

Abgabe: 20. April 2007

1. Synchrotrons: from LEP to LHC

A synchrotron is a circular collider in which particles are kept on a fixed orbit by a magnetic field that depends on the energy of the particles. At one or more places along the orbit, the particles can be accelerated using resonant radio frequency waves. The Large Electron Positron collider (LEP) was the world's largest electron synchrotron, which operated at CERN between 1989 and 2000. The energy of the collisions was initially set to 45 GeV per beam, and was later upgraded to reach maximally 104 GeV per beam.

- Explain what is the problem for an electron synchrotron such as LEP to reach even higher energies?
- What are the possible solutions to achieve higher energy collisions? (hint: which particle emits the most synchrotron radiation, an electron, a muon or a proton?)
- Calculate the maximum energy of the Large Hadron Collider (LHC), the new proton synchrotron that is being built at CERN, when you know that the maximum B-field of the dipole magnets is 8.3T and that the effective bending radius of the LHC about 3000 m is. (hint: balance centrifugal force with the Lorentz force; the speed of the protons is very close to the speed of light)

2. Luminosität am LEP

Als Beispiel zur Berechnung der Luminosität betrachten wir die Situation am L3 Detektor. Am 13.10.2000, am Anfang des LEP fills 8750, betrug die Schwerpunktsenergie 206.8 GeV. LEP lief zu dieser Zeit mit je vier Teilchenpaketen (bunches) von Elektronen und Positronen. Die gemessenen Gesamtströme (alle bunches zusammen) betrugen am Anfang des Fills $I_{e^-} = 2498.1\mu A$, $I_{e^+} = 2497.5\mu A$. LEP hat eine Gesamtlänge von 26.66km.

Am L3 Detektor wird die Grösse des Strahls mit Hilfe von Spuren gemessen, die bis zum Wechselwirkungspunkt extrapoliert werden. Der dabei erhaltene Abstand zum Wechselwirkungspunkt wird gefittet, wobei die Auflösung der Spurenkammer herausgefaltet wird. Man erhält für das Jahr 2000 eine Grösse des Strahls (Gauss'sche Standardabweichungen) von $\sigma_x = 162 \pm 4\mu m$ (horizontal) und $\sigma_y = 24 \pm 6\mu m$ (vertikal).

- Berechne mit Hilfe dieser Daten die Luminosität, welche man im L3 Detektor haben sollte. Hinweis: Die Querschnittsfläche berechnet sich als $A = 4\pi\sigma_x\sigma_y$.
- Gleichzeitig wird die Luminosität am L3 Detektor gemessen, und zwar mit Hilfe von Bhabha Ereignissen. Am Anfang von fill 8750 betrug die gemessene Luminosität $53.0 \cdot 10^{30} cm^{-2} s^{-1}$. Vergleiche diese Zahl mit der aus der Rechnung erhaltenen und mache Dir Gedanken zur Abweichung.

Verwende für den Rest der Aufgabe den gemessenen Wert.

- c) Mit der Zeit fällt die Luminosität etwa linear ab. $2h\ 32min$ später, am Ende des fills, war die gemessene Luminosität noch 6.3% von der Luminosität am Anfang des fills. Berechne die integrierte Luminosität, die L3 während dieser Zeit gesammelt hat.
- d) Der theoretische Wirkungsquerschnitt von Ereignissen des Typs $e^+e^- \rightarrow W^+W^-$ beträgt $17.3pb$, derjenige für $e^+e^- \rightarrow ZZ$ beträgt $1.1pb$. Wieviele Ereignisse von beiden Typen erwartet man während des fills 8750 ?

3. Abweichung von der Rutherford- und Mott-Streuung

Ein Elektronenstrahl mit einer Energie von 137 MeV wird an Goldkernen gestreut.

- a) Berechnen Sie den Rückstoss der Kerne. Kann man ihn vernachlässigen?
- b) Berechnen sie die Abweichung von der Rutherford-Formel beim Streuwinkel $\Theta = 90^\circ$, wenn der Spin des Elektrons berücksichtigt wird.
- c) Warum ist die berechnete Abweichung viel kleiner als die gemessene Abweichung?

4. Entdeckung des Positrons

Lese den beigefügten Artikel von C.D. Anderson über die Entdeckung des Positrons (Phys.Rev.43, 491 (1933)) und beantworte die folgenden Fragen:

- a) Warum handelt es sich bei den beobachteten Spuren nicht um Elektronen, und warum nicht um Protonen ?
- b) In welchem Prozess wurde nach Meinung der Autoren das zitierte Positron vermutlich produziert ?
- c) Was für ein Detektor wurde benutzt ? Versuche, etwas über die Funktionsweise dieses Detektors herauszubekommen. Mit welchem anderen Detektortyp ist er verwandt ? (Hinweis: benutze das WWW.)
- d) Wie misst man die Energie, die ein Teilchen in der Blei-Platte verliert ?
- e) Welche Energien hat das Positron von Figur 1 ?
- f) Woraus besteht nach der offenbar gängigen Meinung von 1933 ein Neutron ?
- g) Wozu diente das Experiment ursprünglich ?

The Positive Electron

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Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the

curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

ON August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron. Later study of the photograph by a whole group of men of the Norman Bridge Laboratory only tended to strengthen this view. The reason that this interpretation seemed so inevitable is that the track appearing on the upper half of the figure cannot possibly have a mass as large as that of a proton for as soon as the mass is fixed the energy is at once fixed by the curvature. The energy of a proton of that curvature comes out 300,000 volts, but a proton of that energy according to well established and universally accepted determinations¹ has a total range of about 5 mm in air while that portion of the range actually visible in this case exceeds 5 cm without a noticeable change in curvature. The only escape from this conclusion would be to assume that at exactly the same instant (and the sharpness of the tracks determines that instant to within about a fiftieth of a second) two independent

¹ Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, p. 294. Assuming $R \propto v^2$ and using data there given the range of a 300,000 volt proton in air S.T.P. is about 5 mm.

It is possible with the present experimental data only to assign rather wide limits to the

² C. D. Anderson, *Science* **76**, 238 (1932).

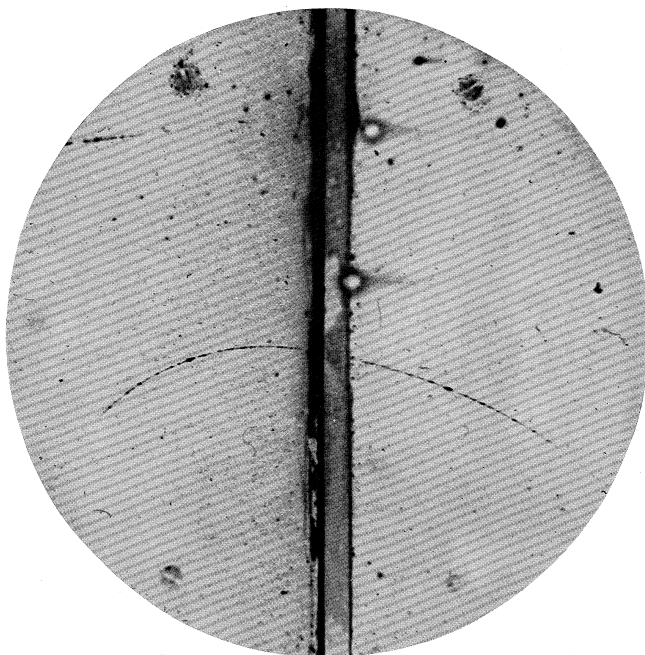


Fig. 1. A 63 million volt positron ($H_0 = 2.1 \times 10^6$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H_0 = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

magnitude of the charge and mass of the particle. The specific ionization was not in these cases measured, but it appears very probable, from a knowledge of the experimental conditions and by comparison with many other photographs of high- and low-speed electrons taken under the same conditions, that the charge cannot differ in magnitude from that of an electron by an amount as great as a factor of two. Furthermore, if the photograph is taken to represent a positive particle penetrating the 6 mm lead plate, then the energy lost, calculated for unit charge, is approximately 38 million electron-volts, this value being practically independent of the proper mass of the particle as long as it is not too many times larger than that of a free negative electron.

This value of 63 million volts per cm energy-loss for the positive particle it was considered legitimate to compare with the measured mean of approximately 35 million volts² for negative electrons of 200–300 million volts energy since the rate of energy-loss for particles of small mass is expected to change only very slowly over an energy range extending from several million to several hundred million volts. Allowance being made for experimental uncertainties, an upper limit to the rate of loss of energy for the positive particle can then be set at less than four times that for an electron, thus fixing, by the usual relation between rate of ionization and

² C. D. Anderson, *Phys. Rev.* **43**, 381A (1933).

charge, an upper limit to the charge less than twice that of the negative electron. It is concluded, therefore, that the magnitude of the charge of the positive electron which we shall henceforth contract to positron is very probably equal to that of a free negative electron which from symmetry considerations would naturally then be called a negatron.

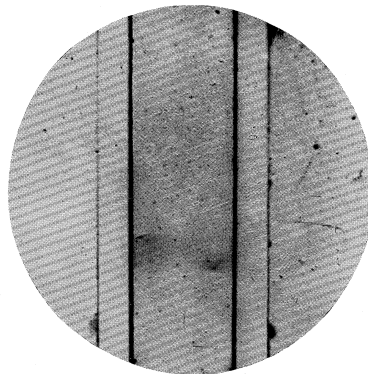


FIG. 2. A positron of 20 million volts energy ($H_0 = 7.1 \times 10^4$ gauss-cm) and a negatron of 30 million volts energy ($H_0 = 10.2 \times 10^4$ gauss-cm) projected from a plate of lead. The range of the positive particle precludes the possibility of ascribing it to a proton of the observed curvature.

It is pointed out that the effective depth of the chamber in the line of sight which is the same as the direction of the magnetic lines of force was 1 cm and its effective diameter at right angles to that line 14 cm, thus insuring that the particle crossed the chamber practically normal to the lines of force. The change in direction due to scattering in the lead,³ in this case about 8° measured in the plane of the chamber, is a probable value for a particle of this energy though less than the most probable value.

The magnitude of the proper mass cannot as yet be given further than to fix an upper limit to it about twenty times that of the electron mass. If Fig. 1 represents a particle of unit charge passing through the lead plate then the curvatures, on the basis of the information at hand on ionization, give too low a value for the energy-loss unless the mass is taken less than

twenty times that of the negative electron mass. Further determinations of H_0 for relatively low energy particles before and after they cross a known amount of matter, together with a study of ballistic effects such as close encounters with electrons, involving large energy transfers, will enable closer limits to be assigned to the mass.

To date, out of a group of 1300 photographs of cosmic-ray tracks 15 of these show positive particles penetrating the lead, none of which can be ascribed to particles with a mass as large as that of a proton, thus establishing the existence of positive particles of unit charge and of mass small compared to that of a proton. In many other cases due either to the short section of track available for measurement or to the high energy of the particle it is not possible to differentiate with certainty between protons and positrons. A comparison of the six or seven hundred positive-ray tracks which we have taken is, however, still consistent with the view that the positive particle which is knocked out of the nucleus by the incoming primary cosmic ray is in many cases a proton.

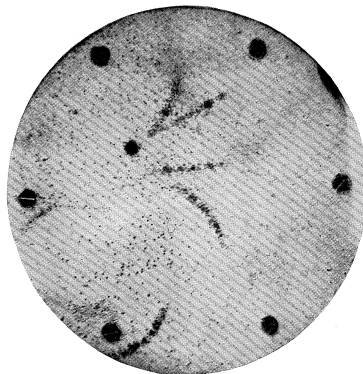


FIG. 3. A group of six particles projected from a region in the wall of the chamber. The track at the left of the central region of about 18 million volts energy ($H_0 = 6.2 \times 10^4$ gauss-cm) and the positron of about 20 million volts energy ($H_0 = 7.0 \times 10^4$ gauss-cm). Identification of the two tracks in the center is not possible. A negatron of about 15 million volts is shown at the left. This group represents early tracks which were broadened by the diffusion of the ions. The uniformity of this broadening for all the tracks shows that the particles entered the chamber at the same time.

From the fact that positrons occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from an atomic nucleus. If we retain the view that a nucleus consists of protons and neutrons (and α -

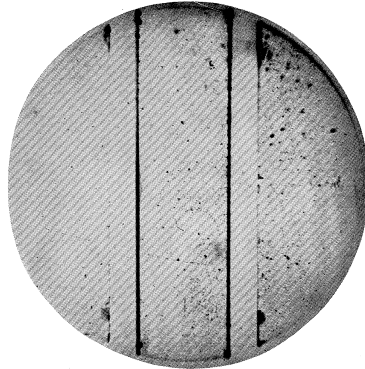


FIG. 4. A positron of about 200 million volts energy ($H_0 = 6.6 \times 10^4$ gauss-cm) penetrates the 11 mm lead plate and emerges with about 125 million volts energy ($H_0 = 4.2 \times 10^4$ gauss-cm). The assumption that the tracks represent a proton traversing the lead plate is inconsistent with the observed curvatures. The energies would then be, respectively, about 20 million and 8 million volts above and below the lead, energies too low to permit the proton to have a range sufficient to penetrate a plate of lead of 11 mm thickness.

particles) and that a neutron represents a close combination of a proton and electron, then from the electromagnetic theory as to the origin of mass the simplest assumption would seem to be that an encounter between the incoming primary

ray and a proton may take place in such a way as to expand the diameter of the proton to the same value as that possessed by the negatron. This process would release an energy of a billion electron-volts appearing as a secondary photon. As a second possibility the primary ray may disintegrate a neutron (or more than one) in the nucleus by the ejection either of a negatron or a positron with the result that a positive or a negative proton, as the case may be, remains in the nucleus in place of the neutron, the event occurring in this instance without the emission of a photon. This alternative, however, postulates the existence in the nucleus of a proton of negative charge, no evidence for which exists. The greater symmetry, however, between the positive and negative charges revealed by the discovery of the positron should prove a stimulus to search for evidence of the existence of negative protons. If the neutron should prove to be a fundamental particle of a new kind rather than a proton and negatron in close combination, the above hypotheses will have to be abandoned for the proton will then in all probability be represented as a complex particle consisting of a neutron and positron.

While this paper was in preparation press reports have announced that P. M. S. Blackett and G. Occhialini in an extensive study of cosmic-ray tracks have also obtained evidence for the existence of light positive particles confirming our earlier report.

I wish to express my great indebtedness to Professor R. A. Millikan for suggesting this research and for many helpful discussions during its progress. The able assistance of Mr. Seth H. Neddermeyer is also appreciated.