Spallation of Vanadium with 60-, 100-, 175-, and 240-Mev Protons*

CLARENCE G. HEININGER† AND EDWIN O. WIIG
Department of Chemistry, University of Rochester, Rochester, New York
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Cross sections have been determined for most of the observable radioactive nuclides produced in the bombardment of vanadium with 60-, 100-, 175-, and 240-Mev protons. The pattern of yields supports the cascade-evaporation theory. The number of nuclides produced in high yield is found to increase with increasing bombarding energy.

I. INTRODUCTION

IRRADIATION of an elemental target with high-energy particles results in a large variety of product nuclides. Several investigations have been made to determine the identity and quantity of these products, in the hope of understanding the reaction process. The results suggest a cascade-evaporation model.[1]

Cross sections for the production of several nuclides resulting from the bombardment of vanadium metal with 60-, 100-, 175-, and 240-Mev protons in the Rochester 130-inch synchrocyclotron have been measured by using radiochemical techniques. The results support the present general theory.

II. EXPERIMENTAL

The target material was vanadium metal, 99.6% pure, purchased from the Vanadium Corporation of America. Impurities were reported to be iron, 0.05%, silicon, 0.05%, aluminum, less than 0.05%, nitrogen and oxygen. Since natural vanadium[2] is 99.76% V^{51} and 0.24% V^{50}, the target can be considered to be pure V^{51} within the experimental error.

Most irradiations were made with a target consisting of irregular 0.1–1 mm diameter vanadium pellets wrapped tightly in an envelope of one mil aluminum foil. The final packing was shaped so as to compress most of the material at the leading edge. This gave an elliptical cross section with the long axis parallel to the beam direction. There was always a large proportion of smaller particles so that voids were reduced to a minimum. In a few 240-Mev bombardments a platinum tube with walls five mils thick was used. Several runs were carried out with two aluminum-wrapped targets mounted back to back. In all cases a thin target could be assumed.

The beam intensity was estimated from the yield of Na^{24} observed in aluminum foil attached to the target. Front and back foils arranged to take account of recoils agreed normally within a factor of less than 1.3. The cross sections assumed for the reaction $Al^{27}(p,3pn)Na^{24}$ were 14.0, 15.2, 13.1, and 11.7 millibarns at 60, 100, 175, and 240 Mev, respectively.[3]

After an hour's bombardment, the target metal was dissolved in either concentrated nitric acid or 6*N* nitric acid. Appropriate carriers in quantities of 10 to 50 mg were added. The vanadium target itself weighed from 60 to 220 mg in different runs. The several chemical fractions were removed by standard chemical methods,[4] and the separated material was mounted on glass cover disks cemented to stainless steel disks. The chemical recovery was determined by weighing or by subsequent solution of the sample followed by colorimetric analysis.

The individual isotopes were identified and their yields computed from data obtained with a helium-filled Geiger counter, a methane-flow beta proportional counter, a NaI(Tl) scintillation counter, and a survey beta-ray spectrometer.

In computing cross sections, back-scattering, self-scattering, self-absorption, air and window absorption, and geometry corrections were applied where necessary. For the unusual backing used, 1.23 and 1.22 were found to be appropriate negatron back-scattering factors for the beta proportional and G-M counters, respectively. Positron factors were 1.15 and 1.20, in the same order. Self-scattering and self-absorption corrections for beta particles were derived from the work of Baker and Katz[5]; correction factors for air and window absorption of electrons were taken from the results of Gleason, Taylor, and Tabern.[6] Air scattering and housing scattering were negligible.

Fortunately, the decay characteristics of the nuclides observed are sufficiently well known.[7] When necessary,

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† Now at Villanova University, Villanova, Pennsylvania.

[1] For example, see the review by D. H. Templeton, Ann. Rev. Nuclear Sci. 2, 93 (1953); and more recent papers by E. Belmont and J. M. Miller, Phys. Rev. 95, 1554 (1954); and by R. W. Fink and E. O. Wiig, Phys. Rev. 94, 1357 and 96, 185 (1954); Batzel, Miller, and Seaborg, Phys. Rev. 84, 671 (1951).

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[4] W. W. Meinke, Atomic Energy Commission Report AECD-2738 (UCRL-432) unpublished); A. A. Noyes and W. C. Bray, *A System of Qualitative Analysis for the Rare Elements* (The Macmillan Company, New York, 1948); F. P. Treadwell and W. T. Hall, *Analytical Chemistry, Vol. I. Qualitative Analysis* (John Wiley and Sons, Inc., New York, 1937).

[5] R. G. Baker and L. Katz, Nucleonics 11, No. 2, 14 (1953).

[6] Gleason, Taylor, and Tabern, Nucleonics 8, No. 5, 12 (1951).

[7] Most decay data were taken from Hollander, Perlman, and Seaborg, reference 2. Exceptions are B. Craseman and H. T. Easterday, Phys. Rev. 90, 1124 (1953), Cr^{48}; Cork, LeBlanc, Brice, and Nester, Phys. Rev. 92, 367 (1953), Sc^{47}, Ca^{47}; T. Lind-

electron-capture positron ratios were estimated from the curves published by Feenberg and Trigg.[8] Electron capture counting efficiencies were calculated from x-ray absorption coefficients. Their contribution was always small.

III. RESULTS

The nuclides observed and their formation cross sections in millibarns are listed in Table I. Data reported by Rudstam,[9] who bombarded vanadium with 187-Mev protons, are included for comparison. The agreement is satisfactory.

Because of the similarity of their decay properties, Sc^{43} and Sc^{44} could not be independently determined. Therefore, their combined cross section is reported. A somewhat similar problem exists with Cl^{34} and Cl^{38}. However, at 240 Mev, sufficient activity was present to permit separation with the beta-ray spectrometer. This result and Rudstam's data strongly suggest that the combined $Cl^{38,34}$ yield can be considered equal to the Cl^{38} yield at 100 and 60 Mev. This assumption is made.

The error placed on the data of Table I is the maximum experimentally observed deviation from the average. If no error is given, only one independent determination was made.

Two pertinent nuclides were not seen. Thirty-three minute V^{47} was missed because of the length of time that invariably elapsed before vanadium counting was begun. The doubtful nuclide, K^{44}, with a reported half-life of about twenty minutes would have been seen if it were formed in reasonable yield. In addition, Sc^{48} was observed only in 60-Mev runs. At other energies, it was probably obscured by the comparatively large yield of Sc^{47} and Sc^{44m}.

At all energies A^{41} was observed, but no yield could be calculated.

TABLE I. Yields of nuclides in millibarns.

Nuclide	60 Mev	100 Mev	175 Mev	187 Mev Rudstam	Mev 240
Cr^{49}	81 ±19	17 ±3	7.1	1.8	2.6 ±0.5
Cr^{48}	3.2 ±0.9	2.1 ±0.8	0.26	0.23	0.29±0.05
V^{48}	83 ±4	37 ±7	17 ±5	28	15 ±5
Ti^{45}	2.4 ±0.5	5.8 ±1.4	6.2 ±1.7	6.1	10 ±4
Sc^{47}	3.1 ±1.9	11 ±2	4.9 ±2.1	10	7.5 ±2.4
Sc^{46}	11 ±6	10 ±2	6.4 ±3.0	20	8.4 ±2.3
Sc^{44m}	···	10 ±4	4.6 ±2.7	8.4	8.0 ±2.5
$Sc^{43,44}$	0.08	20 ±6	7.3 ±4.0	13	12 ±4
Ca^{47}	0.011	0.09±0.02	0.07±0.04	0.11	0.14±0.05
Ca^{45}	0.33	1.0 ±0.4	1.0 ±0.4	3.6	1.7 ±0.7
K^{43}	0.6 ±0.2	0.7	1.5 ±0.6	2.5	4.1 ±0.9
K^{42}	0.19±0.15	2.6	3.6 ±1.2	3.9	7.0 ±1.2
Cl^{39}	0.0009	0.36±0.002	0.20±0.08	0.30	1.5 ±0.9
Cl^{38}	0.02±0.01	0.18±0.02	1.0 ±0.6	0.74	2.4 ±1.1
Cl^{34}	···	···	···	0.031	0.7 ±0.3
S^{35}	···	0.09	0.22±0.08	0.61	0.4 ±0.2
P^{33}	···	···	···	0.32	0.4
P^{32}	···	···	0.22±0.05	0.34	0.9 ±0.5
Mg^{28}	···	···	0.002	···	0.009

qvist and A. C. G. Mitchell, Phys. Rev. **95**, 444 (1954), K^{43}; R. K. Sheline and N. R. Johnson, Phys. Rev. **90**, 325 (1953) and M. Lindner, Phys. Rev. **91**, 642 (1953), Mg^{28}.

[8] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).

[9] G. Rudstam, Phil. Mag. **44**, 1131 (1953).

IV. DISCUSSION

The most general observation to be made from any spallation study in this energy region is that the most probable products are nuclides only a few mass units removed from the target. The yield of nuclides appreciably lighter than the target is lower and decreases with increasing mass difference. In the particular case of vanadium irradiated with 240-Mev protons, a plateau of similar cross section extends from V^{48} to K^{42}. For lower mass numbers the cross sections begin to decrease. As the bombarding energy is decreased, the plateau shortens, until, at 60 Mev, none is apparent, because of the decrease in the yields of the lighter nuclides.

Certain nuclides, such as Ca^{47} and Cr^{48}, which on mass considerations might be expected to be found on the cross-section plateau, are produced in significantly smaller yields. This, according to the well-known evaporation model,[1] is because of their position with respect to the valley of stability. Also, the yields of Ca^{45} are large compared to those of Ca^{47} because of the affect of this "governor" factor.[10]

Chromium, because it can be produced only when the bombarding proton remains in the struck nucleus and no proton emission occurs, presents a special case. The yields of Cr^{49} and Cr^{48} decrease with increasing incident proton energy, with the latter consistently produced in less quantity than Cr^{49}. This suggests that if sufficient energy for four particle emission is available, a proton is likely to be among those nucleons emitted. The high yield of V^{48} suggests the same thing. Its decrease in yield with increasing proton energy can be attributed to the larger number of available competing products at the higher energies.

The scandium isotopes and Ti^{45} show essentially constant yields in the 100-Mev to 240-Mev region. At 60 Mev the titanium and scandium cross sections show a noticeable drop with respect to that of Sc^{46}, which appears to remain constant. There might be some question as to the reliability of distinguishing between the Sc^{47} and Sc^{46} cross sections at 60 Mev. However, inspection of the original data indicates with certainty that the yield of Sc^{46} is significantly greater that that of Sc^{47} at 60 Mev. The general effect is probably due to the decrease in the energy available. Sc^{46} may be formed by a $(p,p\alpha n)$ reaction which would seem more probable than a $(p,p\alpha)$ reaction and would require less energy than a $(p,3p2n)$ reaction to yield Sc^{47}.

The observed calcium isotopes show an approximately constant yield in the 100- to 240-Mev region, with a drop at 60 Mev. The cross sections for K^{43} and for K^{42} drop steadily with decreasing proton energy, with that for K^{42} showing a sudden drop at 60 Mev. This apparent preference for K^{43} over K^{42} at the low

[10] K. S. LeCouteur, Proc. Phys. Soc. (London) **A63**, 259 (1950); H. Bethe and J. Ashkin, *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. 2, p. 141.

energy is probably a matter of energy and suggests significant contribution from reactions involving fragments such as the alpha particle or heavier ones.

The yields of the chlorine isotopes decrease more rapidly with energy in the 100 to 240-Mev region than do those for any other nuclides observed. The cross sections for S^{35} seem to decrease more gradually. Possibly a significant portion of the sulfur yield results from an unsymmetrical fission, while more of the chlorine yield is due to pure spallation. The mere fact that chlorine nuclides are produced from V^{51} with 60-Mev protons indicates that either heavy-particle emission or fission is possible. Probably both occur.

V. ACKNOWLEDGMENTS

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Internal Conversion Coefficients of Ba^{134}, V^{51}, and Tl^{203}†

Z. O'FRIEL* AND A. H. WEBER
Saint Louis University, St. Louis, Missouri
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The internal conversion coefficients of Ba^{134} (parent, Cs^{134}), V^{51} (parent, Cr^{51}) and Tl^{203} (parent, Hg^{203}) have been measured by the determination of the γ-ray yields from the Compton electron spectra produced in an external converter, employing the analysis of R. G. Thomas and T. Lauritsen and a single magnetic lens β-ray spectrometer. The Ba^{134} results involve the extension of the method to several γ-ray conversions measured simultaneously. V^{51} represents the application of the method to K-capture type of decay for which the direct area-under-curves method cannot be used. Tl^{203} requires the correction of the measured conversion spectrum for photoelectric conversions to obtain the pure Compton events. The values obtained for the total internal conversion coefficients are Ba^{134}: 569-kev γ ray, $(9.2\pm1.2)\times10^{-3}$; 605-kev γ ray, $(5.3\pm0.5)\times10^{-3}$; 796-kev γ ray, $(2.4\pm0.3)\times10^{-3}$; 1.367-Mev γ ray, $(0.49\pm.05)\times10^{-3}$; V^{51}: 325-kev γ ray, $(1.5\pm0.2)\times10^{-3}$; Tl^{203}: 279-kev γ ray, for K-shell $(1.5\pm0.1)\times10^{-1}$, and $(4.9\pm0.2)\times10^{-2}$ for the L-shell. In all cases the precision is the standard deviation. The results are in satisfactory agreement with other experimental values and with the predictions of Rose's tables.

THE Compton electron spectrum technique previously used[1] is here employed for measurement of the internal conversion coefficients of several more isotopes. Sources of both high and low activity were prepared using isotopes supplied by Oak Ridge National Laboratories. The single thin magnetic lens β-ray spectrometer[1] was employed for the measurements.

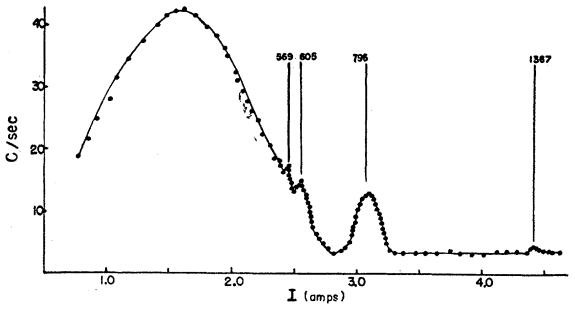

FIG. 1. Spectrometer data for Ba^{134} (parent, Cs^{134}). The raw data is plotted in counts per second *vs* magnet current (I) in amperes. Counting statistics are 7 percent or better probable error. The γ-ray energies are given in kev.

BARIUM-134

The nuclide Ba^{134} (parent, Cs^{134}) contains overlapping Compton spectra which were successfully separated. Figures 1–4 show the essential experimental data. The Compton electron spectra (Fig. 4) were conveniently separated using a log-log plot.[1] The conversion co-

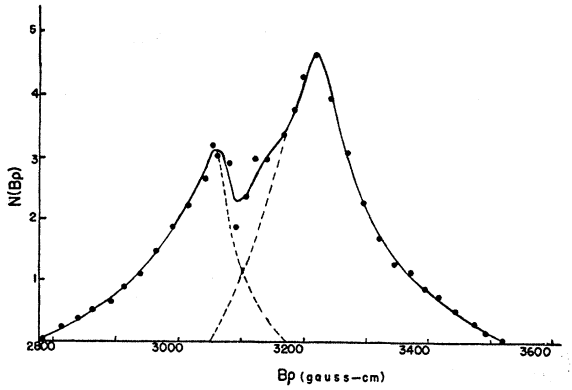

FIG. 2. Left, 569-kev internal conversion peak of Ba^{134} (parent, Cs^{134}); right, 605-kev internal conversion peak of Ba^{134} (parent, Cs^{134}). The beta spectrum has been subtracted; line shapes follow a line shape study upon the 796-kev Ba^{134} conversion line (Fig. 3, upper). Counting statistics are better than 3 percent probable error (except the last 2 points).

† Supported in initial phases by the U. S. Atomic Energy Commission.

* Now at Saint Bonaventure University, St. Bonaventure, New York.

[1] Sturcken, O'Friel, and Weber, Phys. Rev. 93, 1053 (1954).