and at less than 15° for 230-kev electrons; at 100 Mev we can expect the angle within which screening is important to be very small.

Radiative effects in the scattering as predicted by quantum electrodynamics may be large enough to mask the effect due to non-uniform charge density or to a slight change in the radius of the nucleus. Calculations for a pure Coulomb field based on Schwinger's[12] results would indicate this to be the case. However, since these results are based on the Born approximation, and give the deviation due to radiative effects from the Born approximation expression for the scattering, not from the actual scattering, their reliability in the case of heavy elements is doubtful. The order of magnitude given by them is probably still correct.

In our calculation, where we have assumed a continuous charge distribution within the nucleus, we have obtained a result which should approximate rather well the coherent elastic scattering of the electrons by the Z protons in the nucleus. The incoherent scattering[13] by the individual protons we expect to be much smaller than the coherent scattering by the nucleus as a whole. If we think of each proton as contributing to the entire scattering amplitude, which is proportional to Ze^2, an amount proportional to e^2, then the coherent scattering will be of the order of Z times larger than the incoherent scattering.

I would like to express my gratitude to Professor L. I. Schiff for suggesting this problem and for advice and many discussions. I would also like to thank Mrs. Sabra Driscoll for her excellent aid with the computations.

[12] J. Schwinger, Phys. Rev. **75**, 898 (1949).

[13] L. I. Schiff, Microwave Lab., Stanford University Report No. 102 (November, 1949, unpublished).

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The Disintegration of Ti^{45}

M. TER-POGOSSIAN, C. S. COOK, F. T. PORTER, K. H. MORGANSTERN, AND J. HUDIS*
Physics Department, Washington University,† St. Louis, Missouri

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The positron and photo-electron spectra of 3.05-hr. Ti^{45} have been studied. At least 96 percent of the positron transitions are to the ground state of Sc^{45} with a maximum positron kinetic energy of 1.022 ± 0.01 Mev. Less than four percent of the positron transitions are to an excited level of Sc^{45} at 450 kev. In addition, certain longer-lived activities are found in the chemically separated titanium fraction produced by both deuteron and proton bombardment of scandium oxide. Two of the activities are shown to be P^{32} and Sc^{46} impurities.

I. INTRODUCTION

BOTH deuteron and proton bombardment of scandium have been reported[1] to result in a radioactive isotope of titanium having a half-life of 3.05 hr. This activity has been assigned to the isotope Ti^{45}. Its positron spectrum, as obtained from a histogram resulting from cloud-chamber studies, has indicated an end-point energy of about 1.2 Mev.

Subsequent work[2] has confirmed the half-life originally reported for this isotope.

In the most recent table of radioactive isotopes by Seaborg and Perlman[3] a private communication is quoted from Dessauer indicating the presence of a second longer-lived isotope of titanium which can be produced by proton bombardment of scandium, and which is also assigned to the isotope Ti^{45}. In further correspondence with the present authors, Dessauer[4] has indicated that the 21-day half-life reported in the compilation of Seaborg and Perlman[3] is a typographical error. What he actually found in the titanium fraction after irradiating scandium with 7-Mev protons were two half-lives, 3.1 hr. and 3.1 days. At some time the 3.1 days was erroneously copied as 21 days.

It would thus appear that a beta-spectrometer study of the radioactive isotopes of titanium produced by either deuteron or proton bombardment of scandium could perhaps lead to interesting results.

In addition to the study of the disintegration schemes, the shape of the positron spectrum can also be of interest. Using the half-life and energy values reported in the literature Konopinski[5] has calculated a ft-value for the 3.05-hr. Ti^{45} corresponding to an allowed transition. Most recent evidence [6–9] indicates that simple allowed spectra should produce linear Fermi-Kurie plots. Since no gamma-rays had been reported,[1] it was

* Chemistry Department, Washington University.
† Assisted by the joint program of the ONR and AEC.
[1] Allen, Pool, Kurbatov, and Quill, Phys. Rev. **60**, 425 (1941).
[2] Huber, Lienhard, and Wäffler, Helv. Phys. Acta. **16**, 226 (1943); **17**, 195 (1944).
[3] G. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585 (1948).
[4] G. Dessauer (private communication).
[5] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).
[6] Langer, Moffat, and Price, Phys. Rev. **76**, 1725 (1949).
[7] G. E. Owen and C. S. Cook, Phys. Rev. **76**, 1726 (1949).
[8] Lidofsky, Macklin, and Wu, Phys. Rev. **76**, 1888 (1949).
[9] Langer, Motz, and Price, Phys. Rev. **77**, 798 (1950).

assumed for the purpose of this study that the disintegration of the 3.05-hr. Ti^{45} most likely follows a single transition from the ground state of Ti^{45} to the ground state of Sc^{45}. This transition should thus yield a linear F-K plot.

Very recent work at Illinois,[10] however, has indicated the existence of two gamma-rays in the 3.05-hr. Ti^{45}. Since these two are reported as having different intensities, it appears that the assumption of a simple spectrum is probably not correct. The group at Illinois have also found activities in the titanium fraction other than the 3-hr. activity, in this case the reported half-lives being approximately 3.5 and in excess of 21 days.

II. APPARATUS

For the study of the beta- and gamma-spectra in the present investigation either a magnetic spectrometer or a cloud chamber were used, depending upon the relative activity of the source to be studied.

The magnetic spectrometer is of the uniform-field semicircular type and has a beta-particle radius of curvature of 14 cm. It has been described in some detail in previous papers.[11] For this reason no lengthy discussion of the spectrometer will be given here.

The cloud chamber[12] is of the standard type for nuclear work. The chamber has a diameter of 25 cm. It is normally operated with a filling mixture consisting of hydrogen and alcohol vapor. Chamber expansion and camera recording of the ion tracks are performed automatically at given intervals in order that a continuous record of any decaying radiations may be made.

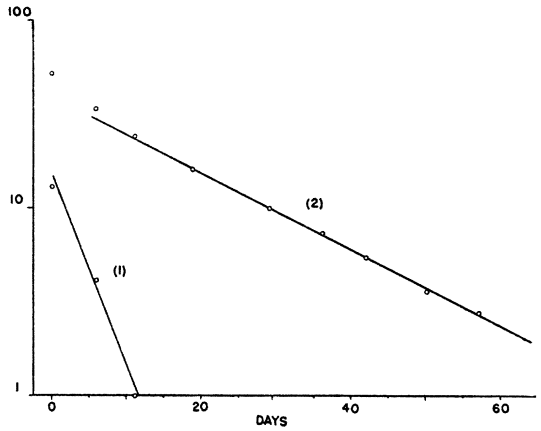

FIG. 1. Decay of titanium fraction beginning three days after completion of cyclotron bombardment. Curve (2) gives a 14-day half-life. Curve (1) gives a 3.4-day half-life produced by the difference between the earlier experimental points and the straight-line extrapolation of the 14-day half-life.

III. PREPARATION OF SOURCES

The active titanium has been produced through bombardment of scandium oxide with both 10-Mev deuterons and 5-Mev protons in the Washington University cyclotron.

The scandium oxide used was chemically pure according to Fairmount Chemical Company, the suppliers. In order to check the purity of the target material two samples were kindly analyzed spectroscopically for us by Dr. Keller at the Mallinckrodt Chemical Works. Both samples were found to be identical with major impurities being boron (impurity of 0.4 percent) and silicon (impurity 0.3 percent). Other impurities listed were calcium (about 0.1 percent), iron (about 0.05 percent), rubidium (less than 0.05 percent, if any), strontium (less than 0.10 percent, if any), and titanium (less than 0.01 percent, if any).

Following the bombardment the titanium was separated in accordance with the procedure outlined by the Ohio State group.[1] After the ScF_3 had been precipitated in the final step outlined by this group, leaving the titanium in solution, inactive $Sc(NO_3)_3$ was added to the solution and the scandium was again precipitated as ScF_3. The purpose of the last step is to dilute any scandium activity which might remain in solution after the first precipitation of ScF_3. Assuming that a small amount of scandium remains, the final dilution will leave most of the scandium in solution as inactive scandium.

In order to prepare beta-sources, the titanium solution was evaporated until only a small amount of liquid remained. A few drops of this solution was then deposited onto a backing consisting of a double layer of zapon, covered by a layer of *LC* 600. Zapon was used to provide mechanical strength, while the layer of *LC* 600

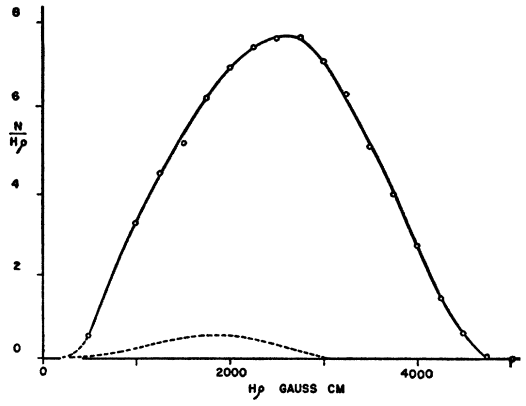

FIG. 2. Momentum distribution of the positrons from Ti^{45}. The dotted curve is the low intensity, low energy group of positrons obtained by subtracting the straight-line extrapolation of the F-K plot from the experimentally determined points.

[10] Kubitschek, Longacre, and Goldhaber, Phys. Rev. **77**, 742 (1950); A. Longacre (private communication); see *Note added in proof* at end of article.

[11] Ter-Pogossian, Cook, Goddard, and Robinson, Phys. Rev. **76**, 909 (1949) give the latest changes in this spectrometer. The basic operating principles of the electronic constant current supply mentioned in that paper are now described in some detail by Elmore and Sands, *Electronics, Experimental Techniques* (McGraw-Hill Book Company, Inc., New York, 1949), National Nuclear Energy Series, pp. 390–393, in addition to the relatively inaccessible AEC document referred to in the previous paper.

[12] K. H. Morganstern and K. P. Wolf, Phys. Rev. **76**, 1261 (1949).

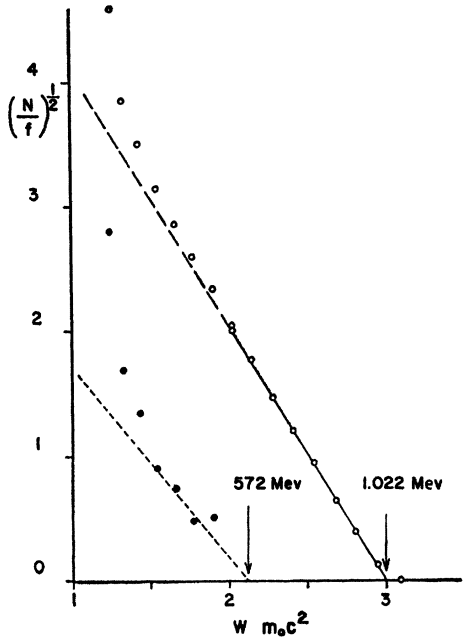

FIG. 3. F-K plot of the positrons from Ti^{45}. Open circles are experimentally determined points. Closed circles are values obtained after subtraction of the straight-line portion of the plot.

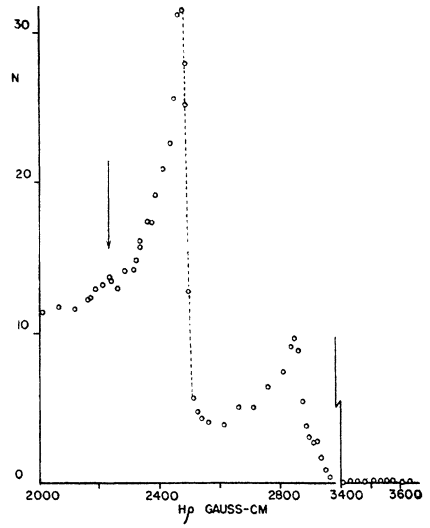

FIG. 4. Photo-electron spectrum of Ti^{45} electromagnetic radiation as produced in a 50-mg/cm² uranium radiator. In addition to the strong annihilation radiation photo-electron lines a small bump characteristic of a possible photo-electron from a gamma-ray of energy 450 kev is indicated by the arrow. The photo-electrons from the gamma-radiation reported by Kubitschek, Longacre, and Goldhaber (see reference 10) could not be found. They should have appeared at 2370 gauss-cm and 3600 gauss-cm.

provided an acid resistant layer,[13] this being necessary, since the titanium existed in a strongly acid solution. After deposition on the zapon-*LC* 600 backing the solution was brought to dryness under a heat lamp.

For the study of the gamma-ray spectrum of Ti^{45}, the concentrated solution prepared from the chemical separation was brought to dryness and the resulting powder was packed into a brass container on the face of which was cemented a strip of 50-mg/cm² uranium, 3 mm in width, which acted as a radiator of photo-electrons. This is the same procedure as was followed previously[11] for the study of secondary electron spectra resulting from gamma-radiation.

Cloud-chamber sources were prepared by deposition of a few drops of the titanium solution into a slight indentation on a special brass source holder for the cloud chamber. Subsequent drying of the source was made by means of a heat lamp. In order to hold the source in place a thin cover of "Krylon" plastic spray was applied as a covering for the source.

IV. RESULTS

A. Half-Life Studies

According to the measurements of the half-life of the activities produced, three isotopes appear to be present in the titanium fraction. These have half-lives of 3.05 hr., 3.4 days, and 14 days. The 3.05-hr. half-life activity has by far the strongest intensity and is the fairly well established Ti^{45} previously reported.[1]

A curve showing the decay of the longer-lived activities is given in Fig. 1. Curve (2) shows the results of the initial data, as a semilog plot. The straight-line section corresponds to a half-life of 14 days. When this straight line is extrapolated to earlier times, a subsequent subtraction from the original data leads to a second group, indicated by (1), which gives a resulting 3.4-day half-life. The relative efficiency of the counter was determined for each experimental point on the curve by means of a uranium standard source. Using a fixed standard geometry throughout the measurement, each experimental point was determined by measuring successive counting rates given by the sources in the following order: the uranium standard, the unknown sample, the uranium standard again, and finally the unknown sample again. In order to insure no change in geometry, sources were sealed in plastic containers which could always be replaced in the same position relative to the G-M counter used for these measurements. A thin mica-window counter was used in order to obtain both beta- and gamma-radiation from the unknown sample.

B. The Positron Spectrum of the 3.05-Hr. Activity

The positrons from the 3.05-hr. half-life Ti^{45} gave a momentum distribution as indicated in Fig. 2. The resulting F-K plot is indicated in Fig. 3. Extrapolation of the straight-line portion of the F-K plot in the higher energy region gives an end-point energy of $W_0=3.0m_0c^2$ ($E_0=1.022\pm0.01$ Mev). The experimental points, however, deviate from this straight line in the region of $W=2m_0c^2$. Subtraction of this straight-line section from the experimental points leads to a pos-

[13] L. M. Langer, Rev. Sci. Inst. **20**, 216 (1949).

sible second group, indicated by the solid circles in Fig. 3. These subtracted points do not form a good linear F-K plot. However, a straight line through the general vicinity of the higher energy points leads to the dotted line of Fig. 3. This gives the dotted line distribution of Fig. 2. The extrapolated end point is approximately $W_0=2.1\pm0.1m_0c^2$ ($E_0=0.57$ Mev). Comparison of areas leads to a relative abundance for this lower energy group of about four percent of the total number of positrons.

C. Photo-Electron Spectrum

The difference in the end-point energies of the two positron groups mentioned in Section IV-B is approximately 450 kev. This is rather close to the energy of one of the gamma-rays reported by the Illinois group.[10] Since this group had reported gamma-rays at 480 and 800 kev, searches were made for these gamma-rays.

Photo-electron sources prepared as described in Section III were studied in the region of energy where one would expect the K-shell photo-electrons from the uranium radiator for these two gamma-rays. The results of this search are shown in Fig. 4. The plot is divided into two parts, one covering the momentum range 2000 to 3000 gauss-cm and the other momentum range 3400 to 3650 gauss-cm. The K-shell photo-electron line from uranium for a gamma-ray having 480 kev energy should appear at 2370 gauss-cm and one for a gamma-ray having 800 kev energy should appear at 3600 gauss-cm. Within experimental limitations, and except for the photo-electron lines produced by the annihilation radiation, at only one place in the spectrum did a repeatable rise and fall occur which might possibly be explained as a photo-electron line. This is indicated by the arrow in Fig. 4. This was found on both gamma-ray sources which were used, the two sources having been prepared at different times from two different containers of scandium oxide. The intensity of this line is, however, only about two or three percent that of the annihilation line, and its momentum corresponds to a gamma-ray energy of 450 ± 10 kev. This intensity is somewhat lower than that reported by the Illinois group for their 480-kev gamma-ray. No indication of an 800-kev gamma-ray could be found.

D. Cloud-Chamber Studies

Cloud-chamber photographs indicated initially a very strong positron activity which died away with the known 3-hr. half-life for Ti^{45}. All photographs taken after sufficient time had elapsed for this 3-hr. activity to become negligible revealed an almost complete absence of any positrons. Negatrons, however, remained in appreciable quantities, though small compared with the original positron activity.

This means that the long-lived activity must be either an impurity emitting negative beta-particles or else a long-lived isomeric state of Sc^{45} following the

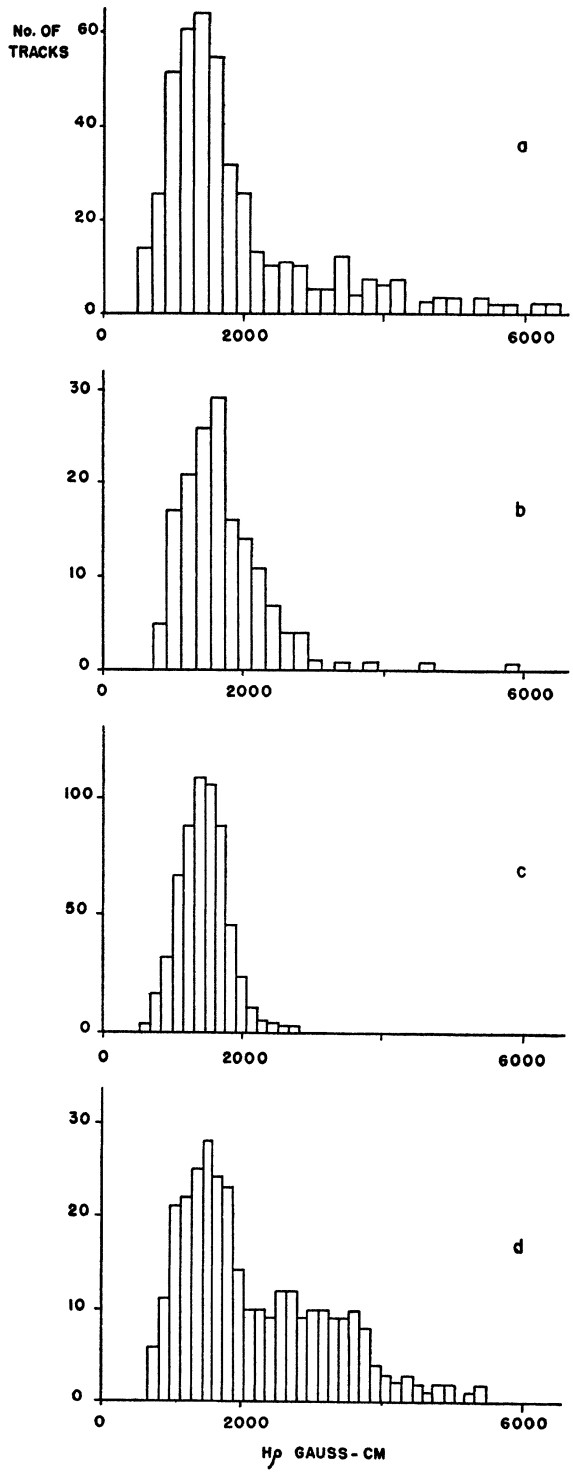

FIG. 5. Cloud-chamber studies of the particle radiations from the chemically separated fractions of the scandium oxide target. (a) The negatron spectrum of the titanium fraction a few days after the target had been removed from the cyclotron; (b) the same negatron spectrum approximately 1½ months later; (c) the scandium fraction a few days after the cyclotron bombardment was completed; (d) the phosphorus fraction a few days after the cyclotron bombardment was complete. Further discussion of the significance of these histograms is given in the text (Section IV–D).

decay of Ti^{45}, this state emitting internal conversion electrons. Titanium activities produced by deuteron bombardment of scandium cannot decay through emission of a negative beta-particle, since there is no stable isotope of higher atomic number and appropriate mass number to which it might decay.

A number of sources were studied by means of the cloud chamber. The histograms in Fig. 5 give the essential results of the studies. Histograms (a) and (b) show the negatron spectra of the titanium fraction. Spectrum (a) was prepared a few days following the removal of the target from the cyclotron and spectrum (b) was prepared approximately $1\frac{1}{2}$ months later using the same source. Spectrum (c) is that of the scandium fraction approximately one week after the cyclotron bombardment was completed. The great similarity in the low energy portion of all three histograms is indicative that this portion of the spectrum is produced by the same isotope. The upper energy limit of this distribution corresponds to the end-point energy[14] of the beta-spectrum of Sc^{46} (360 kev). The higher energy group of negatrons has almost completely disappeared in spectrum (b), indicating that these have a shorter half-life than the lower energy group. The chemical separations as discussed in the next section have shown that they are from the disintegration of P^{32} which apparently was produced from an impurity in the original target material.[15] The existence of P^{32} is of course consistant with the observation of a 14-day half-life in the half-life measurements (see Fig. 1). The reason why the longer 85-day half-life of Sc^{46} was not observed in these measurements can probably be explained by the fact that the counter window and the "Krylon" which covered the source used for the half-life measurements very likely absorbed most of the lower energy electrons which are emitted by Sc^{46}. Spectrum (d) of Fig. 5 is the phosphorus fraction of the target material as observed in the cloud chamber a few days after bombardment. Although some Sc^{46} still remains, the histogram gives a higher energy spectrum characteristic in shape to that which would be expected for P^{32}. This is merely another check on the assumption that P^{32} is present as an impurity in the source.

Perhaps the most interesting fact about histogram (c), the scandium fraction, is that, although 700 tracks were observed in preparing the 360-kev Sc^{46} beta-spectrum, not a single track characteristic of the previously reported[14] higher energy beta-group of Sc^{46} could be found. Statistically this result indicates that, if present, the higher energy beta-group consists of less than one-half of one percent of the total beta-transitions from Sc^{46}.

V. CHEMICAL STUDIES

Chemical studies have also been made in order to seek the source of the negatron radiations which have been observed in the titanium fraction. These studies are outlined in the following paragraphs.

Since a high specific activity of titanium was no longer necessary, titanium carrier was first added to the solution.

To a portion of this solution $CuCl_2$, $BiCl_3$, and $AsCl_5$ were added as carrier and precipitated with H_2S. The activity remained in solution.

$AlCl_3$ was added to the filtrate and the titanium was precipitated with excess NaOH. The activity followed the titanium.

To another portion of the active solution $LaCl_3$, $Sc(NO_3)_3$, and $Ti(SO_4)_2$ were added as carriers. The scandium and lanathanum were precipitated with HF, the titanium remaining in solution.[16] The activity remained with the titanium fraction.

A third portion of the active solution was taken, $ZrOCl_2$ added as carrier, and zirconium phosphate precipitated,[17] titanium being kept in solution by H_2O_2. All of the activity came with the zirconium phosphate.

A final chemical check consisted of adding enough Na_2HPO_4 to the active solution to allow precipitation of 60 mg of Ag_3PO_4. Sufficient $AgNO_3$ to precipitate approximately 20 mg of Ag_3PO_4 was added in three successive steps, Ag_3PO_4 being centrifuged away after each addition of the silver carrier. The three samples thus produced were weighed and counted and were found to have within 15 percent the same specific activity. The last two operations seemed to indicate that the activity was phosphorus.

Finally, an absorption curve was determined for the unknown activity and compared with an absorption curve made under identical experimental conditions from a sample of P^{32} which had been obtained from Oak Ridge. The results are indicated in Fig. 6. As can be seen, the curves of the unknown activity and of the known P^{32} sample are very similar in shape up to about 600 mg/cm^2 of aluminum (1.3 Mev). The counting rate was too low to follow the absorption curve accurately beyond this energy.

VI. DISCUSSION AND CONCLUSIONS

It would appear from this work that the only titanium activity produced in any significant quantities by bombardment of scandium with either 10-Mev deuterons or 5-Mev protons is the 3.05-hr. half-life positron emitter Ti^{45}.

[14] C. L. Peacock and R. G. Wilkinson, Phys. Rev. 74, 297 (1948).

[15] Normally, production of P^{32} occurs through a (d, p) reaction on P^{31} or an (n, p) reaction on S^{32}. Subsequent check with Dr. Keller of Mallinckrodt Chemical Works revealed that either of these target impurities could have been missed in their spectroscopic analysis because of the absence of suitable strong spectral lines in the region of the spectrum studied.

[16] Noyes and Bray, *A System of Qualitative Analysis for the Rare Elements* (The Macmillan Company, New York, 1927) p. 221, outline this procedure in detail.

[17] Noyes and Bray, reference 16, pp. 207–208.

The difficult chemical procedure necessary to give a high specific activity titanium source for spectrometer studies apparently carries with the titanium a certain number of impurities. As discussed in Sections IV and V, the 14-day P^{32} and the 85-day Sc^{46} activities apparently are not easily eliminated from the titanium fraction. Deciding the exact nature of the 3.4-day activity presents a problem which cannot be answered accurately at the present time. It has been reported by all recent investigators[3,10] of the titanium activities produced from deuteron and proton bombardment of scandium. It definitely (but not strongly) appears in the half-life curve (Fig. 1), yet all search for a radiation which can be associated with this half-life has produced no results. All positron activity dies away with a 3.05-hr. half-life, after whose decay the cloud chamber shows no radiation other than that which can be accounted for by the negative beta-spectra of P^{32} and Sc^{46}.

It would appear, therefore, that most probably the only titanium activity present in the samples studied was the 3.05-hr. Ti^{45}. Its disintegration seems to consist almost entirely of transitions from the ground state of Ti^{45} to the ground state of Sc^{45}, with perhaps a small percentage (not more than five or six percent) of the transitions going to an excited state of Sc^{45} 450 kev above the ground state.

Since Ti^{45} emits positrons, it can also decay by the K-capture process. On the basis of the calculations of Feenberg and Trigg[18] the ratio K/β^+ for $W_0=3m_0c^2$, $Z=22$ is 0.50 and the ratio K/β^+ for $W_0=2.1m_0c^2$, $Z=22$ is 1.6.

These results lead to ft-values[19] for the 1.02-Mev transitions of 1.17×10^4 which on the basis of Konopinski's[5] empirical classification is an allowed transition. The lower energy K-capture and positron transition has a lower limit for its ft-value of 1.95×10^5 which means, if it exists, that it is most probably first forbidden.

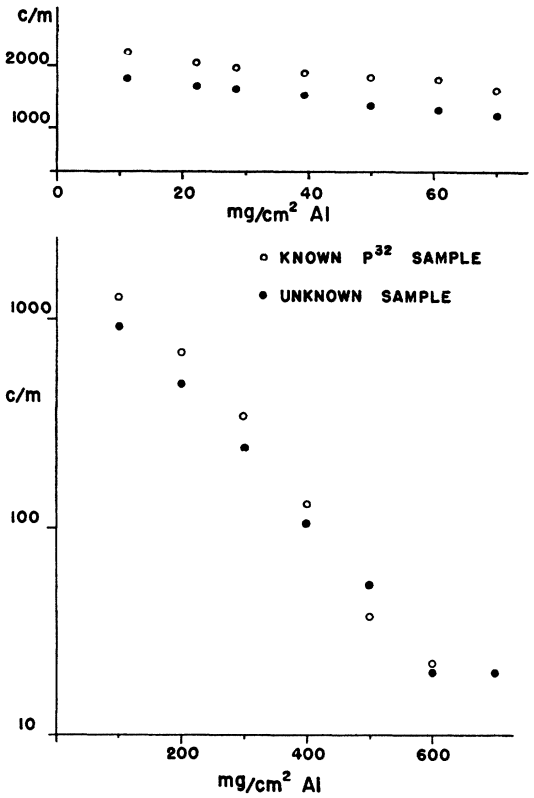

FIG. 6. Absorption curves for the unknown 14-day half-life activity in the chemically separated titanium fraction and for a known P^{32} sample from Oak Ridge. The P^{32} sample was prepared so that its total activity was of the same order of magnitude as the unknown sample. The absorber thickness indicated by the abscissa refers only to the total amount of aluminum interposed between sources and counter. In addition there was a 7-mg/cm² Duraluminum counter window and approximately 5 mg/cm² of air between sources and counter.

The authors are grateful to Mr. P. Hotz for help in scanning the cloud-chamber photographs.

[18] E. Feenberg and G. Trigg, Rev. Mod. Phys. (to be published).
[19] Values of f are again taken from calculations of Feenberg and Trigg.