JANUARY 15, 1938 PHYSICAL REVIEW VOLUME 53

The Radiations Emitted from Artificially Produced Radioactive Substances

IV. Further Studies on the Gamma-Rays from Several Elements

J. REGINALD RICHARDSON*
Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received November 24, 1937)

Further studies on the gamma-radiation from V^{48}, N^{13}, Cu^{64}, Mg^{27}, and Na^{24} have been carried out using a large hydrogen-filled cloud chamber and with several improvements in technique. The most striking feature of the spectra, is the presence of a large amount of 1 Mev radiation from V^{48}. Comparison with the ordinary annihilation radiation indicates that there are four 1 Mev quanta emitted per positron. The possible origin of this radiation is discussed. A difference in the gamma-radiation emitted from N^{13} and Cu^{64} is noted, the latter having a more pronounced high energy tail. A small number of tracks from Mg^{27} have been measured and indicate a monochromatic line at 0.88 ± 0.05 Mev. The radiation from Na^{24} has been re-examined. The results indicate that the quantum energy of the high energy line is 3.00 ± 0.05 Mev. The two other lines with energies of 2 Mev and 1 Mev are confirmed.

INTRODUCTION

IN a previous investigation[1] of the gamma-radiation emitted by the positron radioactive N^{13}, it was found that in addition to the line ascribable to the two quantum annihilation radiation, there was a small amount of more energetic radiation. This latter was provisionally identified as the radiation produced when a positron is annihilated while in motion.

In order to investigate this question further, it was thought desirable (because of experimental convenience) to use a positron emitter of longer half-life. A radioactive isotope of vanadium formed from titanium by deuteron bombardment has been investigated by H. Walke[2] and seemed to offer the desired properties. Provisionally assigned to V^{48}, the positron activity has a half-life of sixteen days. Although, upon examination, the gamma-radiation was found to be unsuitable for the original purpose, it exhibited several interesting features, which it is the main purpose of this paper to report.

APPARATUS

The author is indebted to Dr. H. C. Paxton and Dr. F. N. D. Kurie for permission to adapt a large cloud chamber which they have recently designed and built, to the measurement of gamma-radiation. There are two principal improvements in the new chamber over the one previously used in this work.[3, 1] The diameter has been increased from seven to twelve inches, thus enabling more accurate measurement of the curvature of electron tracks, as they are curved in the magnetic field traversing the cloud chamber. Secondly, enough copper has been used in the coils supplying the magnetic field so that current can be run through them continuously (instead of being turned on just before the expansion, as before). This eliminates the error due to fluctuations in the magnetic field caused by changes in contactor resistance, variation of heating speed of the coils with time, etc. The difficulty of reading the ballistic swing of the ammeter needle is also eliminated.

The cloud chamber was filled with hydrogen to a pressure of about 100 cm Hg. The radiator (from which the Compton electrons were ejected by the gamma-radiation) had a surface density of 40 mg/cm^2, and was made of wood coated with paraffin and lamp black. There is some improvement in nuclear scattering in carbon over the mica which was used previously, but this is important only at low energies. The illumination coming as it did from four lights arranged around the chamber, made it unnecessary that the radiator be transparent. The

---

* Now National Research Fellow at the University of Michigan.

[1] J. R. Richardson and F. N. D. Kurie, Phys. Rev. **50**, 999 (1936).

[2] H. Walke, Phys. Rev. **52**, 777 (1937).

[3] Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936).

lights were ordinary 500-watt clear lamps flashed on 220 volts d.c. The gamma-ray source was placed at one end of a lead collimator, 15 cm outside the chamber wall, arranged in such a way that the source could not see the floor or roof of the chamber. This greatly reduced the chance of Compton electrons being ejected from the floor or roof and appearing to come from the radiator.

The criteria used for the selection of tracks were the same as those developed in work previously reported,[1] except that a greater length of track was required (15 cm). Because of the increased distance between the radiator and the wall of the cloud chamber, it was found that by far the majority of the tracks originating in the wall were bent around by the magnetic field before reaching the radiator. This enabled one to say with greater certainty whether or not a track originated in the radiator. This question is also not complicated nearly as much by the presence of turbulence near the radiator, in a large cloud chamber.

RESULTS

Positron emitters: N^{13}, V^{48}, Cu^{64}

The principal source of the sixteen day vanadium activity was prepared as follows: a sample of titanium metal was bombarded in the cyclotron with 5.5 Mev deuterons for 150 microampere hours. This was allowed to decay for five days before pictures were taken (in order to allow time for the fifteen hour sodium activity to die out). Then it was estimated that the gamma-ray strength of the source was about 0.5 millicuries. The source was arranged so that the positrons form the V^{48} were stopped either in the titanium sample itself or in an adjoining layer of carbon. Altogether, 2700 pictures were taken, using several sources of radio vanadium, from which 1050 measurable tracks were obtained.

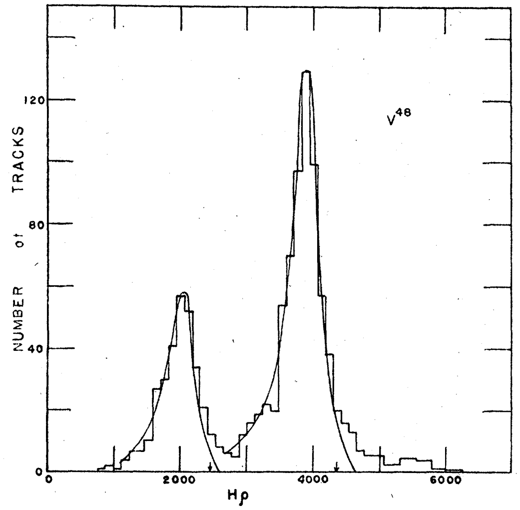

FIG. 1. The momentum distribution of the Compton electrons projected by the gamma-radiation from V^{48}.

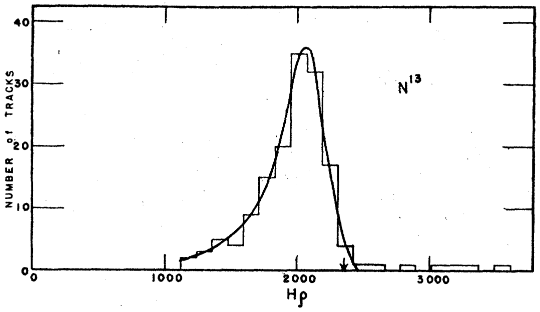

FIG. 2. Distribution curve of the recoil electrons produced by the radiation emitted when the positrons of radio-nitrogen are annihilated in carbon.

The momentum distribution of these Compton recoil electrons is shown in Fig. 1. It is to be observed that there are two main groups, of which the lower corresponds to a gamma-ray energy of 0.53 Mev (2400 $H\rho$ upper limit of Comptons) and the upper to a gamma-ray energy of 1.05 Mev (4250 $H\rho$). The lower group is undoubtedly due to the radiation emitted when a positron is annihilated at rest in free space, resulting in two quanta of 0.51 Mev each. All the positrons were stopped in the immediate neighborhood of the source (by a carbon absorber) so that one can use the number of 0.5 Mev quanta as a measure of the number of positrons. The ratio of the number of quanta in the two lines (assuming that they are both monochromatic) can be obtained from the data as in paper II, Section 3 of this series.[1] Thus it turns out that the ratio of the number of quanta of the 1 Mev radiation to the number of quanta of the 0.5 Mev radiation is 1.9 to 1. Assuming that the latter is the ordinary "two quanta" annihilation radiation, one sees that there must be 3.8 quanta of the 1 Mev radiation emitted per positron. The momentum distribution of the electrons due to this more energetic radiation seems to indicate a monochromatic line. By this statement, it is meant that two components could be quite clearly resolved if they were of about equal intensity and differed in energy by 120 kv, or more.

The measurements on N^{13} were repeated with the new cloud chamber in order to compare with the V^{48}. The results are shown in Fig. 2, which gives the momentum distribution of the Compton recoil electrons ejected from the same radiator as that used for the V^{48}. The single line due to the two quanta radiation produced when a positron is annihilated at rest, is clearly observed; and in addition there is a small tail ascribable to the radiation produced when a positron is annihilated while in motion.

The gamma-radiation from the 12.8 hour activity of Cu^{64} was also investigated under the same conditions. Van Voorhis[4] found that this activity was due to a branch reaction in which both positrons and electrons were emitted, their numbers being in the ratio of two to three. Results from the measurement of the gamma-radiation from this activity are shown in Fig. 3. It is apparent that the major part of the radiation consists of the ordinary two quanta annihilation radiation. However, the high energy tail here is much more pronounced than in the case of N^{13} (Fig. 2). This difference is probably real but one cannot as yet explain it with certainty. It is possible that there is a nuclear gamma-ray of about 700 kv energy, associated with the positron transition (or less probably, with the electron transition). On the other hand, the difference may be due to the higher atomic number of the copper. Theoretically,[5] the probability of a positron's being annihilated while in motion in copper should be very slightly larger than that in carbon. However, the possibility that both effects are contamination, although very unlikely, cannot be entirely ruled out as yet. In the case of V^{48}, the tail, although possibly present, is perhaps obscured by the large amount of 1 Mev radiation emitted.

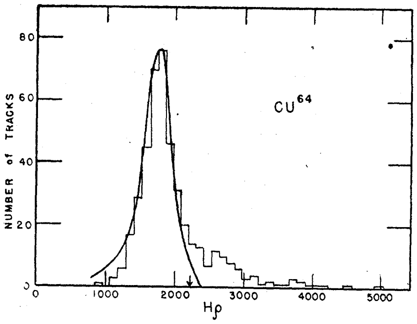

FIG. 3. Momentum distribution curve of the electrons projected by the gamma-radiation emitted by Cu^{64}.

It is apparent that there are several possible explanations of the strong 1 Mev line in V^{48}. If the K radiation observed by Alvarez[6] from this activity corresponds to the same transition as the positron emission, one must take into account the probability of K electron capture when computing the number of gamma quanta per transition. With his estimate of one K quantum emitted per positron, it is seen that there are two quanta of energy 1 Mev each emitted per transition. This would require two excited levels in the Ti^{48} nucleus, one at 1.05 Mev above ground and the other at 2.1 Mev above ground. Transitions from the radioactive V^{48} to the ground level of Ti^{48}, except in cascade, would seem to be practically forbidden, experimentally. There is no evidence of complexity in the beta-spectrum. It is possible, of course, that Alvarez's estimate is too low, for the number of K quanta per positron.

Another possibility that cannot be ignored is that the gamma-radiation corresponds exclusively to a separate transition initiated by K electron capture. In other words, the capture of a K electron by the V^{48} results in an excited state of the Ti^{48} nucleus which cannot be reached by (or is practically forbidden to) positron emission. This is followed by a transition to the ground state of the Ti^{48} in which one or more gamma quanta of 1.05 Mev energy are emitted. This possibility would explain why Jacobsen[7] failed to find any evidence of K radiation from Sc^{43}, but it also throws doubt upon the use of the determination of the ratio of K electron capture to positron emission (in the case of V^{48}) in trying to differentiate between the

---

[4] S. N. Van Voorhis, Phys. Rev. **50**, 895 (1936).
[5] H. A. Bethe, Proc. Roy. Soc. **A150**, 129 (1935).
[6] L. W. Alvarez, Phys. Rev. **52**, 134 (1937).
[7] J. C. Jacobsen, Nature **139**, 879 (1937).

Konopinski-Uhlenbeck modification and the original Fermi theory of beta-emission.

The agreement between the energy of the gamma-ray (1.05 Mev) with the energy to be expected from the annihilation of a positron in the field of the nucleus (1.02 Mev), or with the energy of the upper limit of the beta-spectrum (1.05 Mev) is probably coincidental. Theoretically the energy available from these sources when a *K* electron is captured should not be given off as gamma-radiation.

Probably more light can be thrown on the questions here involved by further investigation of the gamma-radiation given off by positron emitters.

Electron emitters: Mg^{27}, Na^{24}

Since a strong source of gamma-radiation may be made by bombarding magnesium with deuterons,[8] it was thought desirable to investigate the energy of the radiation in case it should prove useful in other research. Only a small number of tracks were measured (120), but these were sufficient to indicate definitely a radiation at 0.88 ± 0.05 Mev, monochromatic to 100 kv. This corresponds to an excited level of the Al^{27} nucleus formed by electron emission from Mg^{27}, the latter having a half-life of 10.2 minutes. It is interesting to note here that an excited level of Al^{27} at about 1 Mev was indicated by the proton groups from the reaction:[9]

$$Mg^{24}+He^{4}\rightarrow Al^{27}+H^{1}.$$

Further work on the gamma-radiation from Na^{24} has been done with improved technique, including a more precise extrapolation from the accurately known gamma-ray line of Th C″. The resulting momentum distribution of the recoil electrons is very similar to that given previously,[1] with the high energy line corresponding to a quantum energy of 3.00 ± 0.05 Mev. The energy of the two other lines (less accurately determinable) appears to be 2.04 Mev and 1.01 Mev. The value for the high energy line agrees very well with that obtained by Richardson and Emo from the photodisintegration of the deuteron[10] (after their result is corrected, using the new proton range energy curve of Parkinson, Herb, Bellamy and Hudson[11]).

The author takes pleasure in acknowledging many helpful discussions with Professor E. O. Lawrence and Professor J. R. Oppenheimer. The friendly cooperation of the staff of the Radiation Laboratory is also gratefully acknowledged, in particular that of Dr. F. N. D. Kurie. The research was made possible by grants from the Chemical Foundation, the Research Corporation, and the Josiah Macy, Jr., Foundation.

---

[8] M. C. Henderson, Phys. Rev. **48**, 855 (1935).

[9] Duncanson and Miller, Proc. Roy. Soc. **146**, 396 (1934); Haxel, Physik. Zeits. **36**, 804 (1935).

[10] J. R. Richardson and L. Emo, Phys. Rev. **51**, 1014 (1937).

[11] Parkinson, Herb, Bellamy and Hudson, Phys. Rev. **52**, 75 (1937).