On the Scattering of the Th C$''$ γ-Rays

The absorption of Th C$''$ γ-rays in matter may be satisfactorily accounted for by the Compton scattering, the photo-effect, and the production of electron positron pairs, for the theoretical formulae[1] for these three effects give an absorption which agrees with experiment within experimental precision and the accuracy of the formulae. For the scattered radiation observed we have no such satisfactory understanding, for the experimental findings[2] here not only fail to agree with theoretical expectation, but disagree radically with each other. The radiation to be expected theoretically is quite complex, and we believe that the discrepant results of various observers must be in part ascribed to an inadequate recognition of this complexity. There are in fact four known sources for this scattered radiation:

(1) The Compton scattered radiation, which must in some cases be corrected for multiple scattering, and, particularly for large angle scattering, for the reabsorption of the radiation in the scatterer.

(2) The annihilation radiation of the positrons, which should consist almost wholly[3] of an isotropic radiation of energy of 500 kilovolts, and with an intensity corresponding to 2 quanta per positron. According to theory[1] there should be 0.25 positron formed for every Compton recoil electron in lead; and this prediction is roughly confirmed[4] by observations on the number of positrons ejected from thick plates. Independent evidence[5] indicates that the annihilation radiation has the hardness and isotropy to be expected from theory, and that the number of quanta per positron is roughly two, and can hardly be less than 1.5 or greater than 2.5. The intensity of this annihilation radiation per atom of scatterer should increase with Z^2.

(3) A coherent radiation[6], highly anisotropic, scattered by the electron positron cloud about nuclei. If the cross section for scattering per atom be expanded in powers of αZ, the first non-vanishing terms are of the order $(\alpha Z)^4 e^4/m^2c^4$. This corresponds to an intensity for the scattered radiation of the order of one percent (in lead) of that of the annihilation radiation, and of this only a small part will be scattered through 90° or more. Unless existing theory be inapplicable to the calculation of this effect, the scattering can hardly be of importance.

(4) A continuous X-radiation, emitted by the secondary electrons (and positrons), and with greatest intensity by the Compton recoil electrons. This radiation is itself complex:

The high frequency limit of the spectrum is at 2.35×10^6 volts. The intensity of the radiation near this limit (which comes from Compton recoil electrons sent directly forward, and which have suffered no great energy loss and have been little deflected by the nuclei of the scatterer) is proportional to Z^2, and is markedly anisotropic[7] (1/2 the radiation of about 1.5×10^6 volts lies within 15°). The intensity of the spectrum will increase rapidly with decreasing frequency. The probability that the fastest Compton recoil electron will emit a quantum of energy greater than 10^6 volts is about 5 percent; that it will emit a quantum harder than 5×10^5 volts about 10 percent. The softer components of this radiation will tend to be nearly isotropic, at least for heavy elements; for not only will the less energetic Compton electrons be ejected at larger angles, but all electrons will be scattered by their elastic impacts with the nuclei of the scatterer. The radiation observed at large angles will come chiefly from electrons which have suffered at least two nuclear impacts, and its intensity will thus increase more rapidly than Z^2 (roughly Z^3).

From (4), and perhaps from (3), we may expect to find a small amount of radiation nearly as hard as the primary γ-ray, strongly anisotropic, increasing in intensity with Z^2, and whose total intensity for radiation harder than 1.5×10^6 volts can hardly be greater than 10 percent of that of the annihilation radiation. Experimentally the existence of such hard radiation from heavy scatterers seems definitely established. Bothe and Horn[2] are able to fit their absorption curve for scattering at 114° in lead by assuming a hard component 10 percent as intense as the annihilation radiation. Because of the anisotropy of the hard components, this value seems rather too high to fit with expectation. On the other hand it must be remembered that in their analysis this component has to represent all radiation harder than 5×10^5 volts.

Quite different are the results of Gray and Tarrant[2], who observe at large scattering angles (135°), and analyze the radiation by a cylindrical absorber immediately surrounding the ionization chamber. They find no radiation harder than 10^6 volts, and can reproduce their absorption curves by assuming, in addition to radiation of about 5×10^5 volts, a component of 10^6 volts, roughly isotropic, increasing in intensity with $Z^{3.3}$; and with an intensity relative to the soft component of about 15 percent in lead. This corresponds qualitatively to what we should expect from the continuous x-ray spectrum. For at these angles the harder parts of this spectrum will be very weak, and the arrangement used is not suitable for detecting a very weak hard component in the presence of large intensities of soft radiation. And radiation of roughly the frequency, absolute intensity, Z-dependence, and isotropy of that observed is to be expected from the x-ray spectrum.

For the softer components of the scattered radiation, where we should expect to find the annihilation radiation of the positrons, there is also an apparent disagreement between observers. Thus Gray and Tarrant find twice as

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[1] H. Hall, Phys. Rev. **45**, 620 (1934). J. R. Oppenheimer and M. S. Plesset, Phys. Rev. **44**, 53 (1933). W. Heitler and F. Sauter, Nature **132**, 892 (1933).

[2] L. H. Gray and G. T. P. Tarrant, Proc. Roy. Soc. **A143**, 681 (1934). W. Bothe and W. Horn, Zeits. f. Physik **88**, 683 (1934). Full references are given in these papers.

[3] E. Fermi and G. Uhlenbeck, Phys. Rev. **44**, 510 (1933).

[4] J. Chadwick, P. M. S. Blackett and G. P. S. Occhialini, Proc. Roy. Soc. **A144**, 235 (1934).

[5] J. Thibaud, Phys. Rev. **35**, 781 (1934). H. R. Crane and C. C. Lauritsen, Phys. Rev. **45**, 430 (1934).

[6] M. Delbrueck, Zeits. f. Physik **84**, 144 (1934).

[7] For quantitative theoretical results on the radiation from such electrons we are indebted to Dr. Carlson and Dr. Phillips, who have investigated the problem in detail.

much radiation as is to be expected, and Bothe and Horn, in making an explicit comparison with expectations, claim to find less than a fifth. This claim appears to be based, however, on the assumption that the Compton scattered radiation at 114° from 2.5 mm of lead has an intensity equal to that from an equivalent thickness of aluminum, whereas the reabsorption in the lead is several times that in aluminum. This leads Bothe and Horn seriously to overestimate the anisotropy of the 5×10^5 volt radiation and to underestimate the isotropic component of this radiation. In fact Bothe and Horn themselves give evidence, based on absorption and reabsorption curves, that the radiation scattered at this angle from lead has a component of energy 5×10^5 volts and of intensity about 47.5 percent of the total intensity. This value for the intensity of the annihilation radiation is 8 times as large as that used by Bothe and Horn, completely resolves the discrepancy which they report, and is in rough agreement with what we should expect. On the other hand, Gray and Tarrant's values inevitably include the softer parts of the continuous x-ray spectrum and will thus give somewhat too high an intensity for the 5×10^5 volt component.

Because of the complications here discussed, which arise essentially from the superposition of a continuous x-ray spectrum upon the partially reabsorbed Compton and annihilation radiations, we believe that the experimental results on the scattered radiation afford no clear evidence for the existence of further sources of absorption of the Th C″ γ-rays. From the absorption measurements themselves we can conclude that such sources can contribute only very little to the total absorption.

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The Production and Identification of Helium of Mass Three

In the May 1 issue of the *Physical Review* we reported experiments which we believed indicate the production of hydrogen of mass three (T) from hydrogen of mass two (D) in quantities great enough to detect, with a mass-spectrograph. The work of Oliphant, Harteck and Rutherford[1] indicates that collisions of deuterium nuclei may produce a T nucleus and a proton or an He^3 nucleus and a neutron. They have not, however, observed the He^3 directly.

Using the same discharge tube and approximately the same conditions that we use for the production of T we have looked for He^3 in the treated gas. To determine its presence with the mass-spectrograph a different procedure is necessary from that used for T. First the sample of gas that has been run in the discharge tube is allowed to stand over night on copper oxide at 300°C with an appendix at liquid air temperature to remove the hydrogen in the form of water. In the meantime the mass-spectrograph is baked out to reduce the amount of mass three (H D) residual gas as much as possible. Though the "peak" due to this ion from the residual gas in the spectrograph can be reduced to an intensity corresponding to a partial pressure of the order of 10^{-10} mm it still gives a current comparable in magnitude to that obtainable in our sample to be analyzed. Therefore in spite of purifying the sample and baking out the mass-spectrograph it is necessary to distinguish between a "peak" at mass three due to pure H D and one due to a mixture of H D and He^3. This can be done by studying the intensity of the mass three ion "peak" as a function of the energy of the electrons producing the ions.

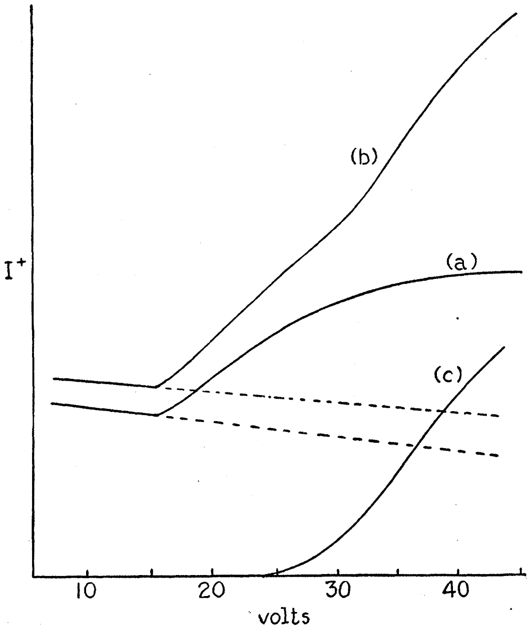

FIG. 1. Ions of mass 3 as a function of electron energy. (a) Residual hydrogen, (b) treated sample, (c) difference after fitting and correcting for electron current and zero drift.

Such a study is represented by curves (a) and (b) in Fig. 1. They are tracings of photographic records showing the variation of the galvanometer deflection measuring the ion current as the electron voltage is varied. Curve (a) was taken on the residual H D peak in the spectrograph. Curve (b) was on a sample that had been treated five hours in the canal-ray discharge at about 80 kv and 10 m.a. The difference in shape of the two curves is obvious and furthermore a definite departure can be seen at about twenty-six volts. This is interpreted as caused by the ionization of He^3 atoms which should take place first at 24.5 volts. If the ordinates of (a) and (b) are adjusted so that the lower parts coincide and a small correction made for the variation in electron current a difference curve (c)

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[1] Oliphant, Harteck and Rutherford, Proc. Roy. Soc. **A144**, 692 (1934).