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## The early antiproton work

*Nobel Lecture, December 11, 1959*

It is a pleasure to have this opportunity of describing to you the early work on the antiproton, particularly that part which led to our first paper on the subject, in 1955, *Observation of Antiprotons*, by Professor Emilio Segrè, Dr. Clyde Wiegand, Professor Thomas Ypsilantis, and myself<sup>1</sup>. At the same time, I would like to convey my impressions of the conclusions that can be drawn purely from the *existence* of the antiproton. The later experiments, that have led to results quite unsuspected in the beginning, will be discussed in Professor Segrè's Nobel Lecture.

The first inkling of the idea that each electrically charged particle might have an oppositely charged counterpart may be seen in the theory of P.A.M. Dirac<sup>2</sup>, proposed in 1930. Perhaps you will allow me to oversimplify the situation, and to refer to the relativistic equation relating momentum  $p$  to energy  $E$ , namely,

$$E^2 = p^2 c^2 + m^2 c^4$$

where  $p$  = momentum,  $E$  = energy,  $m$  = mass,  $c$  = velocity of light.

It is clear that this equation, as it stands, permits either negative or positive values for the energy  $E$ . In everyday life we do not see particles of negative energy. Nevertheless the theory of Dirac encompassed electrons of negative energy. Dirac observed that an electron, which is electrically negative, if in a negative-energy state, would have some of the properties of a positively charged particle. In fact, at one time Dirac believed that the states of negative energy might be somehow related to protons, which are electrically positive, and not at all to electrons. As the Dirac equation was further studied, it became apparent that the negative energy-states represented a new phenomenon, one rather difficult to understand.

In Dirac's theory the negative energy-states were assumed to exist, but were taken to be completely filled with electrons normally. The Pauli exclusion principle (which forbids that two electrons should occupy the same state) was used to explain why an electron in a positive-energy state would

not normally drop into a filled state of negative energy. Perhaps this situation may be made clearer by reference to the following diagrams (see Fig. 1):

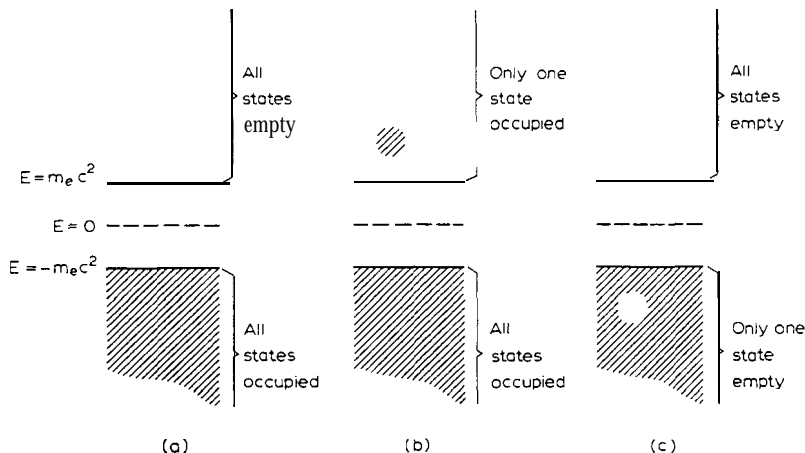


Fig. 1. Diagram of energy levels in the Dirac theory. Part (a) represents a vacuum, (b) a state with one electron present, and (c) a state with one positron.

The sketch on the left shows an empty vacuum, with all the positive-energy states empty and all the negative-energy states filled. Notice that the states of highest energy are represented as highest in the diagram. The second view shows a state with only one electron present, the filled negative-energy states being unobservable. The last view shows a state in which no positive-energy electron is present, but one electron is missing from the states of negative energy. Experimentally, this would correspond to one positive charge being present. This positive charge was shown to move exactly as if its mass were the same as that of the electron.

The Dirac theory was taken much more seriously after Professor C. D. Anderson's discovery of the positrons in 1932. This was the first of the anti-particles to be found, for the positron was really the antielectron, and might have been so named. The positron has the same mass as the electron, but has an opposite charge. Electron and positron are sometimes born as a pair, as in the process we call pair production by gamma rays. Electron and positron die as a pair, in a process we call annihilation. The electron and positron eat each other up, so to speak; what remains is energy in the form of gamma rays.

The Dirac theory was extremely successful in explaining electron and pos-

itron phenomena. Therefore, the question naturally arose: cannot the proton also be treated according to the Dirac theory? The proton, like the electron, has spin of one-half, and obeys the Pauli principle, i.e. two or more protons are never found simultaneously in exactly the same state. Still, the proton in some respects did not fit the Dirac pattern as well as the electron did. For example, the magnetic moment of the proton was not in accord with the theoretical value, while that of the electron was extremely close to it. While Professor Pauli did introduce a form of the Dirac theory that allowed agreement with the observed magnetic moment of the proton, still the theory had lost some of its simplicity.

If the Dirac theory were correct for describing protons as well as electrons, then it clearly would call for the existence of antiprotons as well as of protons, just as it had demanded the existence of positrons as well as of electrons.

According to the Dirac theory, the antiproton should have the properties indicated in Table 1.

Table 1 . Anticipated properties of the antiproton.

<i>Property</i>	<i>Values expected</i>
Mass	Same as the proton mass
Electric charge	Negative, opposite to the proton, equal to the electron charge
Spin	$\frac{1}{2}$ unit, same as the proton
Magnetic moment	Equal in magnitude, opposite in direction to the proton
Statistics	Fermi statistics, like the proton
Intrinsic parity	Opposite to the proton

Here, I would like to make a small digression. Physicists had asked themselves why neutrons and protons may turn into one another but are never completely destroyed. For example, why cannot a reaction such as the one shown here be observed?



Although the answer in deeper terms was not forthcoming, it was generally believed that there must be a fundamental rule specifically providing that the heavy particles are never destroyed (or created) singly. There remained the possibility, however, that one might make a pair, proton and antiproton, at the same time. Similarly, proton and antiproton might annihilate each other,

thus dying in pairs, one particle (the proton) and one antiparticle (the antiproton).

Thus it was expected that the creation of an antiproton would necessitate the simultaneous creation of a proton or a neutron. This meant that the energy necessary to produce a proton-antiproton pair would be twice the proton rest energy, or about 2 billion electron volts. It was also known that high-energy collisions were necessary, such as those between high-energy particles and particles at rest. A likely process might be one in which a very fast proton struck a stationary neutron. The proton would have to have about 6 billion electron volts of energy in order that 2 billion electron volts might be available to make new particles.

For many years physicists working with cosmic rays kept a sharp watch for antiprotons, for it was known that there were particles in the cosmic radiation with sufficient energy to produce antiprotons. Some events were observed<sup>4</sup> which might have involved an antiproton, but it was not possible to determine with certainty the presence of an antiproton. I should also mention that the possible antiproton events were remarkably few. As the years passed, people began to have serious doubts that the antiproton could indeed be produced.

I am told that the men responsible for the early design of the Bevatron, the large accelerator in Berkeley, California, were well aware that about 6 billion electron volts were needed to produce antiprotons, and that this fact was taken into consideration when the Bevatron energy, just 6 billion electron volts, was decided upon. Professor Edwin McMillan and the late Professor Ernest Lawrence were among the men who selected the energy of the Bevatron and were responsible for initiating its construction.

During the years when the Bevatron was under construction, doubts as to the existence of the antiproton tended to increase the interest in an experimental demonstration of the antiproton. To make this demonstration, it was necessary to show that after the Bevatron beam struck a piece of material, there were present among the particles issuing from nuclear collisions some particles of the same mass as that of the proton, but electrically negative, i.e. with an electric charge opposite to that of the proton. It is not difficult to sort out particles that are electrically negative, for in a magnetic field the negative particles are deflected in one direction, while positive particles are deflected in the opposite direction.

From the start it was understood that at least two independent quantities must be measured for the same particle, if the mass of the particle was to be

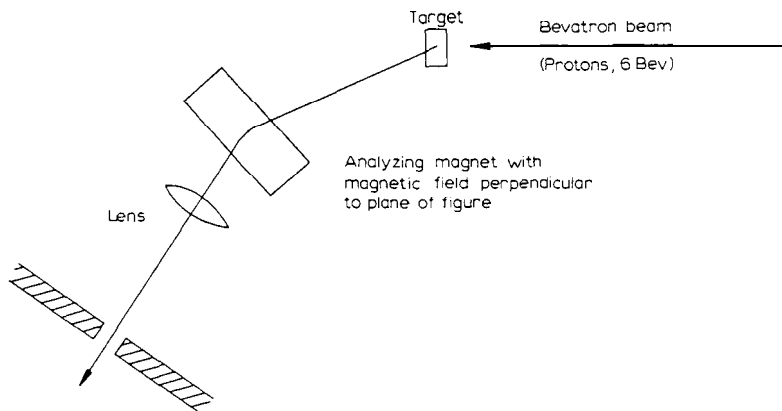


Fig. 2. Simple magnetic spectrograph for producing a beam of charged particles with known momentum.

determined. Any two of the following quantities would be adequate: momentum, energy, velocity, range (distance of penetration into a substance before coming to rest). For example, to measure only the momentum would be insufficient, because particles with various masses may have the same momentum. However, if two quantities are measured, then the mass of the particle can be calculated. After several possibilities were considered, it was decided that the two quantities to be measured should be momentum and velocity.

Perhaps I may remind you of the nonrelativistic relationship between momentum and velocity, namely

$$p = m v$$

where  $p$  = momentum,  $m$  = mass,  $v$  = velocity. Clearly, we may obtain the mass of a particle by measuring momentum and velocity, obtaining the mass as  $m = p/v$ . For particles travelling at nearly the speed of light, the expressions are not as simple as these; but it is still true that if momentum and velocity are simultaneously measured, then the mass of the particle may be determined. The relationships are

$$p = \frac{mv}{\sqrt{1 - v^2/c^2}} \qquad m = \frac{P \sqrt{1 - v^2/c^2}}{v}$$

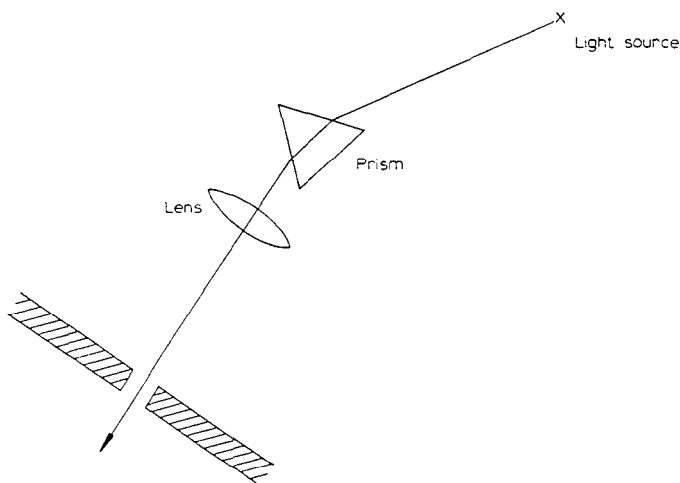


Fig. 3. Optical spectrograph.

The well-established method of measuring the momentum of atomic particles is to measure their deflection in a known magnetic field. In fact, one may set up a system of magnets through which only particles of a certain momentum interval pass. Such a system may be arranged as shown in the diagram of Fig. 2.

The high-energy proton beam strikes a target, which might be a piece of copper. Fragments of nuclear collisions emerge from the target in all directions, some of which enter the region of the magnetic field, the rest being wasted. For certain values of momentum, negative particles are deflected by the correct amount and pass through the aperture in the collimator. Other particles are stopped by the walls of the collimator.

A lens is also shown in the same figure. The use of magnetic lenses was suggested to us by Dr. Oreste Piccioni, who pointed out that a greater number of useful particles would pass through the system if lenses were employed.

I will not describe the lenses in detail, except to say that each lens is composed of three quadrupole magnets. The lens action is very similar to the action of a simple optical lens for light. In fact, the system of magnets we are discussing acts, for charged particles, just as the system shown in Fig. 3 acts for light.

Here a light source replaces the target, and the analyzing magnet is replaced by a glass prism. Through the final slit, the system shown would only

allow light to pass in a narrow range of wavelengths or colors. I will refer to this system as a spectrograph, whether it be for light or for charged particles.

I have said that only negative particles would be present in the beam formed by the magnetic spectrograph, since positive particles would be deflected in the opposite direction and would not pass through the collimator. By reversing the magnetic field, however, we may use the same spectrograph to select positive particles, if these are desired.

The final arrangement of magnets that we have used consists of two such spectrographs, one following the other. It is shown in Fig. 4.

The first spectrograph extends from the target to the first focus point. The second spectrograph extends from the first to the second focus point. The first spectrograph acted as a preliminary sorting device to provide a relatively pure beam of particles for the second spectrograph, where the experiment itself was performed.

Now let us discuss the velocity of the antiprotons that may be found. The most copious production of antiprotons was expected to be at a velocity of 87 percent of the velocity of light, while the other background particles, such as mesons, would be travelling at approximately 99 percent of the velocity of light. To make the experiment somewhat easier, slightly slower antiprotons were chosen, with  $v = 0.78 c$ , or 78 percent of the velocity of light.

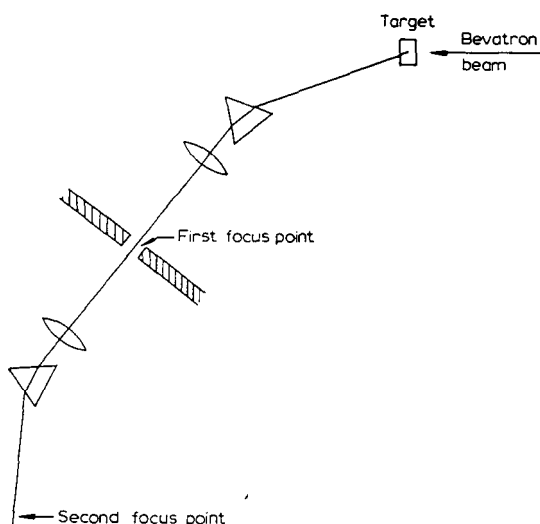


Fig. 4. Final arrangement of magnets, represented in optical analogy.

One of the simplest means of determining velocity is to measure the time of flight between two counters, and this was the method used. A counter was placed at the first focus point, and another counter at the second focus point. The spacing of these counters was 12 meters. Mesons, which travel near the speed of light, would take 40 millimicroseconds (40 billionths of a second) to pass over this distance, but antiprotons of the same momentum would take 51 millimicroseconds. The difference of 11 millimicroseconds is not great, but it is within the capability of modern electronic circuits to distinguish with certainty between the two time intervals.

Unfortunately, when many mesons are passing through the system in close succession, it will sometimes happen that two mesons have exactly the right spacing between them to imitate an antiproton, i.e. just 11 millimicroseconds. We will call this the accidental coincidence of two mesons. To avoid having the electronic circuits « fooled » by two mesons in close succession, it was considered important to have another method of determining velocity in use at the same time. For this purpose, a Čerenkov counter was constructed. In fact, the study of the Čerenkov counter was one of the first steps taken in the preparation of the experiment. I would like to describe it here.

The basic principles of the Čerenkov radiation are familiar, since Professor Čerenkov must have been speaking from this rostrum just one year ago, but those principles especially relevant to the Čerenkov counter used in the antiproton experiment should be reviewed here. In an optical medium such as

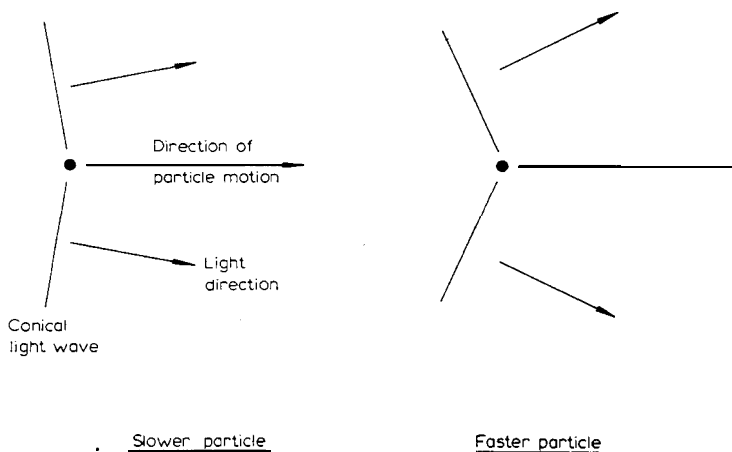


Fig. 5. Diagram of Čerenkov radiation. The angle of emission of Čerenkov light depends on the speed of the charged particle.

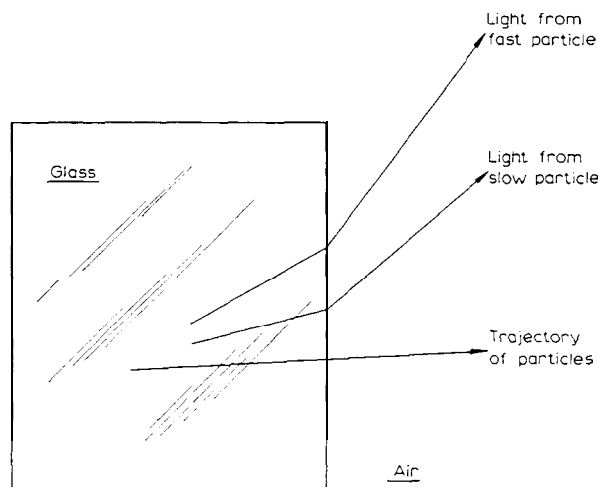


Fig. 6. Refraction of Čerenkov radiation at the interface between glass and air.

glass, light moves more slowly than in a vacuum. Although no particle may move faster than the speed of light in vacuum, a particle may move faster than the speed of light in glass. When this happens with an electrically charged particle, Čerenkov light is emitted, at different angles for particles of different velocity. This is illustrated in Fig. 5.

When the Čerenkov light passes out of the piece of glass into air, it is refracted at the surface, but it continues to be true that the direction of the light in air is dependent upon the velocity of the particle, as is shown in Fig. 6.

A cylindrical mirror was arranged to reflect only light emitted in the right direction. This light was then refocused within a small region where it could be detected by a photomultiplier. The design of this counter is shown in Fig. 7.

For the purpose of understanding the action of the counter, we may think of one photomultiplier, placed along the axis of the instrument, catching the Čerenkov radiation emitted by particles travelling parallel to the axis with the correct velocity. In practice, the light was divided into three parts by three flat mirrors, to avoid having the beam of particles traverse the photomultiplier. In the first experiment the material of the Čerenkov radiator was fused quartz.

At the time that I first designed one of these « velocity selecting » counters I thought that the design was original with me. I later realized, however, that the design is the same as that of Dr. Samuel Lindenbaum. I had heard

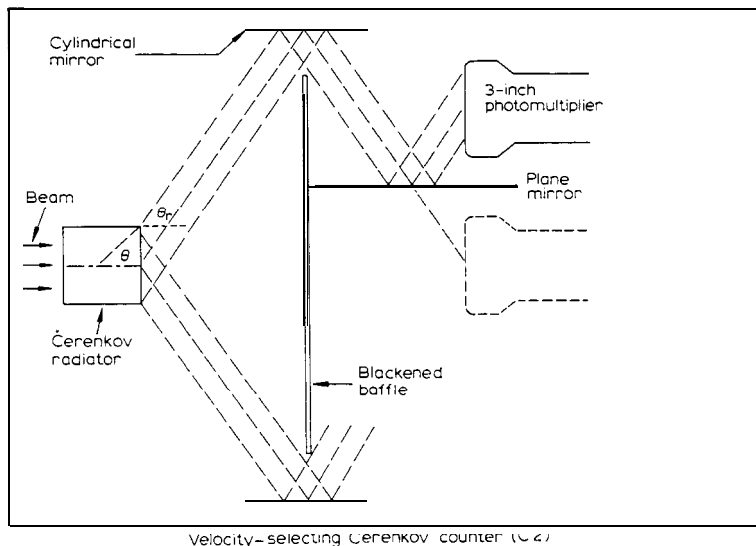


Fig. 7. View of the velocity-selecting Čerenkov counter.

discussion of the Lindenbaum counter, but had not then understood it.

We assumed that our greatest difficulty in identifying antiprotons with certainty would be the possibility of a mistake in the determination of velocity. Accordingly, we also used another Čerenkov counter, of a more conventional design. It was a container of liquid, with an index of refraction of 1.28, viewed directly by a photomultiplier. Particles moving as slowly as our hoped-for antiprotons would produce no Čerenkov light in this material, since they would not be moving faster than light in that medium. However, faster particles, such as mesons and electrons, would produce Čerenkov light in this material and would give rise to a pulse at the output of this counter. Since this counter was to serve as a warning against particles faster than antiprotons, we may call it a guard counter. The liquid used in the guard counter was a fluorocarbon.

As the whole system was assembled, the plan of the apparatus looked as follows (see Fig. 8) :

Our electronic circuits gave out an electrical signal each time the following events occurred within a short time interval: the two counters indicated as S1 and S2 counted with a relative time delay of  $51 \pm 5$  millimicroseconds, and the velocity-selecting counter C<sub>2</sub> also gave a signal in at least two of its three photomultipliers. Whenever these events occurred, it meant a potential

antiproton had been seen in the apparatus. This signal was used to start an oscilloscope, from which a picture of the pulses in the counters S1, S2, and the guard counter could be obtained.

Three such pictures are shown in Fig. 9. The horizontal motion of the dot on the oscilloscope screen is uniform, so the curve shown represents an electrical signal as a function of time. The first pulse on each curve (oscilloscope trace) is due to the counter S1, the second is due to S2, and the third (if present) to the guard counter C1.

The pulses themselves look rather broad in this figure, but by careful measurement of the position of the pulse at its beginning, the difference in time between pulses can be measured to an accuracy of about one millimicrosecond.

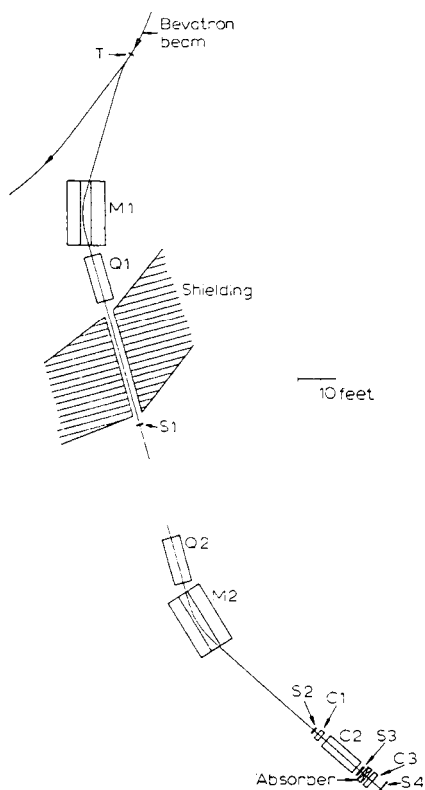


Fig. 8. Plan view of the apparatus used in the discovery of antiprotons. T indicates the target, Q1 and Q2 are magnetic lenses, C1 is the guard counter, and C2 is the velocity-selecting Čerenkov counter. The last two counters (C3 and S4) may be ignored.

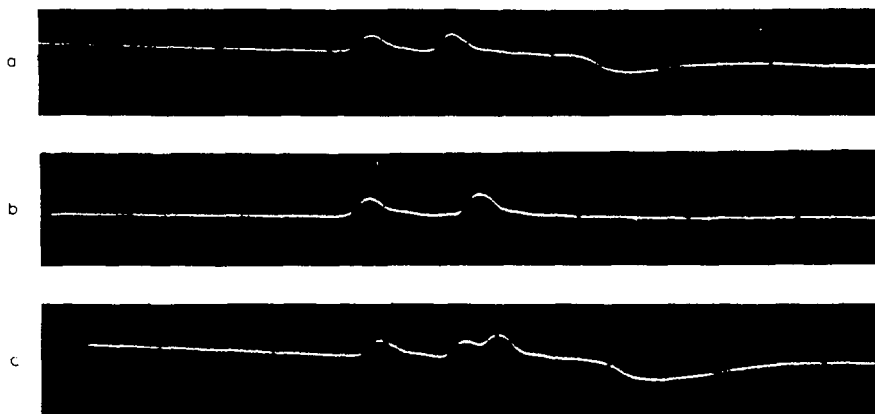


Fig. 9. Oscilloscope traces produced by (a) a meson, (b) an antiproton, (c) an accidental coincidence. The first two pulses are due to scintillation counters S<sub>1</sub> and S<sub>2</sub>. The separation is noticeably different for a meson and for an antiproton.

Since the momentum is accurately known from the magnet arrangement, and since each time measurement determines the velocity of the particle in question, we have in effect a rough mass measurement of each antiproton.

Fig. 10 (a) shows the distribution of the differences in time for mesons. It was obtained when the system was adjusted to register mesons. Fig. 10 (b), the distribution of times of flight for antiprotons, was obtained when the system was adjusted in the normal way, to accept antiprotons but reject mesons. The distribution is well-peaked at the expected time of flight of antiprotons. Fig. 10 (c) shows a representative group of accidental coincidences.

In the early stages of the experiment, we were in some danger of failing to observe antiprotons, because we had set our apparatus for a slightly different mass than the proton mass, without our intending to do so. It was essentially an error in the alignment of the apparatus. Fortunately, we were able to reverse the magnetic fields in all the magnets and thus look for protons. Discovering very few, we soon found the error of alignment. After suitable adjustments, protons were easily observed and, when the magnetic fields were again reversed, possible antiproton events appeared.

Following approximately twenty such possible events, the equipment was subjected to a series of tests designed to determine whether the antiprotons seen were completely real, or whether they might be due to some failure of the apparatus. One effective test involved our intentionally tuning the sys-

tem to a somewhat different mass than the proton mass to test whether it was true that the antiprotons no longer registered. This indicated that the apparatus really was sensitive to the mass of the particles. Another important test entailed lowering the energy of the beam of the Bevatron, to make sure that the supposed antiprotons disappeared when the beam energy was sufficiently low.

Fig. 11 shows the fraction of antiprotons in the beam as a function of the energy of the original proton beam. Later calculations showed that this result was reasonable, and that a few antiprotons should be produced at 5 BeV, as was observed. These tests convinced us that we had indeed observed the production of antiprotons.

The methods I have described are now well-known to physicists working in this field. One may ask, why is the present work considered such an accomplishment? The answer lies partly in the fact that the antiprotons are

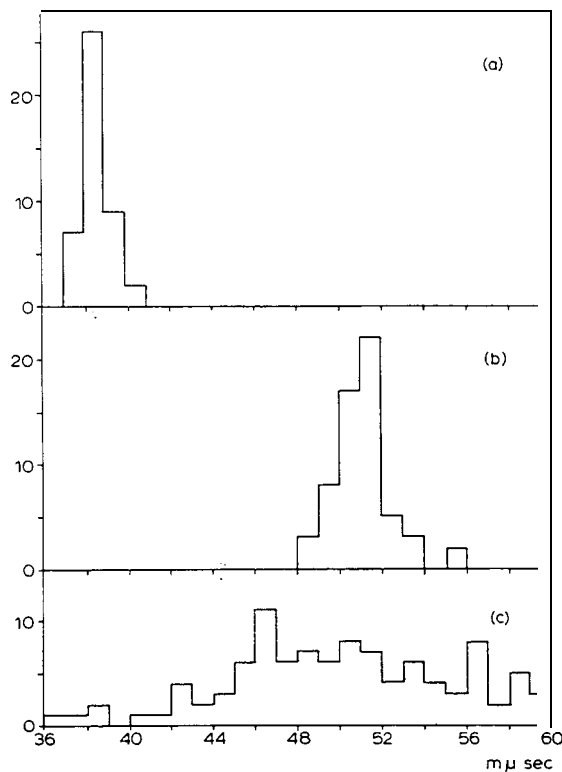


Fig. 10. (a) Histogram of times of flight for mesons; (b) histogram of times of flight for antiprotons; (c) apparent flight times for accidental coincidences.

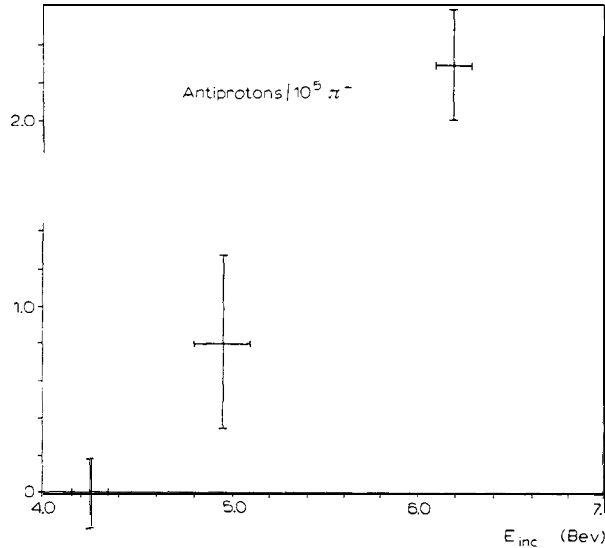


Fig. 11. Excitation curve for the production of antiprotons, relative to meson production, as a function of the energy of the protons in the Bevatron.

extremely rare in a beam of many other particles. Early rough estimates indicated that an antiproton might be produced only once in each million collisions within the Bevatron target. At the same time, it was estimated that antiprotons would largely go in a forward direction with respect to the beam, while to a great extent other particles would go in all directions. This effect was estimated as giving a ten-fold enrichment in the forward direction, meaning that there would be conceivably one antiproton among each 100,000 of the other particles, which were mostly mesons. Fortunately the antiprotons were slightly more numerous, being 1 in 30,000 particles in the magnetically analyzed beam. If there had been appreciably fewer antiprotons, we might altogether have missed seeing them on the first try. As it was, we saw only one antiproton every fifteen minutes with the first apparatus.

In conjunction with the counter experiment I have described, we also collaborated in a related experiment<sup>5</sup> using photographic emulsions. Within a short time after the first counter experiments were completed, examples of the annihilation phenomenon were seen, in which the antiproton and a proton or neutron from an ordinary nucleus die simultaneously. In their place emerge about five  $\pi$  mesons.

Fig. 12 shows how one of the annihilation events looked under the microscope in the photographic emulsion.

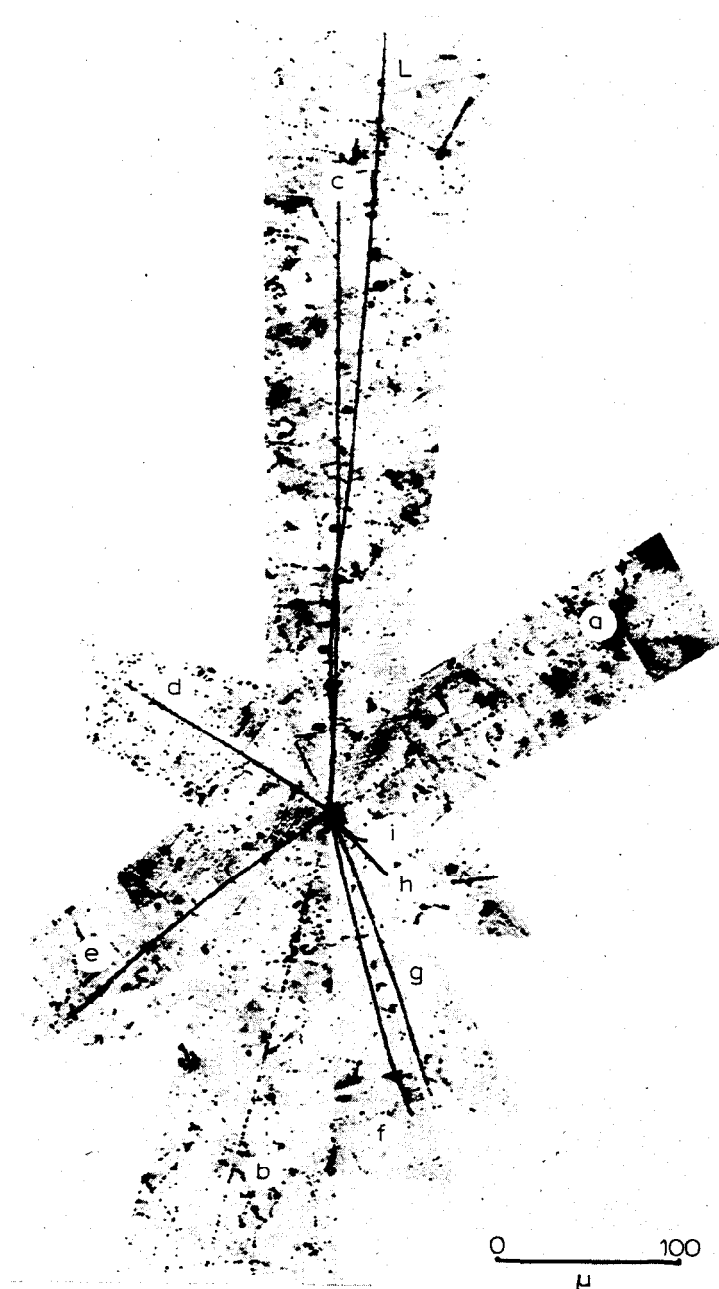


Fig. 12. Reproduction of an antiproton star as seen in nuclear emulsion. L is the incoming antiproton track. Tracks a and b are due to mesons. The remaining tracks are due to protons or alpha particles.

The work with photographic emulsions involved many people, among whom I would like to mention especially Professor Gerson Goldhaber and Professor Edoardo Amaldi from Rome. I would like to mention that it was a young Swedish physicist, Dr. A. G. Ekspong, now at the University of Uppsala but then working with us in Berkeley, who observed under the microscope the first of the annihilation events with very large visible release of energy. That star gave the final visual proof through the phenomenon of annihilation that we were dealing with antiprotons, rather than with any other similar particle. The large release of energy showed not only that the incoming particle (antiproton) died in the production of the star, but that additional energy must have been supplied by the death of an ordinary nucleon (neutron or proton).

By the conclusion of these early experiments, the existence of the antiproton had been established beyond doubt; its charge was of course negative; its mass was established as equal to the proton mass, to within 3 percent. Furthermore, the data on production in the Bevatron at different proton-beam energies clearly indicated that antiprotons are born in pairs with ordinary protons or neutrons. The emulsions showed that they die in the annihilation process.

Since the proton and neutron are close sisters, it was expected that the discovery of the antineutron would quickly follow that of the antiproton. In fact, it is natural to infer that antiparticles of all charged particles exist. This inference also extends to the neutral particles that have some non-zero quantum number analogous to electric charge. Today there is much experimental evidence, as well as strong theoretical suggestions, to confirm this.

In conclusion, I would like to name some of the many people besides Professor Segrè and myself who have been responsible for the success of this work. Obviously, our co-authors, Dr. Clyde Wiegand and Professor Thomas Ypsilantis, have contributed heavily. I wish to mention particularly the work of Dr. Wiegand, for his part was absolutely essential to our achievement. For the very existence of the large accelerator, we owe a great debt to the late Professor Ernest O. Lawrence, to Professor Edwin M. McMillan, now Director of the Lawrence Radiation Laboratory, and especially to Dr. Edward Lofgren, who has been responsible for the construction and operation of the Bevatron. I have mentioned Dr. Oreste Piccioni's contribution with respect to the use of quadrupole lenses. I should also cite the important work of Dr. Herbert M. Steiner, who collaborated with us throughout the whole experiment. Needless to say, we received wonderful cooperation

from the men who operate the Bevatron and from the engineers and technicians who aided us in many ways with the design, the construction, and the installation of the apparatus. Our own work was built directly upon the previous accomplishments of many eminent scientists, including especially P. A. M. Dirac, C. D. Anderson, E. M. McMillan, and P. A. Cerenkov.

Other important work closely related to the same subject has occupied Professor Amaldi with his colleagues at the University of Rome, and Professor Gerson Goldhaber with his collaborators in Berkeley. I think it is clear, therefore, that the work of many people is being honored today.

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