The Positron*

By DR. CARL D. ANDERSON, California Institute of Technology, Pasadena, Calif.

THE existence of free positive electrons or positrons was first reported by me in September 1932[1], from cosmic ray experiments carried out at the California Institute of Technology. In the original paper, all possible alternative interpretations of the effects there presented were discussed in detail, and it was shown that only by calling upon the existence of free positive electrons could those effects be logically interpreted.

As a part of Prof. R. A. Millikan's programme of cosmic ray research, in particular to make energy measurements of the cosmic ray particles by the use of a vertical cloud chamber in a very powerful horizontal magnetic field, photographs were first taken in August 1931 in such an apparatus involving the maintenance of a field of strength up to 20,000 gauss over a space measuring 17 cm. × 17 cm. × 3 cm. As reported in lectures in Paris and Cambridge, England, in November 1931 and published in March 1932 by Millikan and myself[2], this work brought to light for the first time the fact that nuclear effects are of primary importance in the absorption of cosmic rays, as demonstrated by the frequent occurrence of associated tracks or showers containing particles of positive charge as well as those of negative charge.

Through the insertion in May 1932 of a lead plate across the centre of the cloud chamber, it was possible to show definitely in several cases that the mass of these particles of positive charge could not possibly be as great as that of the proton. The direction of motion of the particles was given in two ways: first, by allowing them to pass through the lead plate and suffer a loss in energy, and secondly, by the observation in several instances of two or more tracks all originating at one small region in the material surrounding the chamber. For a given curvature of track, the specific ionisation showed that the mass was small compared with the proton mass, but even more definite evidence was gained from an observation of the range of the particles. The observed ranges were several times, in some instances more than ten times, greater than the possible ranges of proton tracks of the same curvature.

These considerations were the basis of the report announcing the existence of the free positive electron or positron published in September 1932. Within the next five months a large number of confirmatory photographs revealing unambiguously the existence of positrons was taken, and a second report was published in March 1933[3] in which fifteen of these photographs were discussed. The specific ionisation exhibited by the positron tracks on these photographs showed that the magnitude of charge of the positron could not differ by as much as a factor of two from that of the free negative electron, and it was, therefore, concluded, unless one admits fractional values of the elementary unit of charge, that the free positive and negative electrons were exactly alike in magnitude of charge. This fact, together with the curvatures measured in the magnetic field of a positron before and after it penetrated a plate of lead, fixed its mass as not greater than twenty times that of the free negative electron.

Since then[4], an observation of a collision between a moving positron and a free negative electron in the gas of the chamber revealed, on the basis of the conservation laws, that its mass was equal to that of the free negative electron with an error of not more than 30 per cent. More recent measurements[15] of the specific ionisation of the positives and negatives for both high and low speed particles, by actual ion-counts on the tracks in the magnetic field, showed the specific ionisation of the positives and the negatives to be equal to within 20 per cent. This fixes the limits of difference between the positives and negatives with regard to their charges and masses at 10 per cent and 20 per cent respectively. Further details of the history of this discovery were presented at the American Association for the Advancement of Science meeting in Chicago in June 1933[4].

In March 1933 confirmatory evidence for the existence of positrons was presented by Blackett and Occhialini[5], based on similar experiments with a vertical cloud chamber operating in a magnetic field of 3,000 gauss and actuated by the responses of Geiger-Müller counters. In April 1933 Chadwick, Blackett and Occhialini[6], Curie and Joliot[7], and Meitner and Philipp[8] reported that the bombardment of beryllium by α-particles can produce radiation which results in the production of positrons, though in these experiments it was not possible definitely to identify the nature of the radiation producing the positrons. By absorption experiments, however, Curie and Joliot showed that the yield of positrons decreased approximately as was to be expected if the γ-ray rather than the neutron component of the radiation were responsible for their production.

The first experiments proving directly that a γ-ray photon impinging upon a nucleus gives rise to positrons were carried out at the Norman Bridge Laboratory, using the γ-rays from thorium C″, and reported in April 1933[9]. In this paper the fact that free electrons of both positive and negative sign are produced simultaneously by the impact of a single γ-ray photon, an observation of considerable theoretical import, was first presented. Preliminary results of energy measurements were given in June 1933 by Neddermeyer and myself[10]. Curie and Joliot[11] in May 1933, and Meitner and Philipp[12] in June 1933, all of whom used γ-rays from thorium C″, also reported

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the detection of positrons from the same source. Curie and Joliot[13] have also shown that positrons are produced directly in the disintegration of aluminum and boron by α-particle bombardment. The positrons in the case of aluminum cannot here be produced by the internal conversion of a γ-ray photon unless the probability of such internal conversion is vastly greater than that to be expected on theoretical grounds[14]. Rather do these experiments indicate that an elementary positive charge is actually removed from the disintegrating nucleus and appears as a positron.

The foregoing furnishes in brief a historical survey of the early experimental work on positrons and their production.

A detailed study of the energy distribution and frequency of production of free positive and negative electron pairs by filtered thorium C″ γ-rays is of particular value because of the relative simplicity of these effects as compared with those appearing in the cosmic ray range of energies.

γ-RAY EFFECTS

A discussion will now be given of experimental evidence as it bears on the theory suggested by Blackett and Occhialini on the basis of the Dirac electron theory, which postulates the creation of a free positive-negative electron pair out of the absorption of a photon impinging upon a nucleus. The nucleus itself in this picture undergoes no disintegration, but plays merely the rôle of a catalytic agent. This discussion will be given in the light of (1) new statistical studies by Neddermeyer and myself on the thorium C″ γ-ray effects, and (2) new experiments on cosmic ray showers by Millikan, Neddermeyer, Pickering and myself.

The work of Curie and Joliot, and of Chadwick, Blackett and Occhialini on the radiation from thorium and that excited in beryllium by α-particle bombardment, together with our own work on the cosmic radiation[15], has shown that the absorption process which gives rise to positrons becomes increasingly important with high energy radiations and heavy absorbing materials. Further, we have made a statistical study based on a total of more than 2,500 tracks of single electrons, both positive and negative, and positive-negative pairs ejected from plates of lead, aluminum and carbon by γ-rays from radiothorium filtered through 2·5 cm. of lead (in some cases with unfiltered rays for comparison) to determine the frequency of occurrence of pairs and single positrons, and their energy distribution for absorbing materials of different atomic numbers. The ejection of the particles was observed from lead plates of 0·25 mm. thickness, aluminum plates of 0·5 mm. thickness and a graphite plate of 1·4 cm. thickness (used also for cosmic ray studies). The magnetic field was here adjusted to 825 gauss.

We will consider first of all the energies. Both the single positives and the pairs (the sum of the energies of the positive and negative components being taken) ejected from the lead plates showed a maximum energy of about 1·6 *MV* (*MV* = millions of electron-volts), 80 per cent of the single positrons having an energy less than 0·8 *MV*. For the case of the unfiltered γ-rays, the positrons and the pairs, though occurring in relatively fewer numbers compared with those ejected by the filtered rays, showed also a maximum energy of 1·6 *MV*. Further, in the case of the positives and pairs ejected from the plates of aluminum, the maximum energy was about 1·6 *MV*.

The maximum energy of the single negative electrons in all cases was about 2·5 *MV*. Since the errors in the energy measurements may be as high as 15 per cent, this is in good agreement with the highest energy to be expected for extra-nuclear electrons resulting from Compton encounters or photoelectric absorption of the 2·65 *MV* photons.

A maximum energy of 1·6 *MV* for the positives and the pairs, both from the lead and the aluminum, is in good accord with that to be expected on the Dirac picture if 1 *MV* is allowed for the energy required to create a pair of electrons. There occurred, however, one pair the total energy of which was 2·9 *MV*; it is conceivable, though not likely, that it may have been produced by cosmic rays, or again it may represent the rebound of an electron against the under surface of the lead plate.

Of equal importance with the distribution in energy is the distribution in number of single positive electrons and pairs as compared with the single negative electrons. Out of a total of 1,542 electrons ejected from the 0·25 mm. lead plate by γ-rays from radiothorium filtered through 2·5 cm. of lead, there were 1,387 single negatives, 96 single positives and 59 pairs. From an aluminum plate 0·5 mm. thick and ejected by the same radiation there were, out of a total of 943 electron tracks, 916 single negatives, 20 single positives and 7 pairs.

The negatives may be assumed to have arisen in general from Compton and photoelectric encounters with extra-nuclear electrons in the lead or aluminum. But the single positives and the pairs must all, of course, correspond to nuclear encounters. If we assume that on the average an equal number of positives and negatives results from nuclear impacts, we can calculate the ratio of the nuclear to extra-nuclear absorption. This amounts to about 20 per cent for lead and about 50 per cent for aluminum. These values are in reasonably good agreement with those obtained by Chao[16], Meitner[17] and Gray and Tarrant[18] by entirely different methods in the matter of the excess absorption shown by lead over that shown by aluminum and also in the general relation of nuclear to extra-nuclear absorption in both metals.

That the nuclear absorption in carbon is very small for the thorium C″ γ-rays is shown by the fact that, as compared with 415 negatives, there appeared only 2 pairs and 6 single positives.

On the whole, the energy relations of the positives and pairs, from both the aluminum and the lead, appear to be quite consistent with the pair-creation hypothesis, as are also the approximate values of the excess absorption in lead and aluminum calculated on this assumption.

The ratio of the observed numbers of single positives compared with the pairs is also of great importance in this connexion. Whether a positive is always formed paired with a negative, or whether a positive not accompanied by a negative can in some cases be produced, is a question difficult to answer from the data so far obtained. An accurate calculation of the probability of removal of the negative, if a pair is generated, so that only the positive emerges from the plate, is not simple to make, depending as it does on energy loss and plural scattering in the plate, and on the initial space and energy distribution of the components of the pairs. But on the basis of very approximate considerations, it appears somewhat difficult to reconcile the appearance, for example, in the case of aluminum, of 20 single positives and only 7 pairs with the view that they are always formed in pairs. Experiments now planned in which the particles are ejected from very much thinner plates should decide this question.

One case should be cited in which two negatives and two positives were all observed to originate at one point in the lead plate. The possibility that this can represent two pairs accidentally associated in time and position is so remote that it is taken as evidence that *photons of energy even so low as those of the thorium C″ gamma-rays can occasionally give rise to showers such as are a common feature of the cosmic rays*[9].

COSMIC RAY EFFECTS

Our recent stereoscopic photographs taken in a 17,000 gauss magnetic field show numerous showers of more than thirty electrons, some positives and some negatives, originating in lead plates placed across the chamber. In all the observed cases of shower production, it was clearly seen from the photographs that non-ionising particles produced the showers. Also photographs taken in a magnetic field of only 800 gauss showed many examples of single negatives, single positives, pairs and triplets, of energies of the order of only a million or two electron volts, ejected from plates of lead by the impact of non-ionising particles. These low energy ejections are in all respects identical with those produced by the thorium C″ γ-rays and are undoubtedly due to low energy photons. These electron effects cannot be ascribed to ordinary neutrons since a considerable study of neutrons in this very range of energies has shown that their absorption results in projected nuclei and not in electron projection or shower formation. The appearance of several such small electron showers on one photograph which contains evidences of showers which occurred above the chamber, brings to light a new fact, namely, that *in the absorption of the cosmic rays there are produced, in addition to the electron showers, in some instances, sprays of large numbers of secondary photons.* The evidences for this conclusion were presented at the November 1933 meeting of the National Academy of Sciences by Millikan, Neddermeyer, Pickering and myself[10], and a full discussion together with the photographs will appear shortly in the *Physical Review*. In one case, more than eighty low energy electron tracks simultaneously projected were photographed, their positions and orientations in the chamber showing that they must have arisen from nearly as many separate centres in the material surrounding the chamber, and must therefore be ascribed to such a spray of secondary photons.

That pair production or shower formation by a fast electron (positive or negative) is a relatively rare event is shown by the fact that more than a thousand fast electrons have been observed to traverse a 1 cm. lead plate, and only in one instance was a definite pair projected from the lead by a fast electron, while a large number of secondary negative electron tracks appeared as the result of close encounters with the extra-nuclear electrons in the lead plate. The immediate secondaries of fast electrons are therefore seen to consist largely of negative electrons and only in rare cases of positrons.

Because of the powerful magnetic field we are using, it is possible to deflect all but a very small number of the electrons projected in the showers by the photon impacts. In general, in a shower a pronounced asymmetry is noted in the numbers of positive as compared with negative electrons emerging from the lead plates, in one instance 7 positives and 15 negatives, and in a second case 15 positives and 10 negatives These effects are only with some difficulty reconciled with the Dirac theory of the creation of pairs out of the incident photon. Rather might they indicate the existence of a nuclear reaction of a type in which the nucleus plays a more active rôle than merely that of a catalyst, as for example the ejection from it of positive and negative charges which then appear in the showers as free positive and negative electrons. The essential difference, however, between these two points of view may be merely that in one case the nucleus may change its charge, and in the other it does not do so.

To study nuclear absorption in a light element, more than four hundred successful photographs were taken in which a carbon plate of 1·4 cm. thickness replaced the lead plate. Many of these showed showers originating in a block of lead placed above the chamber, but in no instance was a secondary shower observed in the carbon plate. This indicates, in agreement with the thorium C″ data, the relatively small probability in comparison with lead of a carbon nucleus absorbing a photon by shower production.

A consequence of the pair-theory is that, in a suitably dense environment of negative electrons such as obtains in ordinary matter, a positron shall have a high probability of combining with a negative electron, resulting in the annihilation of both particles and the conversion of their proper and kinetic energies into radiation. The theory, though at present incomplete, states that the mean free path for annihilation is in general greater than the range of the positron, so that such annihilation should be evidenced by the appearance of quanta of about half a million electron-volts energy and a very small number of quanta of about one million electron-volts energy when positrons pass through matter[20]. The experiments by Gray and Tarrant[18] on the scattering of thorium C″ γ-rays showed the existence of secondary radiation of such energies, but some of the more recent experiments on the scattering of hard γ-rays fail to show a secondary radiation which can be attributed to the annihilation of positrons. Our cosmic ray photographs show that in the electron showers there are present large numbers of secondary photons, many of which are in this range of energy, but it is not yet certain if they are produced in part by the annihilation of positrons. In two very recent papers, Joliot[21] and Thibaud[22] report the observation in experiments with artificially produced positrons of secondary photons of the energies to be expected if they arise from the annihilation of positrons. By control experiments with negative electrons, they showed that a beam of positrons impinging upon matter results in the production of a considerably greater quantity of photons than does an equal number of negative electrons.

[1] Anderson, *Science*, **76**, 238 ; 1932.

[2] Millikan and Anderson, *Phys. Rev.*, **40**, 325 ; 1932. See also Anderson, *Phys. Rev.*, **41**, 405 ; 1932 : and Kunze, *Z. Phys.*, **80**, 559 ; 1933.

[3] Anderson, *Phys. Rev.*, **43**, 491 ; 1933.

[4] Millikan, *Science*, **78**, 153 ; 1933.

[5] Blackett and Occhialini, *Proc. Roy. Soc.*, A, **139**, 699 ; 1933.

[6] Chadwick, Blackett and Occhialini, NATURE, **131**, 473, April 1, 1933.

[7] Curie and Joliot, *C.R.*, **196**, 1105 ; 1933.

[8] Meitner and Philipp, *Naturwiss.*, **21**, 286 ; 1933.

[9] Anderson, A.A.A.S. meeting, April 28, 1933, and *Science*, **77**, 432 ; 1933.

[10] Anderson and Neddermeyer, *Phys. Rev.*, **43**, 1034 ; 1933.

[11] Curie and Joliot, *C.R.*, **196**, 1581 ; 1933.

[12] Meitner and Philipp, *Naturwiss.*, **24**, 468 ; 1933.

[13] Curie and Joliot, *C.R.*, **197**, 237 ; 1933.

[14] Oppenheimer and Plesset, *Phys. Rev.*, **44**, 53 ; 1933. Beck, *Z. Phys.*, **83**, 498 ; 1933.

[15] Anderson, *Phys. Rev.*, **44**, 406 ; 1933.

[16] Chao, *Proc. Nat. Acad. Sci.*, **16**, 431 ; 1930. *Phys. Rev.*, **36**, 1519 ; 1930.

[17] Meitner and Hupfield, *Naturwiss.*, **19**, 775 ; 1931.

[18] Gray and Tarrant, *Proc. Roy. Soc.*, A, **136**, 662 ; 1932.

[19] Anderson, Millikan, Neddermeyer and Pickering, *Proc. Nat. Acad. Sci.* Autumn meeting Nov. 20, 1933. See also abstract by Anderson and Neddermeyer, A.A.A.S. meeting, Dec. 30, 1933.

[20] Fermi and Uhlenbeck, *Phys. Rev.*, **44**, 510 ; 1933.

[21] Joliot, *C.R.*, **197**, 1623 ; 1933.

[22] Thibaud, *C.R.*, **197**, 1629 ; 1933.

Research in the Cotton Industry

IN a discourse entitled "Industrial Research : A Business Man's View" delivered at the Royal Institution on December 15, Sir Kenneth Lee made some striking references to the place of research in industry, based largely on the actual experience of Messrs. Tootal Broadhurst Lee and Co., Ltd. Up to twenty-four years ago, they had no scientific staff connected with the business, and it was only experience gained during the War which induced them to make a direct attack by means of research on the production of cotton material like wool in its power to resist and recover from creasing. Sir Kenneth proceeded to outline briefly the steps which after fourteen years' work had enabled them to market successfully a creaseless cotton fabric.

The initial step was the assembling of the nucleus of a research staff in the belief that, even in such an old-established industry as that of cotton, research could be of immense advantage ; systematic work on the chemical and physical properties of cotton or on the physical basis of the machine processes to which it was subjected in the course of manufacture should greatly facilitate uniform and steady progress. Alluding to the lack of such systematic work in the cotton industry, Sir Kenneth cited the process of mercerisation. Although Mercer discovered in 1844 that caustic soda had a marked action on cotton, it was nearly fifty years later when Lowe discovered how the conditions must be modified to produce lustre by mercerisation, while Mercer's discovery itself did not attract the active interest of academic scientific workers.

In its progress from the bale, through spinning, weaving, bleaching, dyeing and finishing, cotton is subjected to various physical and chemical processes. It was therefore decided, when the Research Department was formed, that the staff should consist of chemists and physicists who should work together on the problems involved, and when a laboratory solution had been found, should share their knowledge with technical men in an endeavour to harvest their results in manufacture. This was the first time that chemists and physicists had been engaged in co-operation in the cotton industry. It was also decided that lack of experience in dealing with cotton should be no bar to the engagement of any member of the staff. Provided ability to conduct research was evident, this lack of experience was even regarded as an advantage, since such workers would not have got into ruts and would be more likely to contribute a fresh outlook on the problem.

In addition to the decision to adopt a definite research objective, the further important initial decision was made to carry out routine testing by a separate staff, housed in the same laboratory, so as to provide the maximum contact between the research staff and the analytical or testing staff. The wisdom of the policy embodied in these preliminary decisions is attested not only by the results achieved by the Tootal Broadhurst Lee Co., Ltd., but also by the experience of numerous other industrial research organisations in Great Britain and in other countries.

Most of the published work on cotton had previously been concerned with large-scale experiments on yarns and fabrics. In view of the dependence of the physical behaviour of such materials not only on the yarn comprising them but also on the weave, on the twist and diameter of the yarns and the nature of the innumerable