Excitation Function for the $V^{51}(\gamma,\alpha)Sc^{47}$ Reaction*

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Yields of the $V^{51}(\gamma,\alpha)Sc^{47}$ reaction have been determined by measuring the Sc^{47} radioactivity produced in metallic vanadium targets irradiated with bremsstrahlung of maximum energy varying from 10.5 to 25 Mev. The reaction was not observed below 15.5 Mev because of the severe effect of the Coulomb barrier on the outgoing alpha particles. The excitation function derived from these measurements has a maximum value of 0.81 mb at 23 Mev, and the integrated cross section to 24.5 Mev is 4.3 Mev-mb. The observed excitation function agrees very well with one calculated from a statistical theory for the decay of a compound nucleus. This appears to be a general feature of (γ,α) reactions in medium-weight nuclei.

I. INTRODUCTION

THE amount of data available on photonuclear reactions in which alpha particles are emitted is quite limited. This is due to the fact that they are generally much less probable than reactions in which neutrons or protons are emitted. Although photoalpha reactions do not in general contribute much to the total photon absorption cross section, information about them may be very useful in learning more about the detailed features of photonuclear reactions.

Most of the previous measurements were designed to compare the yields of photoalpha reactions in several different target species for bremsstrahlung of one maximum energy.[1–3] The reactions were observed by measuring the radioactivity of an active product or by counting the emitted alpha particles with nuclear emulsions. These experiments do not yield information on the energy dependences of the photoalpha cross sections. Excitation functions have been measured for only a few cases in medium-weight and heavy elements[4–8]; they are for the (γ,α) reactions in Cu^{65}, Br^{81}, Rb^{87}, Ag^{109}, Sb^{121}, and Tl^{205} which were all determined by measuring the radioactivity of the product atoms. In addition to these studies, some information on photoalpha yields has been obtained as a by-product of emulsion studies of photoproton reactions.[9,10]

Heinrich *et al.*[2] showed in 1956 that the data available at that time on (γ,α) yields and excitation functions for medium-weight and heavy elements agreed fairly well with the yields and excitation functions that one would expect assuming compound nucleus formation and subsequent decay following a statistical theory. Direct interactions were apparently not important in explaining the main features of (γ,α) reactions. This work is part of a general program of investigating the details of (γ,α) excitation functions to see to what extent the apparent lack of direct interactions is a general feature of these reactions. The yield of the $V^{51}(\gamma,\alpha)Sc^{47}$ reaction has been previously measured by others for 21.5-,[3] 23-,[1] and 32-Mev[8] bremsstrahlung, but there has been no previous determination of the excitation function.

II. EXPERIMENTAL

Targets of metallic vanadium were irradiated with the external bremsstrahlung beam of the University of Illinois 22-Mev betatron. Since natural vanadium is 99.75% V^{51} and only 0.25% V^{50}, vanadium metal is essentially a V^{51} target.[11] The (γ,n) and (γ,p) products are both stable, so the only activity produced with bremsstrahlung of maximum energy up to 19 Mev is that of the (γ,α) product, Sc^{47}. Reactions involving emission of two light particles are possible above 19 Mev, but the resulting products are either stable or very long-lived and do not contribute much to the resulting activity. It is thus not necessary to separate the scandium product chemically in order to measure its radioactivity if the activity level produced from impurities in the sample can be kept low.

The experiments can be divided into two groups. The first is a determination of the shape of the activation curve (relative yield per mole-roentgen as a function of betatron energy). The second is an absolute measurement of the yield per mole-roentgen for one betatron operating energy (21.2 Mev). Ten-gram samples of granular vanadium (99.7% pure) were used in the relative yield measurements, and one-mil thick vanadium foils (99.7% pure) were used for the absolute yield determination.[12]

The beam was monitored with an aluminum-walled air-filled ionization chamber placed behind a two-inch

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[3] M. E. Toms and J. McElhinney, Phys. Rev. **111**, 561 (1958).
[4] Haslam, Smith, and Taylor, Phys. Rev. **84**, 840 (1951).
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[10] M. E. Toms and W. E. Stephens, Phys. Rev. **95**, 1209 (1954).
[11] Unless stated otherwise, all isotopic abundances and decay properties are taken from Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585 (1958).
[12] The granular vanadium was purchased from Fairmount Chemical Company, Incorporated, of New York and the vanadium foils from A. D. Mackay, Incorporated, of New York.

thick lead converter. The ionization current collected in the chamber was measured with a vibrating reed electrometer. Penfold[13] has shown that the ratio of the response of this monitor to the response of a Victoreen thimble behind 4 cm of Lucite is constant to better than one percent over the betatron energy range used in these irradiations. Thus, the vibrating reed electrometer readings can be used directly for calculating relative yields per mole-roentgen. For the absolute yield measurements at 21.2 Mev, the response of the monitoring system was calibrated in two different ways. In one method, the response of the ionization chamber was compared to the number of roentgens recorded by a Victoreen "r" thimble located in the center of an 8-cm cube of Lucite. In the other method, the response in ergs per square centimeter was calculated from the ionization current collected in the same ionization chamber without the lead converter but with the front aluminum wall extended to a thickness of 5 cm. The theoretical work of Flowers *et al.*[14] on the response of such an ionization chamber to bremsstrahlung of various energies was used as the basis for these calculations. The dose in roentgens behind 4 cm of Lucite was then calculated using the data of Johns *et al.*[15] on the response of a Victoreen thimble in Lucite. The two calibrations agreed to ten percent, the second method giving a lower dose than the first.

The energy calibration and the energy control of this betatron have recently been discussed by Axel and Fox[16] and by Schmitt and Duffield.[17] Their discussions apply to the operation of the betatron for this work, and these items will not be discussed further.

The Sc^{47} radioactivity was determined by counting its prominent 160-kev gamma ray with a scintillation spectrometer. A $1\frac{1}{2}$-inch diameter by $1\frac{1}{2}$-inch long NaI(Tl activated) crystal was used as the scintillator, and a Model 3300 Radiation Instrument Development Laboratory 100-channel pulse-height analyzer was used as the analyzing and recording device. The scintillation probe (containing the crystal, photomultiplier tube, and cathode-follower preamplifier) was mounted vertically so that the foils or 50-ml beakers containing the granular samples could be placed directly on the crystal housing. The probe unit and samples were shielded with two inches of lead.

The gamma-ray spectrum of a typical sample observed immediately after the bombardment showed peaks at 160 kev and 511 kev. The 511-kev radiation was short-lived, and after two or three hours was no longer an important feature of the spectrum. Thus, by waiting for several hours before counting, the 160-kev radiation from Sc^{47} could be measured with very little interference from other gamma rays. The 511-kev radiation arises from positron activity produced by (γ,n) reactions on impurities in the samples. The intensity of the 511-kev peak could be accounted for by the known impurities. The 160-kev peak decayed with a 3.4-day half-life in all cases in which its decay was followed. This half-life is consistent with the literature values for Sc^{47}.

In the absolute yield determination runs, several corrections had to be made to the counting data before the absolute yield per mole-roentgen could be calculated. The number of counts in the photopeak had to be corrected for the geometry of the system, the photopeak efficiency of the crystal, absorption in the sample and crystal housing, a spread source effect, and the abundance of the gamma ray in the decay scheme. The geometry was calculated assuming a point source. The photopeak efficiency was taken as the product of the total point-source efficiency for a $1\frac{1}{2}$- by $1\frac{1}{2}$-in. crystal as given by Stanford and Rivers[18] and an experimental peak to total ratio which Dillman[19] has measured for our system. Absorption in the thin sample foils was negligible; the correction for absorption in the crystal housing was taken from Dillman's work.[19] The fact that the sources were circular foils one inch in diameter and not point sources made a correction to the assumed point-source geometry and efficiency necessary. The spread source correction was determined experimentally by observing the change in the photopeak counting rate as a point source was moved across the face of the crystal and then calculating the average change for the area covered by the sample, taking into account the fact that the activity was not uniformly distributed across the foil because the beam intensity was not uniform. The magnitude of the spread source correction was five percent. Even though the abundance of the 160-kev gamma ray has not been directly measured, it can be inferred from the work of Graves and Suri.[20] They showed that the 160-kev gamma ray follows a beta group which is 60% abundant. They set an upper limit on the lifetime for emission of the gamma ray and concluded from it that the gamma transition was $M1$ in nature. Thus, the conversion coefficient should be negligibly small. So, the gamma-ray abundance was taken to be that of the beta group leading to it, 60%.

Some additional experiments were conducted to see to what extent Sc^{47} was being produced by (γ,p) reactions on Ti^{48} impurities in the target material. This could be a serious source of error at the lower energies even with just small amounts of titanium present. The decay of the 511-kev peak was followed in several

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[14] Flowers, Lawson, and Fossey, Proc. Phys. Soc. (London) **B65**, 286 (1952).
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[18] A. L. Stanford, Jr., and W. K. Rivers, Jr., Rev. Sci. Instr. **29**, 406 (1958).
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[20] W. E. Graves and S. K. Suri, Phys. Rev. **101**, 1368 (1956).

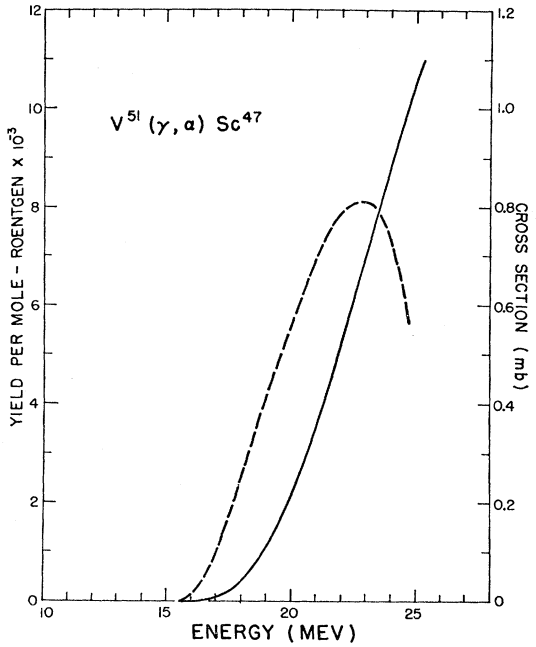

FIG. 1. Solid line—yield curve for the $V^{51}(\gamma,\alpha)Sc^{47}$ reaction (use scale on left; abscissa is the betatron operating energy). Dashed line—cross sections for the $V^{51}(\gamma,\alpha)Sc^{47}$ reaction (use scale on right; abscissa is the gamma-ray energy).

vanadium samples which had been bombarded with bremsstrahlung of different energies to set an upper limit on the amount of a 3.1-hour component in the annihilation radiation (3.1-hour Ti^{45} produced by a gamma-neutron reaction on Ti^{46} impurity). Several titanium samples were then irradiated at various betatron energies and a ratio of the amounts of the 3.1-hour 511-kev radiation and the 3.4-day 160-kev radiation was determined in each case. These two sets of data were then used to determine the maximum contribution from titanium impurities to the 160-kev peak observed in the vanadium samples. The maximum contribution of titanium impurities was less than one percent for energies above 18 Mev and increased below 18 Mev to ten percent at the lowest energies at which the 160-kev peak was observed. Since these maximum contributions were about the same as the counting-data uncertainties and since they represented conservative maximum contributions, no corrections were made.

III. RESULTS

The activation curve is shown in Fig. 1 where the number of reactions per mole-roentgen is plotted against the bremsstrahlung maximum energy. The apparent threshold is at 15.5 Mev which is well above the mass threshold of 10.3 Mev[21] because of the severe effect of the Coulomb barrier on low-energy alpha particles. A total of 67 irradiations were made between 10.5 and 25 Mev to define the shape of the activation curve. The ordinate scale was determined by measuring the absolute yield with 21.2-Mev bremsstrahlung. The average of four runs was $(4.0\pm0.4)\times10^3$ reactions per mole-roentgen, the indicated uncertainty accounting only for counting statistics and the uncertainty in the total dose. The yield with 21.5-Mev bremsstrahlung is 4.3×10^3 reactions per mole-roentgen which agrees well with $(4.2\pm1.5)\times10^3$ alphas per mole-roentgen reported by Toms and McElhinney[3] from an emulsion experiment. The yield at 23 Mev is 7.0×10^3 reactions per mole-roentgen which is to be compared with the value of 9×10^3 reported by Greenberg *et al.*[1] from a residual activity measurement.

The photon difference method[22] was used to extract cross sections from the smoothed activation curve. The resulting excitation function is also shown in Fig. 1. The cross section reaches a maximum value of 0.81 mb at 23 Mev. The integrated cross section to 24.5 Mev is 4.3 ± 0.4 Mev-mb. Erdos *et al.*[8] have estimated the integrated cross section to 32 Mev to be 5.5 ± 2 Mev-mb which is in good agreement with our value. Their estimate of the integrated cross section was made on the basis of the yield obtained with 32-Mev bremsstrahlung.

IV. DISCUSSION

A comparison of the observed cross sections with those calculated on the basis of compound nucleus formation followed by evaporation of alpha particles is

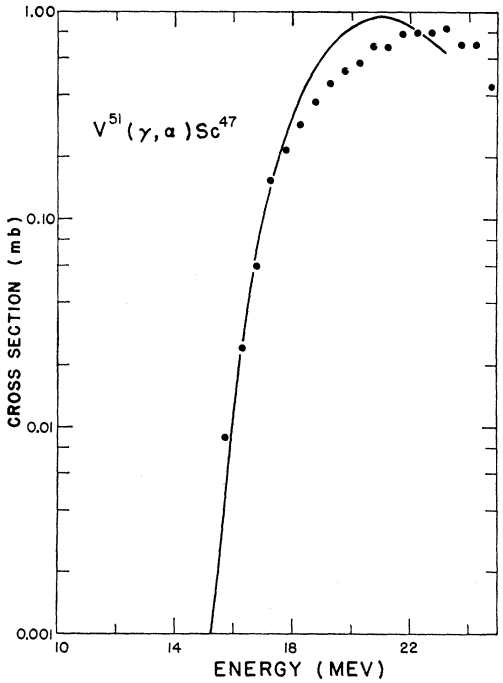

FIG. 2. Comparison of observed and theoretical cross sections for the $V^{51}(\gamma,\alpha)Sc^{47}$ reaction. The solid line represents the theoretical excitation function, and the points are the experimental cross sections derived from the yield curve by the photon difference method.

[21] C. F Giese and J. L. Benson, Phys. Rev. **110**, 712 (1958).

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shown in Fig. 2. The theoretical cross sections were obtained by calculating the ratio of the (γ,α) and (γ, total neutron) cross sections from a statistical theory for compound nucleus decay[23] and multiplying this ratio by the experimental (γ, total neutron) cross section obtained by Goldemberg and Katz.[24] For photon energies below the threshold for the emission of two particles, the (γ, total neutron) cross section is just the (γ,n) cross section. The ratio of the (γ,α) and (γ,n) cross sections is given by

$$\frac{\sigma(\gamma,\alpha)}{\sigma(\gamma,n)}=\frac{(2S_\alpha+1)m_\alpha\int_0^{E_{\alpha\,\max}}E_\alpha\sigma_c(E_\alpha)W_{47}(E_{\alpha\,\max}-E_\alpha)dE_\alpha}{(2S_n+1)m_n\int_0^{E_{n\,\max}}E_n\sigma_c(E_n)W_{50}(E_{n\,\max}-E_n)dE_n}. \tag{1}$$

In the numerator, S_α, m_α, and E_α are the spin, mass, and energy of an alpha particle. The $\sigma_c(E_\alpha)$ is the cross section for the inverse process, capture of an alpha particle of energy E by the residual nucleus. $W_{47}(E_{\alpha\,\max}-E_\alpha)$ is the level density of the residual nucleus at an excitation energy of $(E_{\alpha\,\max}-E_\alpha)$. The maximum alpha-particle energy is determined by the compound nucleus excitation energy (assumed to be the same as the energy of the incoming gamma ray) and the threshold for the (γ,α) reaction. The symbols in the denominator where neutron emission is considered have analogous meanings. The values for the capture cross sections were taken from the graphs and tables of Blatt and Weisskopf[23] for a nuclear radius parameter, r_0, of 1.5×10^{-13} cm. The level densities used were of the form $W(E)=C\exp[(aE)^{\frac{1}{2}}]$, where E is the excitation energy of the residual nucleus. The formula $a=1.6(A-40)^{\frac{1}{2}}$ was used for the parameter a. Using this formula for a, Byerly and Stephens[9] were able to get a reasonable fit for the energy distribution of photoneutrons from copper. Since we calculated a ratio of cross sections, the magnitudes of the C's used is not important. They were set proportional to 2 for V^{50} (an odd-odd nucleus) and 1 for Sc^{47} (an odd-even nucleus).[2] The ratio in Eq. (1) was evaluated for several different compound-nucleus excitation energies. For excitation energies above the $(\gamma,2n)$, (γ,pn), $(\gamma,\alpha n)$, and $(\gamma,\alpha p)$ thresholds, Eq. (1) had to be modified somewhat to account for the contribution of secondary reactions to the total neutron cross section and the effect of secondary reactions on the (γ,α) cross section. In calculating the effects of the secondary reactions, it was assumed that a particle would be emitted whenever it was energetically possible to do so; i.e., any competition from de-excitation by gamma-ray emission was neglected.

It is apparent in Fig. 2 that the calculations based on the compound nucleus mechanism agree reasonably well with the experimental values over the entire range of cross sections measured in this experiment. It should be pointed out that it is possible to fit the data reasonably well by using other choices for the level-density parameters. For example, doubling a and taking the ratio of C (odd-even) to C (odd-odd) to be 0.85 gives a somewhat better fit than that seen in Fig. 2. However, any attempt to use these data to make conclusions about the level-density parameters is probably not warranted as there is some uncertainty in the experimental (γ, total neutron) excitation function. Nathans and Halpern[25] have also measured the photoneutron yield from vanadium and report somewhat lower cross sections between 14 and 19 Mev than Goldemberg and Katz.[24] Also, there is undoubtedly some direct reaction contribution to the observed total neutron emission cross section which would have to be considered before taking seriously any conclusions about the level-density parameters.

Heinrich *et al.*[2] have made similar calculations to compare the (γ,α) excitation functions for Cu^{65}, Br^{81}, Rb^{87}, and Ag^{109} with those that one would expect from the statistical theory. In general, the agreement seems to be about as good as in this case. The most significant difference between the results of this work and the other data is that the reaction in V^{51} has been observed at least two Mev closer to the mass threshold than in the other cases. This is due mainly to the lower Coulomb barrier in vanadium and the fact that the mass threshold is higher (closer to the giant resonance region) than in the other cases.

Additional evidence for compound nucleus formation in photoalpha reactions has been reported by Toms and McElhinney[3] from an emulsion experiment. They have measured the yield and the energy distribution of photoalpha particles from copper irradiated with 22-Mev bremsstrahlung. Both the yield and the energy distribution can be explained in terms of evaporation from a compound nucleus. Toms and McElhinney[3] also measured the yields of alpha particles from targets of several medium-weight elements for 21.5-Mev bremsstrahlung. The yield from vanadium was a factor of five or more smaller than the yields from other nearby elements (iron, cobalt, nickel, copper, and zinc). This yield variation can also be explained in terms of the statistical theory. The factor that is most responsible

[23] J. M. Blatt and V. S. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. VIII.

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[25] R. Nathans and J. Halpern, Phys. Rev. **93**, 437 (1954).

for the lower yield from vanadium is that the reaction threshold is much higher for V^{51} than for the other cases. For example, the $V^{51}(\gamma,\alpha)Sc^{47}$ threshold is 10.3 Mev[21] while the $Cu^{65}(\gamma,\alpha)Co^{61}$ threshold is 6.3 Mev.[8] This means that for a given compound-nucleus excitation energy, the integral in the numerator of Eq. (1) will be evaluated over a smaller energy range (involving lower capture cross sections and level densities) for V^{51} than for the other cases, accounting for the observed yield differences.

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Measurement of Spin Polarization by Nuclear Scattering*†

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Accurate measurements of differential cross sections for elastic scattering of protons from He^4 and C^{12}, and of He^3 from He^4 in the energy range 2–6 Mev have been phase-shift analyzed and the expected spin polarization of scattered particles calculated. The results, plotted as contours of equal spin polarization *versus* energy and angle, should be useful in accurate measurements of spin polarization and in addition show a number of rather striking complexities due to interference effects.

INTRODUCTION

BECAUSE of the recognized importance of spin-orbit and spin-spin contributions to nuclear forces it is important to develop precise experimental techniques for measuring the spin polarization of particles emitted from nuclear reactions. This paper is concerned with a systematic study of possible techniques to measure spin polarization of charged spin-$\frac{1}{2}$ particles by nuclear scattering from spin-zero nuclei. It seems important to develop methods for making polarization measurements more precise and absolute; and it may be hoped that elastic scattering from different target materials may make a wider range of experiments possible both as regards intensity and the ease of target preparation.

We have studied the elastic scattering of spin-$\frac{1}{2}$ particles from spin-zero nuclei, especially for those cases where the only available channel is elastic scattering. This problem, fortunately, may be analyzed exactly, in the sense that the determination of precise differential cross sections at a number of angles and over a continuous range of energies (starting at low energies) usually allows a unique fit to all the data in terms of a few anomalous nuclear phase shifts corresponding to the nuclear scattering of low angular momentum partial waves. The wave function, f_c, for coherent scattering (no change of the projectile spin), and the incoherent (change of spin) wave function, f_i, are then determined for all distances outside the nucleus and the spin polarization effects are calculable.[1] The polarization along x, for scattering in the y-z plane, is

$$P_x(k,\theta)=\frac{2|f_i|\times|f_c|\sin[\arg f_c-\arg f_i]}{|f_c|^2+|f_i|^2},$$

and the notation is the same as in reference 1. Thus

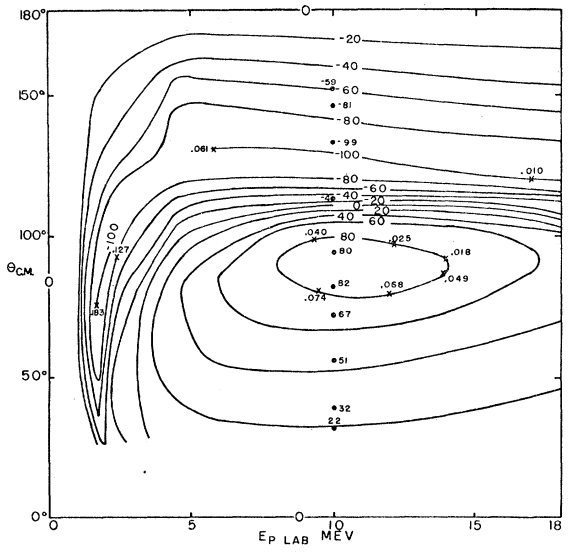

FIG. 1. H+He^4 scattering. Contour map of percent spin polarization along x for elastic scattering in the z-y plane. Contours of equal spin polarization are plotted *vs* the laboratory energy and the cm angle. The solid circles indicate experimental points of L. Rosen and J. E. Brolley [Phys. Rev. **107**, 1454 (1957)]. Each x and associated number gives cross section values in barns/steradian.

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† The contents of this work were presented at the Paris Conference, July, 1958, and published in Compt. rend. congr. intern. phys. Nucléaire (Dunod, Paris, 1959).
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