PREHISTORY OF THE ANTIPROTON DISCOVERY

Laurie M. Brown, Northwestern University

Introduction—Antiproton Jubilee and Einstein Year 2005

From relativity to quantum mechanics

Quantum mechanics and the positron

Negative protons in nuclear structure

Negative protons in the cosmic rays

Was it "obvious" that antiprotons should exist?

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Introduction.

It is a great pleasure to be here at the laboratory which fifty years ago first produced and detected the antiproton. The symposium organizers have asked me to discuss the prehistory of the discovery, beginning with 1905. One of the leaders of the experimental team, Owen Chamberlain, has said: "I believe the antiproton story starts with P.A.M. Dirac, who in 1930 published his paper 'A Theory of Electrons and Protons'."[1,2] (Chamberlain pointed out that the "protons" in the title should really be "positrons," as Dirac realized a year later.) However, perhaps the story starts earlier, even before the advent of quantum mechanics.[3] Since this antiproton jubilee year is also known as the "Einstein Year", we begin by recalling one of Einstein's great papers of 1905.

One hundred years ago Einstein taught us that $E=mc^2$, which allows the conversion of mass into energy and energy into particles. Performing the latter feat was one of the aims of the post WW II accelerators, including, of course, Berkeley's Bevatron. Einstein's 1921 Nobel Prize was "for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect," but not (as a letter from the Nobel Committee informed him) for relativity; that was still too controversial. The 1923 prize went to Robert Millikan, in part for confirming Einstein's photoelectric equation and also for measuring the electron charge. However, Millikan still objected to what he called "Einstein's 'unthinkable', 'bold' and 'reckless' hypothesis of an 'electromagnetic light corpuscle of energy $h\nu$'."[4]

Using α-particle bombardment of nitrogen, toward the end of the First World War, Ernest Rutherford produced the first artificial nuclear reaction and showed that one of the products was the hydrogen nucleus, for which he invented the name *proton*. By 1920, we could say there were at least two elementary particles. (Most physicists thought there no others!) Rutherford also speculated on the existence of a "collapsed" form of the hydrogen atom that he named *neutron*. As for the light quantum, Millikan's negative attitude was widely shared by physicists well into the 1920s.[5]

From relativity to quantum mechanics

Rutherford had bombarded metallic foils with α-particles and showed in 1909-1911 that the atom has a dense positive nucleus surrounded by electrons, like a tiny solar system. The α-particle itself was a helium nucleus, and some regarded it as a more elementary constituent of other nuclei. Niels Bohr removed the instability of Rutherford's atomic model by quantizing the electron orbits and introducing integer quantum numbers. Planck's constant h acquired a new role in physics when Bohr postulated that spectral lines of frequency ν obey the equation $h\nu = E_i - E_f$, the difference of energies of the initial and final orbits. In 1912, Victor Hess showed that the cosmic rays have extraterrestrial origin, and it became clear that such penetrating rays could not originate from decaying atoms or radioactive nuclei.

X-ray studies of Henry Moseley in 1913 showed that the atomic number Z of the chemists was the number of electrons per atom, and thus began the study of atomic and nuclear physics throughout the periodic table. Arnold Sommerfeld extended Bohr's atomic theory with additional quantum numbers; the Bohr-Sommerfeld theory gave a semi-quantitative account of the periodic table if one adopted Wolfgang Pauli's empirical exclusion principle. In 1925 Goudsmit and Uhlenbeck proposed that half-integer quantum numbers, needed to explain the so-called anomalous Zeeman effect, arose because the electron has a spin angular momentum of $(1/2)\hbar$ and a magnetic moment $e\hbar/mc$.

In 1922, Arthur Compton scattered X-rays from almost free electrons, and proved that light quanta have particle-like properties, including momentum. In 1924, Louis de Broglie proposed, and later experiments confirmed, that electrons have wave-like properties. As a result there was a wave-particle paradox for *both* photons and electrons

Quantum mechanics and the positron

I will merely touch on the history of quantum mechanics, which has been treated in a work comprising six large volumes.[6] Four of these deal with the six months between Heisenberg's discovery of quantum mechanics, published in September 1925, and Schrödinger's equation, published in March 1926, during which the following concepts were established:

a) Observable quantities are represented by non-commuting operators for which Dirac worked out a "quantum algebra." (His "transformation theory" of 1927 includes Heisenberg's matrix mechanics and Schrödinger's wave mechanics as limiting cases.)

b) The allowed atomic energy states are described by eigenstates of a suitable Hamiltonian operator, the energies being the corresponding eigenvalues.

c) Atomic transition probabilities (or spectral line intensities) are proportional to the absolute squares of complex amplitudes relating the initial and final atomic states.

d) Dirac and Pauli (independently) solved the non-relativistic hydrogen spectrum.

e) Enrico Fermi proposed a new kind of quantum statistics consistent with the Pauli exclusion principle. (February 1926)

This theoretical understanding would prove to be sufficient to solve many problems of atomic, nuclear, and condensed matter physics for decades or more, but there remained three outstanding fundamental problems: to make the theory relativistic, to explain the origin of the electron's spin and magnetic moment, and to make a quantum theory of the interacting electromagnetic field (*QED*). Within a few years Paul Dirac addressed all these problems successfully.[7]

Setting out to make a relativistic electron theory, he found that as a bonus he had solved the spin and magnetic moment problems as well. Dirac's transformation theory required observables, such as the energy operator **H**, to be represented by *linear* operators. Then the equation $\mathbf{H}\psi = E\psi$ describes a stationary state of relativistic energy E, where $E^2 = \mathbf{p}^2 + m^2$ (with c=1). The linearity of **H** implies that it has the form $\beta m + \boldsymbol{\alpha}\cdot\mathbf{p}$, so that $(\beta m + \boldsymbol{\alpha}\cdot\mathbf{p})^2 = E^2$. Satisfying the last equation requires that β and $\boldsymbol{\alpha}$ $(=\alpha_x, \alpha_y, \alpha_z)$ must be anti-commuting 4x4 matrices, and thus ψ is a column matrix having four components. Two components are indeed necessary to describe the electron's spin of ½, but what do the other two degrees of freedom represent?

The answer is that both signs of E are permitted by the energy-momentum equation. In relativity, negative energy means negative mass, a meaningless concept. But in quantum theory transitions can take place across the $2mc^2$ energy gap, and theorists showed that the negative energy states were *essential* to obtain even the well-known Thomson scattering formula for light. The "extra" states were at first a terrible nuisance, tolerated only because the rest of the theory worked so well and gave the correct electron spin, magnetic moment, and hydrogen spectrum.

This brings us to the point where Owen Chamberlain began his story—to Dirac's article of 1930.[2] Referring to the need for negative energy solutions of his relativistic electron equation, Dirac wrote: "This result has led people to suspect a connection between the negative energy electron and the proton." However, protons do not have negative energy! Dirac's solution was the "hole theory", in which one assumes that "all the states of negative energy are occupied, except perhaps for a few of small velocity." (Few, that is relative to the total number of such states, which is infinite.) The Pauli exclusion principle, he wrote, will prevent most electrons from jumping into the occupied, states. "[The] holes will be things of positive energy and will therefore be in this respect like ordinary particles…We are therefore led to the assumption that the holes in the distribution of negative energy electrons are the protons."

Many physicists, however, considered Dirac's bold suggestion of "holes" being protons to be foolhardy, and he also realized that the same transformation of the Dirac equation that gives solutions of opposite charge (charge conjugation), requires that their masses be equal. In a lecture given in 1978, Dirac explained that in 1930: "People believed that the whole of matter had to be explained in terms of electrons and protons."[8] He continued:

> I just didn't dare to postulate a new particle at that stage, because the whole climate of opinion at that time was against new particles. So I thought that this hole would have to be a proton. I was very well aware that there was an enormous mass difference between the proton and the electron, but I thought that in some way the Coulomb force between the electrons in the sea might lead to the appearance of a different rest mass for the proton. So I published my paper on this subject as a theory of electrons and protons.

But in 1931, in an article in which he introduced quantized magnetic monopoles, Dirac wrote that the interpretation of holes as protons must be abandoned:[9]

> A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to the electron. We may call such a particle an anti-electron…The protons on the above view are quite unconnected with electrons. Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton.

In September 1932, Carl Anderson announced the observation of a positive electron in a cosmic-ray cloud chamber picture and in 1933 P.M.S. Blackett and G.P.S. Occhialini, using a counter-operated cloud chamber, observed examples of electron-positron pair production.[10] The following year, Irène Curie and Frederic Joliot observed positrons in artificially induced radioactivity.

In the first edition (1930) of his great treatise, "The Principles of Quantum Mechanics," Dirac had the theory right but the particle wrong. In the chapter on the relativity theory of the electron, he said, "We are led to infer that the negative energy solutions refer to the motion of protons." In the second edition (1935) the language of the corresponding section is almost identical, except that "positron" replaces "proton" everywhere. The phrase above is replaced by:

> We are led to infer that the negative energy solutions refer to the motion of a new kind of particle having the mass of an electron and opposite charge. Such particles have been observed and are called positrons.

Negative protons in nuclear structure

In Dirac's 1931 article on "quantized singularities" (i.e., magnetic monopoles) he expressed the view that protons "presumably" obey their own hole theory and thus antiprotons should exist. However, in his Nobel Address in 1933 he mentioned "some recent experimental evidence by Stern about the spin magnetic moment of the proton, which conflicts with this theory for the proton."[11] Perhaps the heavy proton obeyed some more complicated theory.

Nevertheless, he continued:

> In any case I think it is probable that negative protons can exist, since…there is a complete and perfect symmetry between positive and negative electric charge, and if this symmetry is really fundamental in nature, it must be possible to reverse the charge on any kind of particle.

That would make a case for the existence of a new kind of matter, and Dirac concluded his address by saying:

> It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact there may be half the stars of each kind. The two kinds of stars both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Dirac was not the only one who felt, on general symmetry grounds, that negative protons should exist. But these were not necessarily antiprotons, capable of annihilation with protons.[12] One of the main exponents of negative protons as stable nuclear constituents was George Gamow.[13] Using Heisenberg's neutron–proton model of 1933, in which n-p exchange forces dominate the nuclear binding, if negative and positive protons had a net attractive force, that would require stable nuclei to have *too many* negative protons. Thus Gamow assumed a repulsive force, so that a small number of negative protons would just raise the stability curve sufficiently to match some of the observations of the time. The outstanding case was Be^9, which is stable but was predicted to spontaneously decay. Gamow wanted it to consist of five protons, three neutrons, and a negative proton.

At an international conference held in London in October 1934, Enrico Fermi said: "I heartily agree with Dr. Gamow that both his empirical evidence and the more general argument of symmetry strongly support the possibility of the existence of a negative proton."[14] Although pointing out a difficulty with the proposal, he said, "I agree with Dr. Gamow that this difficulty is in no way a fundamental one." Others supporting Gamow were Niels Bohr and Wolfgang Pauli, who remained skeptical about Dirac's hole theory, even after the positron discovery.

In the 1937 edition of Gamow's book on nuclear theory, he included a section headed "The possible existence of negative protons."[15] The stability of Be^9 on the ordinary model had been rescued by more accurate measurements of nuclear masses, but Gamow argued that negative protons would permit observed nuclear isomerism. However, he said: "These protons would be symmetrical to positive protons with respect to neutrons; their relation to ordinary protons would not…be analogous to that between positrons and electrons on Dirac's theory." (In modern language, he was proposing that p^+, p^-, and n would be an isotriplet, but without invoking the charge independence of their forces.)

Even as late as 1946, experimental searches for negative proton as nuclear constituents in fission fragments were reported at an international conference held at the Cavendish Laboratory in Cambridge. Negative results were obtained at Chalk River, Canada, as well as Cambridge, with the conclusion that "the transition probability for the production of a pair of protons of opposite charge from two neutrons in a nucleus of intermediate charge ($34<Z<60$) must be set lower than 10^{-8} sec^{-1}."[16]

Negative protons in the cosmic rays

One reason that Gamow introduced negative protons was that cosmic rays physicists had reported observing them in 1933. Immediately following Gamow's *Letter* of 1934 in the *Physical Review* on negative protons was one by E.J. Williams. (Both physicists were at the time at Bohr's institute in Copenhagen.) Williams' *Letter* called attention to the cloud -chamber measurements of a German, Paul Kunze, who identified charged particles up to a GeV in energy by their curvature in a strong magnetic field. There were both positive and negative charges and according to Williams, "these high energy particles are protons rather than electrons."[17]

When Carl Anderson announced his discovery of a positive electron in the cosmic rays in 1932 he was not aware of Dirac's theory. In February 1933 he published an experiment with fifteen tracks that he called "positrons", but he had not observed pair production (as Blackett and Occhialini had). Anderson suggested as a possible mechanism: "A primary cosmic ray [at Caltech that meant a gamma ray] may disintegrate a neutron…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 the place of the neutron." While there was no evidence for a negative proton, Anderson said: "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."[18]

In 1936, Anderson received the Nobel Prize for the positron discovery (sharing it with Victor Hess for the discovery of cosmic rays). In his Nobel Address he mentioned observing other new particles of both charges, concluding with the sentence: "These highly penetrating particles, although not free positive and negative electrons, will provide interesting material for future study." The particles in question were much more massive than the electron and were at first confused with protons. Then they were identified as the mesons that that Yukawa had proposed as the "heavy quanta" carrying the nuclear force. They remained enigmatic for the next decade and were called by many names: heavy electrons, mesotrons, mesons, Yukons, etc.--eventually they were called muons and were found to really be "heavy electrons."

Various physicists did suggest that true antiprotons are present in the primary cosmic rays. I will mention only Niels Arley of Bohr's institute, who began a survey off cosmic ray data in 1944 and whose paper published in 1946 has an abstract containing these lines:[19]

> The hypothesis is here put forward that the primary radiation consists of *negative protons* as well as positive ones, the former being mainly annihilated at the top of the atmosphere thus giving rise to the soft component, the latter ones being transformed into mesons thus giving rise to the hard component.

The annihilation cross-section calculated from the Dirac theory was much too small to account for the absence of antiprotons at lower altitudes, but Arley stated that Heisenberg had given arguments why "a break-down of the present theory must just be expected to take place for this process." However, Arley's analysis did not win many converts.

The decade following the end of World War II saw a rich flourishing of particle physics, with new accelerators and the development of detection techniques. The cosmic rays were responsible for most of the new particle discoveries before 1955, at which point the big accelerators took over. The nuclear emulsion physicists observed the *pi-mu-e* decay chain, while the operators of a triggered cloud chamber discovered the V-particles, leading to the concept of *strangeness*.

No dedicated search for antiprotons took place before the Bevatron, but the Rome group of Eduardo Amaldi found one very suggestive event, a double star in a large emulsion stack exposed in a high altitude balloon flight over Sardinia in 1953.[20] The track connecting the two stars was of protonic mass and the energy release in the second star was compatible with antiproton annihilation. Soon after this event was observed, the Berkeley group began seeing antiprotons with counters at the Bevatron. Emulsions placed in the beam by a Berkeley-Rome collaboration also began to turn up events.[21]

Was it "obvious" that antiprotons should exist?

Victor Weisskopf, describing the attitude of physicists in the 1930s, wrote:

> How unreasonable the idea of antimatter seemed at that time may be illustrated by the fact that many of us did not believe in the existence of an antiparticle to the proton because of its anomalous moment. The latter was measured by Otto Stern in 1933 and could be interpreted as an indication that that the proton does not obey the Dirac equation. The fundamental character of the matter-antimatter symmetry and its independence of the special wave equations were recognized only very slowly by most physicists.[22]

Although the hole theory became accepted for electrons after the discovery of pair production and annihilation, it was not always applied for other particles. For example, Enrico Fermi tried to distance himself from it when he proposed his β-decay theory, writing:

> The total number of electrons and neutrinos is not necessarily constant. Electrons (or neutrinos) can be created or destroyed. This possibility, however, has no analogy with the possibility of creation or destruction of an electron-positron pair; if in fact one interprets the positron as a "hole" of Dirac, one can consider simply the last process as a quantum jump of an electron from a state of negative energy to one of positive energy, with conservation of the total number (infinitely large) of the electrons.[23]

However, Fermi's student Gian-Carlo Wick and, also Yukawa, imagined that in β-decay an electron jumps from a negative energy state and leaves behind a neutrino hole, i.e., an antineutrino.

Pauli wrote to Heisenberg in 1934 about Niels Bohr's attitude, as follows:

> Bohr thought much about negative protons and believes to have evidence for their existence in the cosmic radiation. There are theoretical a swell as experimental (Stern's experiment) reasons for assuming that the relativistic Dirac wave equation is not at all applicable to heavy particles, and Bohr believes therefore that the negative protons should not be related to the hole idea and hence not annihilate with the positive protons.[24]

In the two decades that followed, attitudes began to change, as the complexity of particle physics became more apparent. The new heavy electrons (muons) defied the attempt to make them conform to Hideki Yukawa's postulated nuclear-force mesons until, following the interruption of the Second World War, cosmic ray physicists revealed the pion. As we have mentioned, searches for negative protons in nuclear physics and in the cosmic rays proved unsuccessful. Owen Chamberlain referred to this situation in his Nobel Address:

> For many years physicists working with cosmic rays kept a sharp watch for antiprotons…Some events were observed 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 be produced.[25]

Another reason for suspecting that the antiproton production rate might be almost unobservable, in contrast to the rate predicted for pointlike Dirac particle was the complex picture of the nucleon as a Dirac pointlike "core" surrounded by a sea of mesons. (I recall Richard Feynman remarking that even producing an anti-uranium atom was theoretically possible, but with a negligible production cross-section.) Robert Marshak argued in his book *Meson Physics* that "the rapid decay of a neutral π meson into two γ rays offers a striking qualitative argument in support of the existence of virtual antinucleons…" However, he cautions that "the evidence for the existence of antinucleons is indirect and cannot be regarded as conclusive—putting aside for the moment all theoretical arguments based on the symmetry of nature, etc."[26]

We can conclude that producing antiprotons at an observable rate at the Bevatron was by no means a foregone conclusion, either on experimental or theoretical grounds. Finding them did much to increase the confidence of physicists in far-reaching general laws of symmetry, such as charge conjugation symmetry. Ironically, the "parity revolution" that was poised to begin in the year following the discovery of the antinucleons, would prove that faith to be too far-reaching and to require the deeper-lying TCP symmetry.

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[1] Owen Chamberlain, "The discovery of the antiproton," in *Pions to Quarks,* p. 273.

[2] P.A.M. Dirac, "A theory of electrons and protons," *Proc. Roy. Soc. (London)* **A126** (1930), pp. 360-5.

[3] See Joan Bromberg, "The concept of particle creation before and after quantum mechanics," *Historical Studies in the Physical Sciences* **7** (1976), 161-191.

[4]As quoted by Robert H, Kargon, *The Rise of Robert Millikan* (Ithaca: Cornell University Press, 1982), p. 66.

[5] Abraham Pais, *Subtle is the Lord...* (New York: Oxford University Press, 1982), p.357.

[6] Jagdish Mehra and Helmut Rechenberg, *The Historical development of Quantum Theory, Vols. 1-6* (New York: Springer-Verlag, 1982-2000)

[7]Schrödinger actually first wrote a relativistic wave equation, starting from the relativistic energy expression for a free particle. He replaced E and $\boldsymbol{p}$ by appropriate time and space derivatives (using $E\text{-}eA_0$ and $\boldsymbol{p}\text{-}e\boldsymbol{A}$ to introduce the electromagnetic field). The new equation had the right non-relativistic limit but gave the wrong relativistic fine structure for the hydrogen spectrum. For that reason Schrödinger published only the non-relativistic theory. His first equation, later known as the Klein-Gordon equation; is correct for a relativistic *spinless* point particle.

[8]"The prediction of antimatter." The 1st H.R. Crane Lecture at The University of Michigan, Apr. 17, 1978.

[9] P.A.M Dirac, "Quantized singularities in the electromagnetic field," *Proc. Roy. Soc. (London)* **A133** (1931), pp. 60-72.

[10] Carl Anderson's autobiography is called *The Discovery of Antimatter* (Singapore: World Scientific, 1999). However, atoms of antihydrogen were first produced only recently at CERN. See CERN Courier **42** (9), November 2002.

[11] O. Frisch and O. Stern, "Über die magnetische Ablenkung von Wasserstoffmolekülen und das magnetische Moment des Protons," Zeit. Phys. **85** (1933), 4-16.

[12] There are two studies that deal with this question in much more detail than is possible here: J.L. Heilbron, "The detection of the antiproton," in *The Restructuring of Physical Sciences In Europe and the United States 1945-1960*, ed. M. De Maria, M. Grilli, F. Sebastiano (Singapore: World Scientific, 1989), 161-209; Helge Kragh, "The negative proton: its earliest history," *Am. J. Phys.* **57**, Nov. 1989, 1034-39.

[13] G. Gamow, "Negative protons and nuclear structure," *Phys. Rev.* **45** (1934), 728-9. (*Letter)*

[14] Enrico Fermi, *Collected Papers*, Vol. 1 (Chicago: U. of Chicago Press, 1962), p.752. Also quoted in ref. 12.

[15] G. Gamow, *Structure of Atomic Nuclei and Nuclear Transformations* (Oxford: Clarendon Press, 1937), p. 14-18.

[16]E. Broda, N. Feather, and D.H. Wilkinson, "A search for negative protons emitted as a result of fission," in *Report of an International Conference (22-27 July 1946)*, Volume 1, *Fundamental Particles,* pp. 114-125.

[17]E.J. Williams, "Nature of the high energy particles of penetrating radiation and status of ionization and radiation formulas," *Phys. Rev.* **45** (1934), 729-30. (*Letter)*

[18] Carl D. Anderson, "The positive electron," *Phys. Rev.* **43** (1933), pp. 491-4.

[19] Niels Arley, "On the possible existence of negative protons in the primary component of cosmic radiation," *Physica* 12 (1946), pp. 177-81. Arley's papers and others on this subject are discussed in Heilbron (ref. 12, pp. 170-175).

[20]E. Amaldi *et al.*, "Unusual event produced by cosmic rays," *Nuovo Cimento* **1** (1955), pp. 492-500. (received 18 Feb. 1955). A similar event was reported in the cosmic rays by a University of Bern emulsion group: M. Teucher *et. al.*, "A possible example of production and annihilation of an antiproton," *Nuovo Cimento* **3** (1956), pp. 228-30.

[21]O. Chamberlain *et. al*, "Antiproton star observed in emulsion," *Phys. Rev.* **101** (1956), pp. 909-10. O. Chamberlain *et. al*, "On the observation of an antiproton star in emulsion exposed at the Bevatron," *Nuovo Cimento* **3** (1956), 447-67.

[22]Victor F. Weisskopf, "Growing up with field theory: the development of quantum elecrodynamics," in L.M. Brown and L. Hoddeson, ed., *The Birth of Particle Physics* (Cambridge, UK, Cambridge University Press, 1983), p. 66.

[23]E. Fermi, "Tentativo di una teoria dei raggi β", *Nuovo Cimento* **11** (1934), pp. 1-19. Reprinted in *Enrico Fermi, Collected Papers, Vol. 1* (Chicago: University of Chicago Press, 1962), on p. 560. (Also published in German.)

[24]Pauli to Heisenberg, 17 April 1934, in *Wissenschaftlicher Briefwechsel,* K. v. Meyenn, A. Hermann, and V.F. Weisskopf, ed., Vol. 2, p. 316. Quoted by H. Kragh, ref. 12, on p. 1035. Bohr's idea was prompted by ideas of Gamow and others about negative protons as discussed above.

[25]Owen Chamberlain, *Nobel Lectures in Physics* (Amsterdam: Elsevier, 1964), pp. 489-505;quote on p. 492.

[26] Robert E. Marshak, *Meson Physics* (New York: McGraw-Hill, 1952), p. 328. (Also quoted in part by Heilbron, ref. 12)

Introduction—Antiproton 1955 and Einstein Year 1905

Joan Bromberg: "The Concept of Particle Creation before and after Quantum Mechanics", Historical Studies in the Physical Sciences (1976)—*(James Jeans, Walther Nernst, A.S. Eddington, etc.)*

1900: Rays (*x-; α-, β-, γ-); e/m;* Planck *(k; h; c)*

1905: $E = h\nu$ **(photon);**

$E = kT$ **(Brownian motion)**

$E = mc^2$ **(relativity)**

Use last to calculate antiproton threshold energy (M=1, c=1)

E,p	M=1	M=4
⟶	•	••••
LAB, before		CM, after

$$(\text{total mass})^2 = (E+1)^2 - p^2 = E^2+2E+1-p^2 = 16$$

$$= 2E+2$$

As (total mass)^2 is an invariant, E = 7, KE = 6 = 5.6 GeV

During the six months between Heisenberg's discovery of quantum mechanics, published in September 1925, and Schrödinger's equation, published in March 1926, the following concepts were established:

a) Atomic transition probabilities (or spectral line intensities) are proportional to the absolute squares of complex amplitudes relating the initial and final atomic states.

b) The allowed atomic energy states are described by eigenstates of a suitable Hamiltonian operator; the energies are the corresponding eigenvalues.

c) Observable quantities are represented by non-commuting operators for which Dirac worked out a "quantum algebra." (His "transformation theory" of 1927 includes Heisenberg's matrix mechanics and Schrödinger's wave mechanics as limiting cases.)

d) Dirac and Pauli (independently) solved the non-relativistic hydrogen spectrum.

e) Fermi proposed a new kind of quantum statistics consistent with the Pauli exclusion principle.

A Theory of Electrons and Protons.

By P. A. M. DIRAC, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received December 6, 1929.)

Proc. Roy Soc. (London) **A126** (1930), 360-5.

On the Annihilation of Electrons and Protons. By P. A. M. [DI]RAC, Ph.D., St John's College.

[*Received* 26 March, *read* 19 May 1930.]

Proc. Camb. Phil. Soc. **26** (1930), 361-75.

Quantised Singularities in the Electromagnetic Field.

By P. A. M. DIRAC, F.R.S., St. John's College, Cambridge.

(Received May 29, 1931.)

Proc. Roy Soc. (London) **A133** (1931), 60-72.

The Prediction of Antimatter

P. A. M. DIRAC

The 1st
H. R. CRANE LECTURE

April 17, 1978

At
The University of Michigan
Ann Arbor, Michigan

Series In Popular Science – Vol. 2

The Discovery of Anti-matter

The Autobiography of Carl David Anderson, the Youngest Man to Win the Nobel Prize

World Scientific

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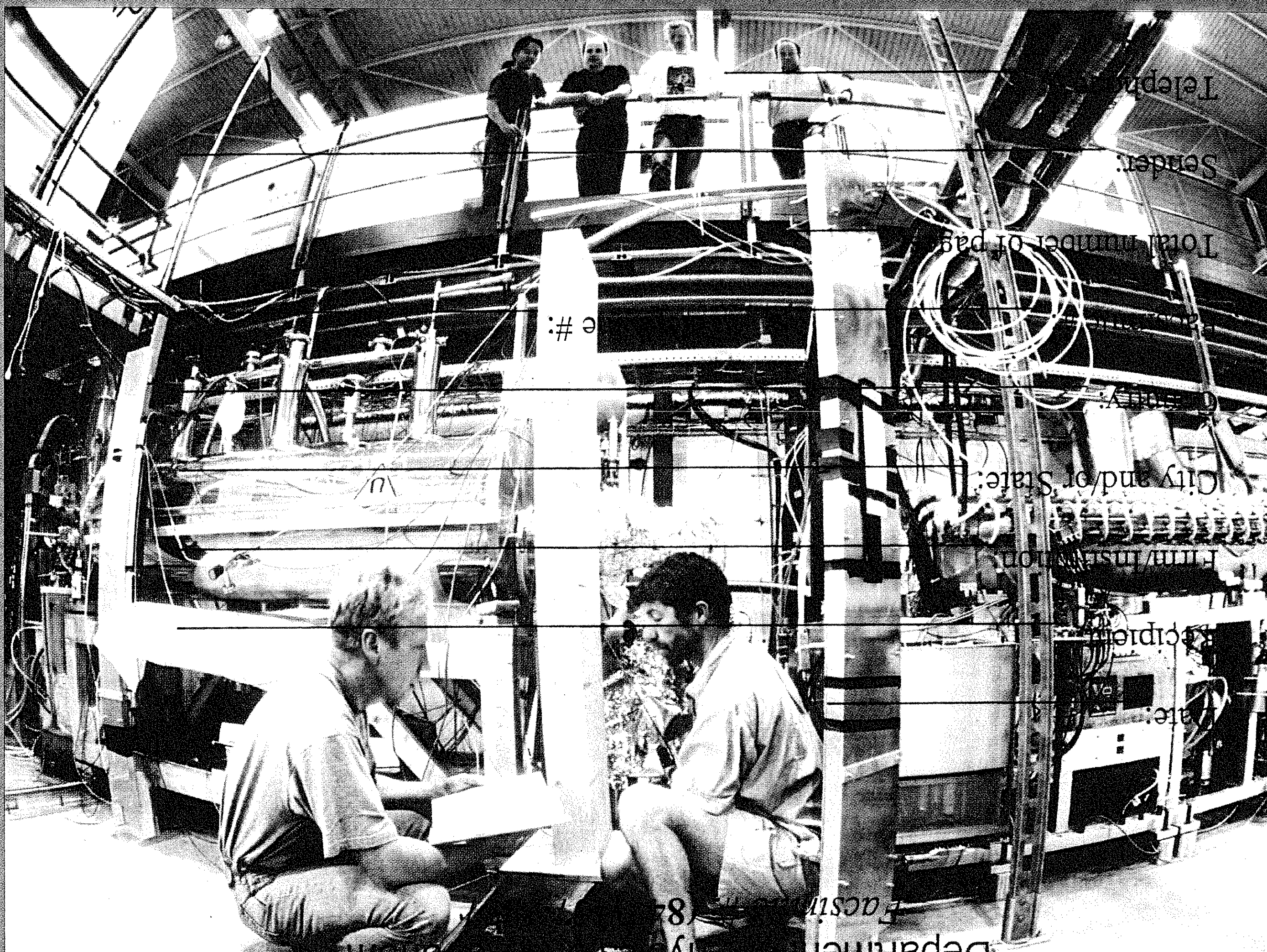

Cold antihydrogen made at CERN

NOBEL
Physics award goes to astrophysics pioneers p6

SESAME
Middle East synchrotron moves forward p6

ESO
European Southern Observatory reaches 40 p11

STRUCTURE OF ATOMIC NUCLEI AND NUCLEAR TRANSFORMATIONS

BY

G. GAMOW

Being a
Second Edition of
CONSTITUTION OF ATOMIC NUCLEI
AND RADIOACTIVITY

OXFORD
AT THE CLARENDON PRESS
1937

4. The possible existence of negative protons†

After the discovery of the positive electron, which was predicted in Dirac's theory, the dissymmetry previously existing in the problem of the elementary particle has practically disappeared. It is true that many more negative electrons than positive electrons are observed in our common experience, but this may now be regarded as merely the local peculiarity of the part of the universe in which we are living. Dissymmetry still exists, however, in the matter of heavy particles, in order to get rid of which it would be necessary to postulate the existence of negative protons in addition to neutrons and positive protons. These negative protons would be symmetrical to positive protons with respect to neutrons; their relation to ordinary protons would not, it will be shown, be analogous to that between positrons and electrons on Dirac's theory. This conclusion may be reached as follows. Bohr has shown that Dirac's equations may be applied—with all the consequences which follow from them—to any particle, only if its radius is small compared with the length $2\pi\hbar/mc$, where m is the mass of the particle in question. This condition is easily fulfilled for an electron, as in this case $2\pi\hbar/mc = 2{\cdot}4\times 10^{-10}$ cm.,

† G. Gamow, *Phys. Rev.* **45** (1934), 728; *Nature*, **135** (1935), 858.

MAY 15, 1934 PHYSICAL REVIEW VOLUME 45

LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the twentieth of the preceding month; for the second issue, the fifth of the month. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

Negative Protons and Nuclear Structure

In connection with the discovery of positive electrons, predicted by Dirac's theory, it is interesting to discuss the possibility of the existence of negative protons.

between a proton and a neutron, because in both cases the exchange takes place between two different particles. The question whether these exchange-forces are attractive or repulsive can be settled if we turn our attention to the

Physica XII, no. 4 Juli 1946

ON THE POSSIBLE EXISTENCE OF NEGATIVE PROTONS IN THE PRIMARY COMPONENT OF COSMIC RADIATION

by NIELS ARLEY

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Summary

The experimental results of Schein, Jesse and Wollan, Johnson and others seem to show that both the soft and the hard component of the cosmic radiation are secondary radiations produced by primary protons. This result involves, however, two difficulties, one regarding the propagation in interstellar space and one regarding the latitude and east-west effect of the soft component. The hypothesis is here put forward that the primary radiation consists of *negative protons* as well as positive ones, the former being mainly annihilated at the top of the atmosphere thus giving rise to the soft component, the latter ones being transformed into mesons thus giving rise to the hard component. Arguments are given in favour of this hypothesis which is shown to be compatible with all the present experimental evidence, although not with the present quantum theory which gives a far too small cross-section for the annihilation of fast, negative protons. It follows, however, from arguments given by Heisenberg that a break-down of the present theory must just be expected to take place for this process.

Until recently it was generally assumed that the primary cosmic radiation consists mainly of positive and negative *electrons*. As Alfvén[1]), Johnson and Barry[9]), Swann[14]) and others have pointed out, a charged primary radiation can hardly be stable in interstellar space if it consists only of particles of the same sign. In this case it would, namely, due to the enormous distances give rise to electric and magnetic fields of considerable magnitudes, which would be incompatible with the further propagation of the radiation. From the east-west effect showing already an asymmetry at sea level it follows, however, unambiguously that the field-sensitive part of the primary energy spectrum, i.e. energies below 1.5×10^{10} e.v., contains more

Unusual Event Produced by Cosmic Rays.

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Summary. — The authors describe an event consisting of two stars respectively of about 5 and 1-2 GeV energy. The probable value of the number of accidental space coincidences that one expects to observe in the scanned volume, is about $4\cdot10^{-4}$. This value, although it does not allow us to exclude an accidental process, justifies the consideration of interpretations in terms of some physical process. Special attention is devoted to the production, capture and annihilation of a negative proton.

1. – Description of the Event.

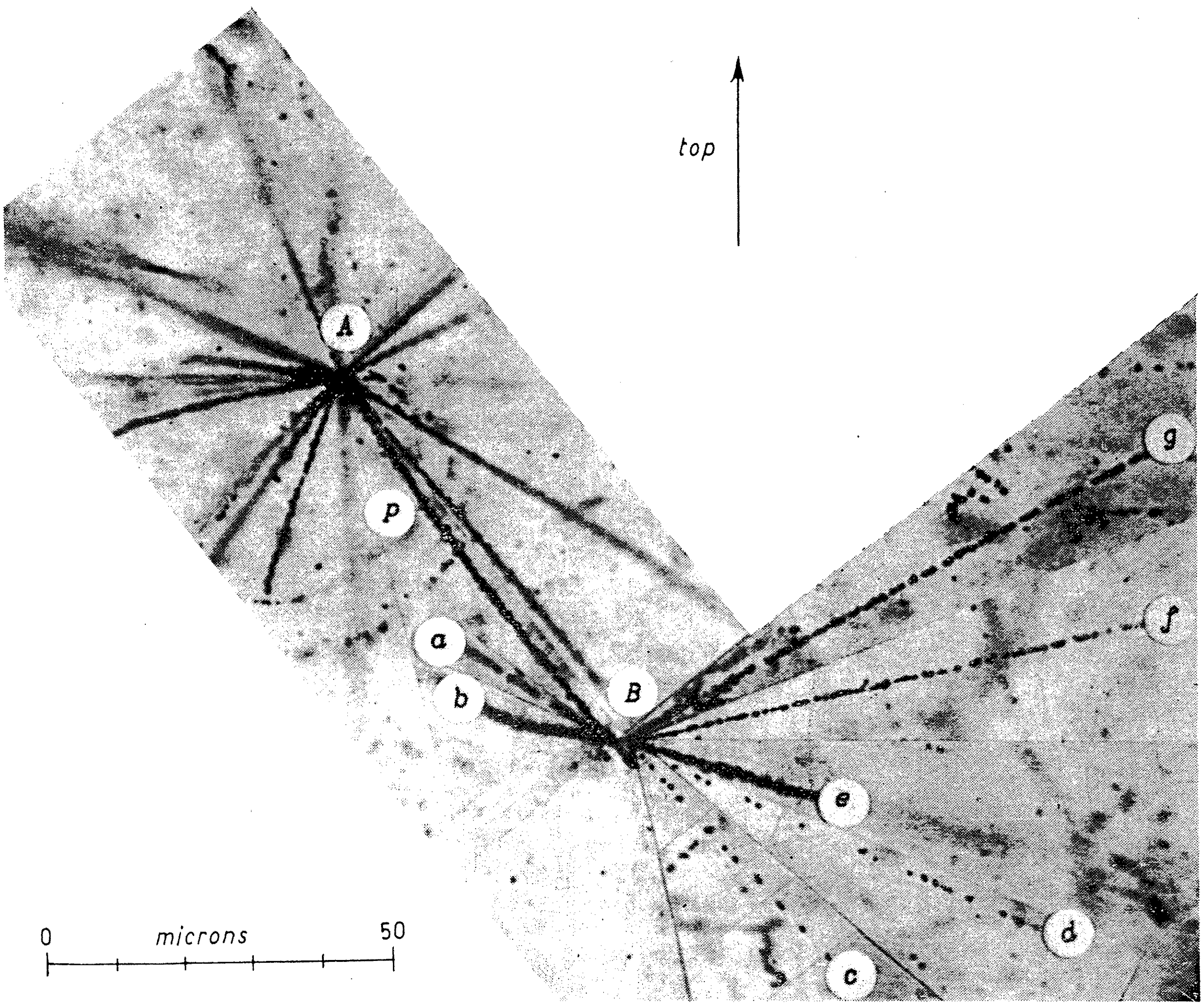
In the course of an investigation on the capture and decay processes of heavy unstable particles, produced by cosmic rays in stripped emulsions, exposed at high altitude during the Sardinian Expedition 1953 (1), we have observed a peculiar event, a microphotograph of which is given in Fig. 1.

The event consists of two stars A and B connected by a black track p, 89 μ long.

Star A shows 20 black and 3 grey tracks in addition to 3 shower particles. Its energy, evaluated by the usual methods (2,3), is of the order of 5 GeV.

The track connecting the two stars undergoes a deflection of 91° at a

(1) *Suppl. Nuovo Cimento*, 12, 480 (1954), *Rendiconti del Congresso Internazionale di Padova*.



Observed by C. CASTAGNOLI

Fig. 1.

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[2]P.A.M. Dirac, "A theory of electrons and protons," *Proc. Roy. Soc. (London)* **A126** (1930), pp. 360-5.

[3] See Joan Bromberg, "The concept of particle creation before and after quantum mechanics," *Historical Studies in the Physical Sciences* 7 (1976), 161-191.

[4]As quoted by Robert H, Kargon, *The Rise of Robert Millikan* (Ithaca: Cornell University Press, 1982), p. 66.

[1] Abraham Pais, *Subtle is the Lord...* (New York: Oxford University Press, 1982), p.357.

[1] Jagdish Mehra and Helmut Rechenberg, *The Historical development of Quantum Theory, Vols. 1-6* (New York: Springer-Verlag, 1982-2000)

[7]Schrödinger actually first wrote a relativistic wave equation, starting from the relativistic energy expression for a free particle. He replaced E and $\boldsymbol{p}$ by appropriate time and space derivatives (using $E\text{-}eA_0$ and $\boldsymbol{p}\text{-}e\boldsymbol{A}$ to introduce the electromagnetic field). The new equation had the right non-relativistic limit but gave the wrong relativistic fine structure for the hydrogen spectrum. For that reason Schrödinger published only the non-relativistic theory. His first equation, later known as the Klein-Gordon equation; is correct for a relativistic *spinless* point particle.

[8]"The prediction of antimatter." The 1st H.R. Crane Lecture at The University of Michigan, Apr. 17, 1978.

[9] P.A.M Dirac, "Quantized singularities in the electromagnetic field," *Proc. Roy. Soc. (London)* **A133** (1931), pp. 60-72.

[10] Carl Anderson's autobiography is called *The Discovery of Antimatter* (Singapore: World Scientific, 1999). However, atoms of antihydrogen were first produced only recently at CERN. See CERN Courier **42** (9), November 2002.

[11] O. Frisch and O. Stern, "Über die magnetische Ablenkung von Wasserstoffmolekülen und das magnetische Moment des Protons," Zeit. Phys. **85** (1933), 4-16.

[12] There are two studies that deal with this question in much more detail than is possible here: J.L. Heilbron, "The detection of the antiproton," in *The Restructuring of Physical Sciences In Europe and the United States 1945-1960*, ed. M. De Maria, M. Grilli, F. Sebastiano (Singapore: World Scientific, 1989), 161-209; Helge Kragh, "The negative proton: its earliest history," *Am. J. Phys.* **57**, Nov. 1989, 1034-39.

[1] G. Gamow, "Negative protons and nuclear structure," *Phys. Rev.* **45** (1934), 728-9. *(Letter)*

[1] Enrico Fermi, *Collected Papers*, Vol. 1 (Chicago: U. of Chicago Press, 1962), p.752. Also quoted in ref. 12.

[15] G. Gamow, *Structure of Atomic Nuclei and Nuclear Transformations* (Oxford: Clarendon Press, 1937), p. 14-18.

[16]E. Broda, N. Feather, and D.H. Wilkinson, "A search for negative protons emitted as a result of fission," in *Report of an International Conference (22-27 July 1946)*, Volume 1, *Fundamental Particles,* pp. 114-125.

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[20]E. Amaldi *et al.*, "Unusual event produced by cosmic rays," *Nuovo Cimento* **1** (1955), pp. 492-500. (received 18 Feb. 1955). A similar event was reported in the cosmic rays by a University of Bern emulsion group: M. Teucher *et. al.*, "A possible example of production and annihilation of an antiproton," *Nuovo Cimento* **3** (1956), pp. 228-30.

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[22]Victor F. Weisskopf, "Growing up with field theory: the development of quantum elecrodynamics," in L.M. Brown and L. Hoddeson, ed., *The Birth of Particle Physics* (Cambridge, UK, Cambridge University Press, 1983), p. 66.

[23]E. Fermi, "Tentativo di una teoria dei raggi β", *Nuovo Cimento* **11** (1934), pp. 1-19. Reprinted in *Enrico Fermi, Collected Papers, Vol. 1* (Chicago: University of Chicago Press, 1962), on p. 560. (Also published in German.)

[24]Pauli to Heisenberg, 17 April 1934, in *Wissenschaftlicher Briefwechsel,* K. v. Meyenn, A. Hermann, and V.F. Weisskopf, ed., Vol. 2, p. 316. Quoted by H. Kragh, ref. 12, on p. 1035. Bohr's idea was prompted by ideas of Gamow and others about negative protons as discussed above.

[25]Owen Chamberlain, *Nobel Lectures in Physics* (Amsterdam: Elsevier, 1964), pp. 489-505;quote on p. 492.

[26]Robert E. Marshak, *Meson Physics* (New York: McGraw-Hill, 1952), p. 328. (Also quoted in part by Heilbron, ref. 12)