclide Cr^{48} and totally confirms the findings of Rudstam, Stevenson, and Folger.[1]

The growth of the gamma peak at 0.512-Mev is attributed to the annihilation radiation of the 0.69-Mev positron of V^{48}. The apparent gamma ray at 2.32-Mev is due largely to the sum line of the 0.99-Mev and 1.32-Mev gamma rays. The coincidence of these gamma rays is consistent with the decay scheme of V^{48}.[3] The weak peak at 2.23-Mev reported by several workers[8–10] was obscured by the 2.32-Mev sum line. Gamma spectra of Cr^{48} taken 2 hours after separation of vanadium and after an interval of 2 days are shown in Fig. 1.

The half-life of Cr^{48} was determined by means of the integrating scintillation counter. The result of these measurements is shown in Fig. 2. The half-life of 15.8 days for V^{48} is in close agreement with the half-life reported for this nuclide by Walke.[11] The half-life of Cr^{48} determined by these measurements is 24 ± 1.0 hours.

DECAY SCHEMES OF Cr^{48} AND V^{48}

The decay scheme for Cr^{48} must involve an energy level scheme in V^{48} which will permit the following: (1) an orbital electron capture to one of the excited states of V^{48}; (2) a coincidence between the 118-kev and 307-kev gamma rays; (3) very similar intensities in the 118-kev and 307-kev gamma rays.

It is highly probable that the decay of Cr^{48} to V^{48} is an allowed transition. In the first place, the parities of

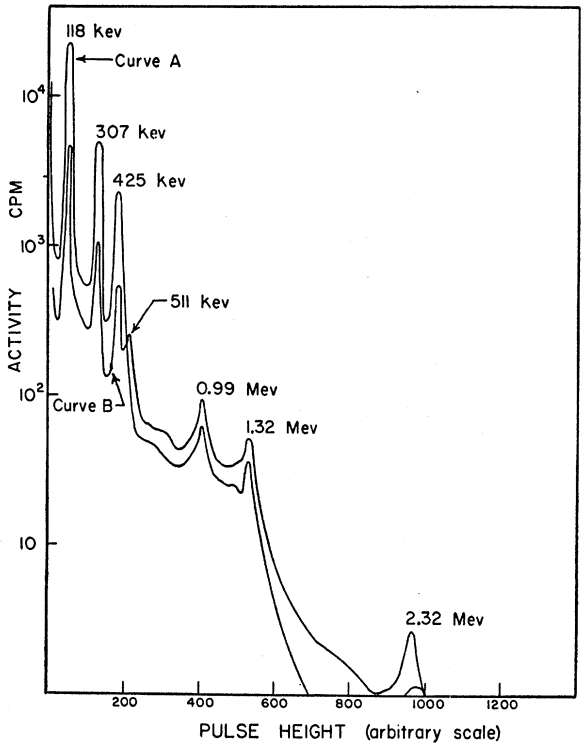

FIG. 1. The gamma spectra of Cr^{48} showing growth of V^{48} gamma rays. Curve *A* shows spectrum taken 2 hours after separation of vanadium; curve *B* shows spectrum taken 2 days after separation of vanadium.

[4] E. Fairstein, Rev. Sci. Instr. **22**, 76 (1951).
[5] W. C. Peacock and M. Deutsch, Phys. Rev. **69**, 306 (1946).
[6] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).
[7] Robinson, Ter-Pogossian, and Cook, Phys. Rev. **75**, 1099 (1949).
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[11] H. Walke, Phys. Rev. **52**, 777 (1937).

the ground state and low-lying excited states of V^{48} will be even, as long as these particles reflect shell particle levels. Any decay of Cr^{48} to a state of 2+ or higher would result in an *ft* value high enough that an energy for the decay would have to be excessively high in order to result in a 24-hour half-life. Even if such a high energy were available, there would certainly be competition between an orbital electron capture and positron emission. Since no positron is observed, a 0+ or 1+ spin and parity must be assigned to the state to which the Cr^{48} decays.

The fact that the intensities of the 118-kev and 307-kev gamma rays are very nearly the same makes it much more probable to assume that these gamma rays are very slightly internally converted than to assume the two gamma rays are highly internally converted and to the same extent. Assuming a small amount of internal conversion, from the experimental results on gamma ray intensities, it can be said that the internal conversion of these gamma rays will be at most 5 percent. If the α_K is small, then the *K*-shell internal conversion coefficients of Rose *et al.*[12] indicate that the 118-kev gamma ray can only be an *E*1 or *M*1 transition. Because of the even parity one is led to expect for the low-lying excited states of V^{48}, the 118-kev gamma ray can only be assigned as an *M*1 transition.[13] Also, if the α_K is small, the transition possibilities for the 307-kev gamma ray can only be *E*1, *E*2, *M*1, *M*2, and *M*3. The even parity to be expected in low-lying excited states of V^{48} rules out *E*1 and *M*2. Accordingly, the 307-kev gamma ray should be *E*2, *M*1, or *M*3. The possibilities for the decay of Cr^{48} are shown in Fig. 3.

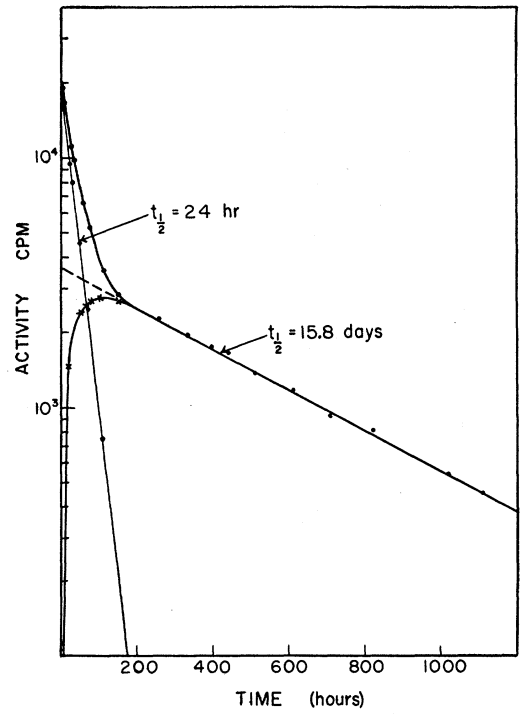

FIG. 2. The decay curve of Cr^{48} showing the growth of V^{48} in the nonequilibrium parent-daughter genetic relationship.

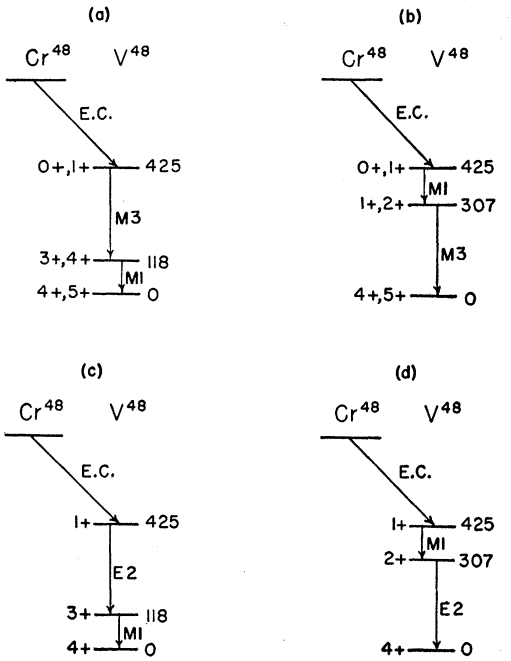

FIG. 3. Various assignments of the spins and parities of the V^{48} daughter in the Cr^{48} decay.

Recent work by van Lieshout, Greenberg, and Wu[14] has indicated the α_K for the 118-kev gamma ray is 2×10^{-2} and that for the 307-kev gamma ray is 0.6×10^{-2}. They correlated these values with the assignment of the 118-kev gamma ray as *M*1 and the 307-kev gamma ray as *E*2. The decay of Cr^{48} is thereby limited to Fig. 3(c) or (d). Some indication as to which of these two schemes actually represent the decay of Cr^{48} might be found by comparing the decay of Cr^{48} with the decay of nuclides one alpha particle on either side of Cr^{48}. Unfortunately, Fe^{52} has no gamma rays in its decay.[15] However, recent work on Ni^{56},[16] which is two alpha particles away, indicates that there is a 170-kev gamma ray from the first excited state of Co^{56} to the ground state of Co^{56}. In the decay of Ti^{44}, there is a single gamma ray of 160-kev from the first excited state of Sc^{44} to the ground state of Sc^{44}.[17] It is therefore our belief that the 118-kev gamma ray present in the decay of Cr^{48} represents the transition from the first excited state of V^{48} and that Fig. 3(c) represents the decay scheme of Cr^{48}.

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[13] M. Goldhaber and W. Sunyar, Phys. Rev. **83**, 960 (1951).
[14] van Lieshout, Greenberg, and Wu, paper presented at the New York Meeting of the American Physical Society, January, 1955 [Bull. Am. Phys. Soc. **30**, No. 1, 32 (1955)].
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[17] R. A. Sharp and R. M. Diamond, Phys. Rev. **93**, 358 (1954).

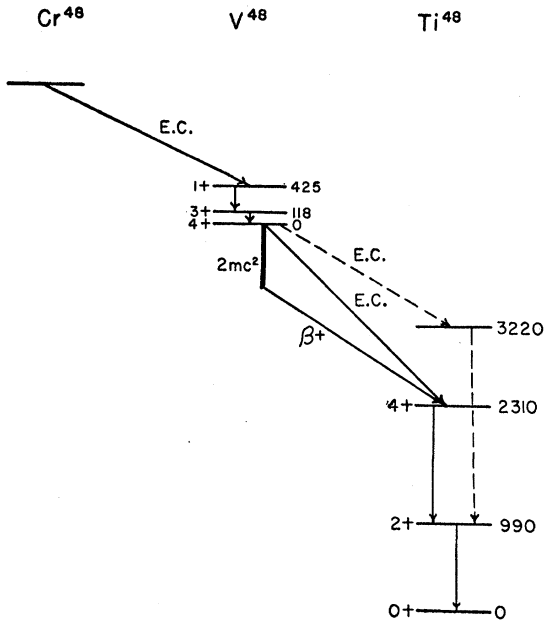

FIG. 4. A decay scheme for the isobaric triplet $Cr^{48}-V^{48}-Ti^{48}$.

Mayer, Moszkowski, and Nordheim[18] have found that the majority of allowed transitions have a log *ft* value of 5.0±0.3. However, log *ft* values for allowed transitions ranging from 4.5 to 5.9 were reported. No annihilation radiation in the gamma spectra of Cr^{48} was observed. However, due to nearby gamma rays it is only possible to set an upper limit of less than 2 percent positron emission for the decay. Using the upper limit of 2 percent positron emission and the tables of Feenberg and Trigg,[19] it is possible to calculate that the upper limit of the energy for the Cr^{48} to V^{48} transition is 1.28 Mev. From the tables of Moszkowski,[20] it is found that an energy of 1.28 Mev and a 24-hour half-life corresponds to a log *ft* value of 4.4. This is a relatively low log *ft* value even for an allowed transition. However, any higher log *ft* value would result in a positron to orbital electron capture ratio higher than we observed in our experiments. We therefore believe that the orbital electron capture energy for the Cr^{48} decay is approximately 1.30 Mev with a very low log *ft* value.

The decay of V^{48} is considered to be an allowed transition.[3] Angular correlation studies[10,21,22] of the 0.99-Mev and 1.32-Mev gamma rays indicate the spin and parity assignment of 0+, 2+, and 4+ for the ground and first two excited states of Ti^{48}.

The decay scheme of V^{48} is shown in Fig. 4. These results are in close agreement with the observation of Casson, Goodman, and Krohn.[3] The orbital electron capture from the ground state of V^{48} to the 3.22-Mev level of Ti^{48} and the 2.23-Mev gamma ray from the 3.22-Mev level of Ti^{48} to the 0.99-Mev level are shown as dotted lines in Fig. 4 since it is not possible to say from our data whether or not the 2.23-Mev gamma ray has been observed. The sum line at 2.32 Mev is slightly broader than one would normally expect and this could be atrributed to the very weak 2.23-Mev gamma-ray. It is true that the area under the 2.32-Mev sum line is approximately what one would expect for the sum line of the 0.99-Mev and 1.32-Mev gamma rays. However, the 2.23-Mev gamma ray is so weak (2 percent) that very little increase in the area under the sum line would be expected.

MASSES OF V^{48} AND CR^{48}

The mass of Ti^{48} has been reported as 47.96317±6.[23] The masses of V^{48} and Cr^{48} have been calculated on the basis of the decay scheme shown in Fig. 4. The transition energy of V^{48} is 4.02-Mev with an estimated error of ±0.028-Mev and the transition energy of Cr^{48} is 1.724-Mev with an estimated error of ±0.2-Mev. The conversion factor of 931.152[24] gives 47.96749±7 as the mass of V^{48} and 47.96934±22 as the mass of Cr^{48}. The mass of 47.96934±22 for Cr^{48} differs by 0.00087 ±22 mass units from the value obtained by Green[25] on the basis of empirical considerations.

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[18] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951).
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[21] Sterk, Wapstra, and Kropveld, Physica **19**, 135 (1953).
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