THIRTY YEARS THAT SHOOK PHYSICS

The Story of Quantum Theory

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Illustrations by the Author

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CHAPTER VI

P. A. M. DIRAC AND ANTI-PARTICLES

The Theory of Relativity and the Quantum Theory, which appeared almost simultaneously at the start of the present century, were two great explosions of the human mind and shook the very foundations of classical physics: relativity in the case of velocities approaching that of light; quantum in the case of motions confined to very small (atomic) dimensions. But for almost three decades these two great theories stood apart, more or less, from each other. Bohr's original theory of quantized orbits, as well as Schrödinger's wave equations into which it developed, were essentially non-relativistic; both were applicable only to par-

ticles moving with a velocity small as compared with that of light. But the velocities of electrons within the atoms are not that small. For example, the electron on the first hydrogen orbit, calculated on the basis of Bohr's theory, has the velocity of 2.2×10^8 cm/sec, which is only a little less than 1 per cent of the speed of light. The velocity of electrons inside heavier atoms is considerably larger. Of course, a few per cents is not too much, and the calculated value could be improved by introducing "relativistic corrections," which would make the agreement with direct experimental measurement somewhat better. But this was only an improvement and not the completion of the theory.

Another trouble arose in the case of the electron's magnetic moment. In 1925, Goudsmit and Uhlenbeck showed that in order to explain certain details of atomic spectra it is necessary to ascribe to the electron certain angular and magnetic momenta† commonly known as the *electron spin*. The naïve picture at that time was that the electron is a little charged sphere about 3×10^{-13} cm in diameter. The rapid rotation of this sphere around its axis was supposed to produce a magnetic moment, resulting in additional interaction with its orbital motion and with the magnetic moments of other electrons. It turned out, however, that in order to produce the necessary magnetic field the electron would have to rotate so fast that the points on its equator would move at much higher velocities than light! Here again one encountered a conflict between quantum and relativistic physics. It was becoming clear that relativity and quantum physics could not just be added together. A more general theory which would contain both relativistic and quantum ideas in a harmoniously unified form was needed.

† See Francis Bitter, *Magnets*. Doubleday, Science Study Series (1959).

The most important step in this direction was taken in 1928 by a British physicist, P. A. M. Dirac, who started his career as an electrical engineer but, finding it difficult to get satisfactory employment, applied for a fellowship in physics at Cambridge University. His application (which was accepted) now hangs, attractively framed, in the University Library, side by side with the Nobel Prize certificate which he received not too many years after changing from electrical engineering to quantum physics.

Now it often happens that "absent-minded-professor" stories grow up around famous scientists. In most cases these stories are not true, merely the inventions of wags, but in the case of Dirac all the stories are really true, at least in the opinion of this writer. For the benefit of future historians we give some of them here.

Being a great theoretical physicist, Dirac liked to theorize about all the problems of daily life, rather than to find solutions by direct experiment. Once, at a party in Copenhagen, he proposed a theory according to which there must be a certain distance at which a woman's face looks its best. He argued that at $d = \infty$ one cannot see anything anyway, while at $d = 0$ the oval of the face is deformed because of the small aperture of the human eye, and many other imperfections (such as small wrinkles) become exaggerated. Thus there is a certain optimum distance at which the face looks its best.

"Tell me, Paul," I asked, "how close have you ever seen a woman's face?"

"Oh," replied Dirac, holding his palms about two feet apart, "about that close."

Several years later Dirac married "Wigner's sister," so known among the physicists because she was the sister of the noted Hungarian theoretical physicist Eugene Wigner. When one of Dirac's old friends, who had not yet heard of the marriage, dropped into his home he found with Dirac an attractive woman who served tea and then sat down comfortably on a sofa. "How do you do!" said the friend, wondering who the woman might be. "Oh!" exclaimed Dirac, "I am sorry. I forgot to introduce you. This is . . . this is Wigner's sister."‡

Dirac's sense of quantum humor was often demonstrated at scientific meetings. Once, in Copenhagen, Klein and Nishina reported their derivation of the famous Kline-Nishina formula describing collisions between electrons and gamma quanta. After the final formula was written on the board, somebody in the audience who already had seen the manuscript of the paper remarked that in the formula as written on the blackboard the second term had the negative sign, whereas in the manuscript the sign was positive.

"Oh," said Nishina, who was delivering the talk, "in the manuscript the signs are certainly correct, but here on the blackboard I must have made a sign mistake in some place."

"In *odd* number of places!" commented Dirac.

Another example of Dirac's acute observation has a literary flavor. His friend Peter Kapitza, the Russian physicist, gave him an English translation of Dostoevski's *Crime and Punishment*.

"Well, how do you like it?" asked Kapitza when Dirac returned the book.

"It is nice," said Dirac, "but in one of the chapters the author made a mistake. He describes the Sun as

‡ In a recent conversation with Mrs. Dirac (in Austin, Texas, of all places!) the author asked whether this story is really true. She said that what Dirac actually said was: "This is Wigner's sister, who is now my wife."

rising twice on the same day." This was his one and only comment on Dostoevski's novel.§

Another time, visiting Kapitza's home, Dirac was watching Anya Kapitza knitting while he was talking physics to Peter. A couple of hours after he left, Dirac rushed back, very excited. "You know, Anya," he said, "watching the way you were making this sweater I got interested in the topological aspect of the problem. I found that there is another way of doing it and that there are only two possible ways. One is the one you were using; another is like that. . . ." And he demonstrated the other way, using his long thin fingers. His newly discovered "other way," Anya informed him, is well known to women and is none other than "purling."

Just to finish "Dirac stories" before we go on to his scientific achievements, let me mention one more. At the question period after a Dirac lecture at the University of Toronto, somebody in the audience remarked: "Professor Dirac, I do not understand how you derived the formula on the top left side of the blackboard."

"This is not a question," snapped Dirac, "it is a statement. Next question, please."

Unifying Relativity and Quantum Theory

Let us turn now to Dirac's achievement in physics. As was stated in the beginning of the chapter, the Quantum Theory and the Theory of Relativity could not be fitted exactly together like pieces of a Chinese puzzle. One can get a very close fit, but there were always some minor discrepancies, making the solution not quite per-

§ The author, who heard this from Kapitza, was too lazy to read *Crime and Punishment* once more to find out in which chapter this occurred. But some of the readers of this present book may wish to try.

fect. Schrödinger's wave equation of the Quantum Theory looked very similar to the classical wave equation describing the propagation of sound or electromagnetic waves, but . . .

In classical physics the quantities under consideration, be they the density of air or electromagnetic forces, always enter the wave equation in the form of *second derivatives;*¶ that is, the rates of rates of change on x, y, z, and t, conventionally written as

$$\frac{\partial^2 u}{\partial x^2};\ \frac{\partial^2 u}{\partial y^2};\ \frac{\partial^2 u}{\partial z^2};\ \text{and}\ \frac{\partial^2 u}{\partial t^2}$$

The exact mathematical solution of such equations always leads to harmonic waves propagating through space. Schrödinger's wave equation contained the second derivatives on x, y, and z, but only the first derivative on t. The reason was that this equation was derived from classical Newtonian mechanics in which the acceleration of a moving material particle is proportional to the acting force. In fact, if x is the position of the particle, its velocity v (that is, the rate of change of its position with time) is the *first* derivative of x on t

$$\left(\frac{\partial x}{\partial t}\right)$$

whereas its *acceleration* a (that is, the rate of change of its velocity with time) is the second derivative:

$$\frac{\partial\left(\frac{\partial x}{\partial t}\right)}{\partial t}$$

¶ The notion of derivatives is discussed in an elementary way in Chapter 3 ("Calculus") of the author's book *Gravity,* published in 1962 in this same series. See also *Mathematical Aspects of Physics* (Doubleday, Science Study Series, 1963) by Francis Bitter.

customarily written as

$$\frac{\partial^2 x}{\partial t^2}$$

On the other hand, the force F is the first derivative of the potential P on the position:

$$\frac{\partial P}{\partial x};\ \frac{\partial P}{\partial y}\ \text{and}\ \frac{\partial P}{\partial z}$$

Thus, the basic Newton law of motion, stating that the acceleration is proportional to the force, contained the first derivatives on the space coordinates, and the second derivative on time. This fact made the Newtonian equation of the motion of a particle mathematically inhomogeneous, giving to the time t a different status than to the coordinates x, y, z. This situation, which existed for centuries in classical mechanics, is reflected in Schrödinger's non-relativistic wave mechanics, in which space and time are treated as quite different entities.

But as soon as we try to formulate the laws of Quantum Theory on a relativistic basis, we run into the difficulty that space and time are much more closely connected with each other. In fact, following up Einstein's basic ideas, H. Minkowski formulated the notion of a four-dimensional space-time continuum in which time, multiplied by an imaginary unit $i = \sqrt{-1}$, is regarded as equivalent to the three space coordinates. In Minkowski's world there is no difference between x, y, z, and ict (where c†† is introduced through purely dimensional considerations).

(In this book, dedicated to the Quantum Theory, we have no space to discuss the Theory of Relativity in detail; the reader unfamiliar with the subject must get

†† And the factor c (velocity of light) to keep the physical dimensions correct.

his information from other books.‡‡ The author must assume, however, that the person reading the following chapters has at least an elementary acquaintance with the basic ideas of Einstein's theory.)

As was discussed earlier, the wave mechanical equation must contain the same derivatives in all four coordinates. Schrödinger's equation, however, being derived from Newton's equation, does not satisfy that condition. The first attempts to straighten out this defect were made independently by O. Klein and W. Gordon, who turned Schrödinger's non-relativistic wave equation into a relativistic form simply by introducing the second derivatives on time, instead of the first derivatives. But although the Klein-Gordon wave equation looked very nice and very relativistic, it suffered from a number of internal contradictions, and all attempts to introduce the electron spin into it in any reasonable way led to a complete failure.

Then, one evening of the year 1928, sitting in an armchair in his St. John's College study, with his long legs stretched toward the burning logs in the fireplace, Paul Adrien Maurice Dirac hit on a very simple and very brilliant idea.

If no good result can be obtained by using the second derivatives on the time coordinate in the relativistic wave equation, why not use the first derivatives on space coordinates in it? Of course, it would mean the introduction of more imaginary units i, but it would make the wave equation symmetrical in space and time. Thus appeared Dirac's linear (containing only first derivatives) equation which, applied to the hydrogen atom, immediately led to glorious results. All the splittings of the spectral lines, which had stubbornly resisted interpretation in terms of the spin and magnetic

‡‡ See Hermann Bondi, *Relativity and Common Sense*. Doubleday, Science Study Series (1964).

moment of the electron, came out completely correct on the basis of the new theory. This success was particularly surprising because, in formulating his equation, Dirac aimed only to make it relativistically correct; the spinning electron appeared as the bonus for uniting in a correct way the relativity and quantum theories. And it was not a small electrically charged and rapidly rotating sphere but a point charge which, by virtue of Dirac's equation, behaved *as if it were* a tiny magnet.

But, having written the wave equation, which represented a perfect unification of the relativity and quantum theories, Dirac had to face another difficulty which was characteristic of any attempt at uniting these two theories. According to the famous Einstein relation, a rest mass m_0 (expressed in grams) was equivalent to the energy m_0c^2 (expressed in ergs) where c is the velocity of light. If that mass is moving with a certain velocity v, thus having (in the first approximation) the kinetic energy $K = \frac{1}{2}m_0v^2$§§ the total energy is:

$$E = \frac{m_0c^2}{\sqrt{1-\frac{v^2}{c^2}}} \cong \text{¶¶}\, m_0c^2 + \frac{1}{2}m_0v^2$$

But, due to the mathematical properties of Einstein's relativistic mechanics, one should expect also the type of motion corresponding to the total energy:

$$E = -\frac{m_0c^2}{\sqrt{1-\frac{v^2}{c^2}}} \cong \text{¶¶}\, -m_0c^2 - \frac{1}{2}m_0v^2$$

§§ or more exactly: $m_0c^2\left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\right) - 1$

which becomes equal to $\frac{1}{2}m_0v^2$ if $v << c$.

¶¶ for $v << c$.

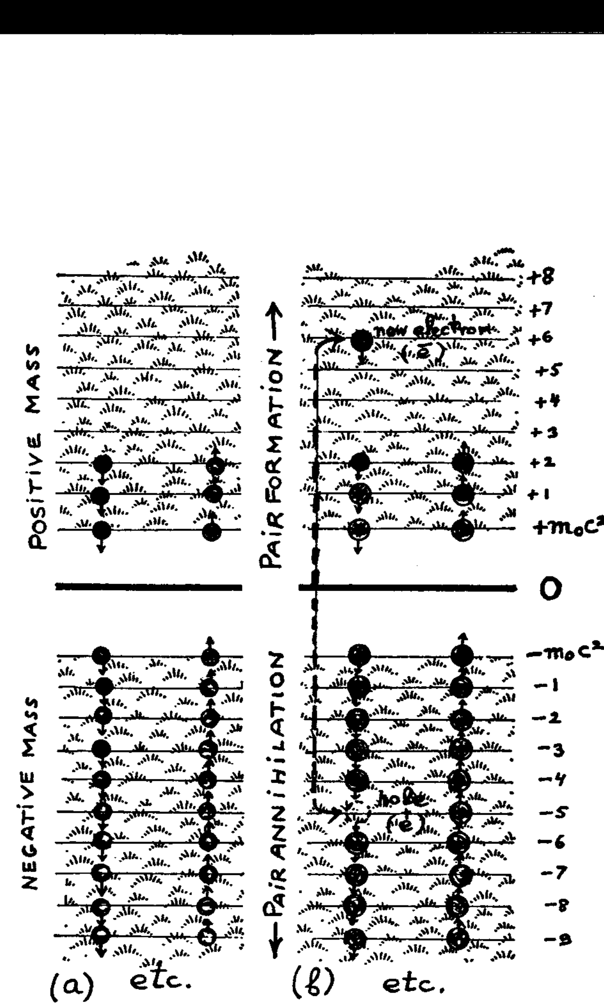


Fig. 26. Dirac's picture of the energy level distribution of the particles with positive and negative mass. On the left (a) all negative energy levels are completely filled up, and only six ordinary electrons can exist on the normal positive levels. On the right (b) one of the electrons from a negative level is lifted to a positive level, leaving behind it a "hole" which behaves as an ordinary positive electron with positive mass. If this extra electron from a positive level falls back into the hole (annihilation process of $\bar{e}$ and $\dot{e}$ the energy difference will be emitted as γ-radiation.

This equation can be obtained from the previous one by writing $-m_0$ instead of $+m_0$, which means physically the introduction of *negative mass*. Thus relativistic mechanics permits in principle two separate sets of levels: those with rest energy $+m_0c^2$ and higher, another with the rest energy $-m_0c^2$ and lower (Fig. 26).

While the energy levels shown in the upper part of the diagram ($E>0$) correspond to familiar types of motion of material particles (electron, proton, etc.), the energy levels in the lower part of the diagram ($E<0$) do not correspond to any physical reality. Particles having negative inertial mass do not correspond to anything observed in nature. Indeed, because of the negative value of their mass they would be accelerated in the direction *opposite* to the force acting on them, and, in order to stop a moving particle of that kind, one should push it in the direction of its motion and not against it! Imagine two particles, let us say two electrons, with numerically equal masses having, however, opposite signs ($+m$ and $-m$). According to the Coulomb law, they will be repelled by each other by electrostatic forces having the same numerical values, but acting in the opposite direction. If both particles had positive masses, this interaction would result in equal but oppositely directed accelerations (Fig. 27a), and they would fly away from each other with increasing velocities. If, however, one of the particles has a negative mass (Fig. 27b), it will be accelerated in the same direction as the other particle, and they will fly together, keeping a constant distance between themselves and speeding up beyond any limit ($<c$ of course). There is no contradiction of the Law of Conservation of Energy, since the combined kinetic energy of the two particles will be:

$$\frac{1}{2}mv^2 + \frac{1}{2}(-m)\,v^2 = 0$$

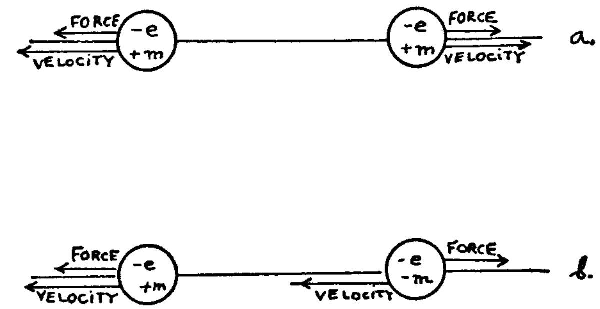


Fig. 27. Interaction between the particles with a positive and those with a negative mass.

the same as it was before the motion started. The whole thing is completely fantastic, and particles having these properties have never been observed.

In classical relativistic mechanics (which does not take into consideration the quantum phenomena) the difficulty of particles with negative mass can easily be eliminated. Indeed, as one can see from Fig. 26, the regions of positive and negative energies are separated by an interval of 2 m_0c^2 (about 1 million electron volts in the case of electrons). Since in non-quantum mechanics (classical and relativistic) the changes of energy must be continuous, a particle from the upper part of the diagram cannot move to the lower part because it would require a discontinuous change of its energy. Thus in the physical description of nature the states with negative mass could be rejected as undesirable mathematical possibilities. However, as soon as one introduces the quantum phenomena, the situation changes quite radically: in Quantum Theory electrons and other elementary particles just love to *jump* from higher levels to lower ones. Thus in the relativistic Quantum Theory a paradoxical event should happen: all the normal electrons would jump from positive mass states to negative mass states, and all the Universe would go haywire!

The only way Dirac could see to overcome this paradox was by the use of the Pauli Principle, and the assumption that all the states corresponding to the negative mass are already occupied (two electrons with opposite spin per each state), leaving no place for electrons from the positive mass states to jump into. The situation is similar to that of the familiar electron-shells of an atom where the electron from M shell cannot jump down to L or K shells because these are completely occupied by the electrons which got there first. But, whereas atoms are limited structures containing a finite number of electrons, Dirac's theory pertained to limitless space and called for an infinite number of electrons per each cubic centimeter of vacuum. So far so good, if one neglects the infinite mass of these electrons which, according to Einstein's relativistic theory of gravity (sometimes called the General Theory of Relativity), would make the radius of curvature of empty space equal to zero!

Putting aside this difficulty, Dirac asked himself whether that distribution of negatively charged electrons with negative mass would be observable, that is, detectable with any kind of physical measuring instruments. The answer was no. With no kind of electric equipment can one detect a uniform charge distribution in space, no matter how high it is per unit volume. To understand that statement, let us imagine a deep sea fish which never comes up to the ocean's surface and never sinks all the way down to the ocean floor. If we assume that the ocean water is frictionless (something like liquid helium), we must conclude that the fish, intelligent as it may be, cannot tell whether it is moving through water or through a complete vacuum. And, if something is unobservable, it should not be used in the

physical description of nature. Our deep sea fish is accustomed to seeing objects moving downward, be they bits of garbage thrown overboard from ships sailing across the ocean or, in rare cases, sinking ships themselves. Thus, following Aristotle, the fish will conceive the notion of gravity which makes all material objects move downward.

But suppose now that a sinking, empty Coca-Cola bottle, or a sinking ocean liner, has some trapped air which is released when the vessel hits the bottom. What will our intelligent fish see? It will see a bunch of silvery spheres (air bubbles in common human language) rising upward. What will our intelligent fish think on observing these objects? Well, it will be astonished that they move in the direction opposite to that of the force of gravity and it will be inclined to ascribe to them a mass of the opposite sign in respect to ordinary objects, which move downward.

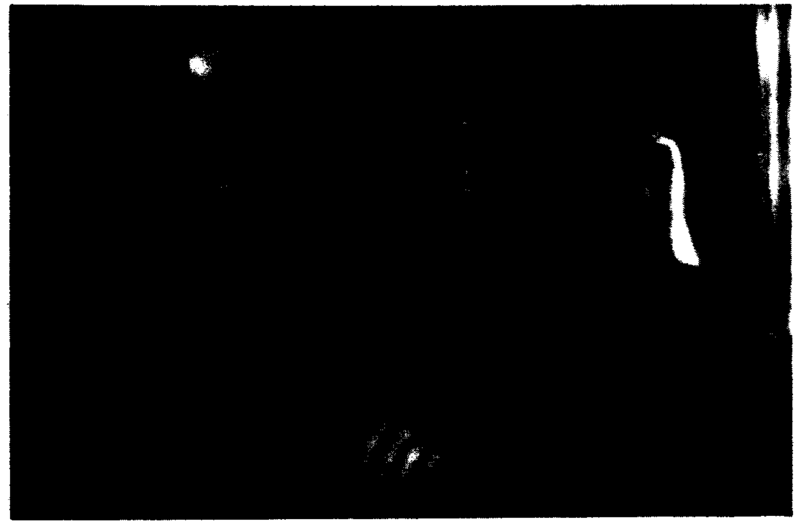
A somewhat closer analogy may be given by considering a complex atom with completed K, L, and M shells, which has been hit by a hard X-ray and lost one of the two electrons on the K shell. There will be an empty space (Pauli vacancy) in the K shell, and one of the L shell electrons will jump into it, leaving an empty space in its shell. The next step will be transition of a most agile electron from the M shell into the vacant place in the L shell. Of course, there is also the possibility that the M shell will beat the L shell to it, and the vacancy in the K shell will be occupied directly by one of the M shell electrons.

Anti-Particle Physics

But we can look on the problem from a different point of view. The fact that a negative electron is missing from the K shell is equivalent to a positive charge sitting there. The transition of a negative electron from the L shell down to the K shell is equivalent to the raising of that positive charge from the K shell up to the L shell and later up to the M shell. From this point of view we have a fictitious positively charged particle moving from the lowest K level to the much higher M level and later out into interatomic space. Since, according to the Coulomb law, the positively charged nucleus should repel the positively charged fictitious electron, everything is fine and dandy.

Returning to Dirac's ocean filled with negatively charged electrons possessing negative mass, we can ask ourselves how an experimentalist will apprehend the situation in which one negative electron with negative mass is missing from its level. Apparently there are two straightforward conclusions: (1) The absence of negative charge will be observed as the presence of positive charge. Thus the experimentalist will observe a particle with electric charge $+e$. (2) The absence of negative mass is equivalent to the presence of positive mass. Thus the particle will behave in a normal way and will be observed as a positively charged ordinary particle. Having gone so far, Dirac overstretched his idea. He thought that it could be proved that the numerical value of the mass of this hole in the ocean of electrons with negative mass is equal to about 1840 times the mass of an ordinary electron. If this were really so, the holes in Dirac's ocean would be observed as ordinary protons.

Dirac's paper published in 1930 (or rather, the private conversations and correspondence prior to its publication) resulted in violent opposition to his idea. Niels Bohr, who for some reason unknown to the writer was interested in elephants, composed a hunting story "How to Catch Elephants Alive." For the benefit of African big game hunters he proposed the following



TOP *N. Bohr and A. Einstein, presumably during the 1930 Solvay Congress in Brussels. (Photographer unknown)*
BOTTOM *George Gamow on a mountaintop discussing nuclear physics with Leon Rosenfeld. (Photographed by Rudolph Peierls)*

method: At a watering spot on a river where the elephants come to drink and to wash, one should erect a large poster explaining in a short sentence Dirac's proposal. When the elephant, who is proverbially a very wise animal, comes to have a drink of water, he reads the text on the poster and becomes spellbound for several minutes. Using this time interval, the hunters hiding in the bush will slip out and tie the elephant's legs securely with heavy ropes. Then the elephant is shipped to the Hagenbeck Zoo in Hamburg.

Pauli, who liked jokes too, made some calculations which showed that if protons in the hydrogen atoms were Dirac's holes the electrons would jump into them within a negligible fraction of a second, and the hydrogen atom (as well as the atoms of all other elements) would be annihilated instantaneously in a burst of high-frequency radiation. Pauli proposed what was known as the "Second Pauli Principle," according to which any theory suggested by a theoretician would become immediately applicable to his body. Thus Dirac would be turned into gamma-rays before he could tell anybody about his idea.

All this was a lot of fun, but one year later, after the publication of Dirac's paper, an American physicist, Carl Anderson, studying cosmic ray electrons passing through a strong magnetic field, found that while one-half of them were deflected in the direction expected for properly behaving negatively charged particles, the other half were deflected at the same angle *in the opposite direction*. Those were the positively charged electrons, sometimes called positrons, predicted by Dirac's theory. Experimental studies of the positrons have shown that they behave exactly as Dirac's holes were supposed to do. Although the positrons were first discovered in cosmic rays, one soon found that they could also be produced under controlled laboratory conditions simply by shooting hard gamma-rays at the metal plates. Colliding with the atomic nucleus, a γ-quantum disappears and all its energy is converted into two electrons, one negative and one positive, as is shown in Fig. 28a. Since the mass of one electron

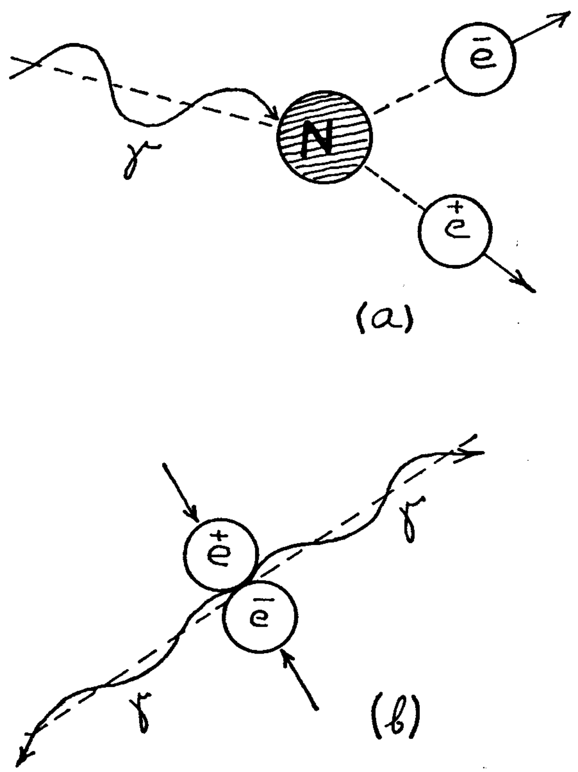


Fig. 28. The "creation" and "annihilation" of negative and positive electrons ($\bar{e}$ *and* $\overset{+}{e}$) *according to Dirac's theory: (a) a high-energy γ-ray hits a nucleus* (N) *and turns into* $\bar{e}$ *and* $\overset{+}{e}$ *pair; (b) an* $\bar{e}$ *and* $\overset{+}{e}$ *pair collide in free space and produce two γ-rays moving in opposite directions.*

expressed in energy units is equal to 0.5 mev, the process takes place only if the energy $h\nu$ of the γ-ray is greater than 1.0 mev. The excess of energy:

$$h\nu - 2m_0c^2$$

is communicated to the electron pair ($\overset{+}{e}$, $\bar{e}$) "created" in the collision. The fates of these two electrons are quite different. The negative (ordinary) electron $\bar{e}$ is slowed down gradually in collisions with other negative electrons forming matter and becomes one of them. The positive electron $\overset{+}{e}$ does not last long but is annihilated in the collision with one of the (ordinary) negative electrons emitting two γ-quanta (Fig. 28b). The terms "created" and "annihilated" should not be understood in a metaphysical sense; one can just as well say that ice is "created" from water when it is brought below the freezing point, and "annihilated" at room temperature, turning into water. The Laws of Conservation of Mass and Energy (which are actually one single law because of Einstein's formula $E = mc^2$) are sustained in both processes, and we deal here just with the transformation of radiation into particles and the transformation of particles into radiation on an equal basis.

The detection of anti-electrons (positrons) raised the question whether or not there also exist anti-protons, particles having the mass of a proton but carrying a negative charge. Since a proton is some 1840 times heavier than an electron, the production of proton-anti-proton pairs demands energies of billions, rather than millions, of electron volts. With this in mind, the Atomic Energy Commission spent proportionate amounts of dollars to build accelerators which could communicate to nuclear projectiles the necessary amounts of energy. And within a few years two giant accelerators were constructed in the United States: a

Bevatron at the Radiation Laboratory of the University of California at Berkeley; and a *Cosmotron* at the Brookhaven National Laboratory on Long Island, New York. Soon thereafter similar European machines were built, at CERN near Geneva, Switzerland, and in Soviet Russia, near Moscow. It was a hard competition which was finally won by Californians when Emilio Segré and his co-workers announced in October 1955 that they had detected negative protons ejected from the bombarded targets. Later, they also found the anti-neutrons, the particles which are annihilated in collision with ordinary neutrons. As we shall see later in the book, all the other more recently discovered particles (various kinds of mesons and hyperons) also possess their antis.

Thus, although Dirac failed in his original intention to explain a proton as an anti-electron, he opened a broad field of anti-particle physics.

There are two unsolved mysteries about anti-particles. The atoms forming our globe are built of negative electrons, positive protons, and ordinary neutrons. According to astronomical studies the same is true of the entire planetary system and the Sun itself. In fact, the protons and electrons ejected from the Sun and entering the terrestrial atmosphere are the (ordinary) positive protons and negative electrons. More uncertain, but probably true, is the statement that all the stars and interstellar material of the Milky Way are formed of ordinary matter, since otherwise one would observe intensive gamma-radiation from all the various parts of our galaxy. But what about billions of other galaxies which are separated from our Milky Way by millions of light years? Is our Universe lopsided, being formed entirely from "ordinary" matter, or is it a collection of galaxies, half of which are composed of "ordinary" matter while the other half are composed

of "anti-matter"? This we do not know, and there seems to be no way to find out.

Another riddle is whether or not the anti-particles produced in abundance in our modern accelerators have a positive or a negative gravitational mass. It seems at first sight that this question might easily be answered by direct experiment. Just produce a beam of anti-protons in a high-energy accelerator and send it horizontally along an evacuated tube and see whether under the action of terrestrial gravity it will bend down as a horizontally thrown stone or bend up. If the latter one would be justified in inferring that anti-particles are repelled by the mass of the Earth. The trouble is, however, that the anti-particles produced in our laboratories move with velocities almost equal to that of light (3×10^{10} cm/sec). Thus, if the tube is, let us say, 3 km long (3×10^5 cm), the anti-particles will pass it in the time interval of 10^{-5} sec. According to the law of free fall, they will be displaced downward (or upward, in the case of negative gravitational mass) by the amount of $\frac{1}{2}\, gt^2$ cm where g is about 10^3 cm/sec^2. If $t = 10^{-5}$ sec, the vertical displacement will be of the order of $10^3 \times 10^{-10} = 10^{-7}$ cm, which is comparable with atomic diameter! It is clear that no experimental arrangement can detect such a small deflection of the beam. To carry out the experiment one could try to slow down the anti-particle to more reasonable speeds, say a few centimeters per second, when downward or upward deflection would become easily noticeable. But how does one do it? In the atomic piles one slows down neutrons by passing them through various "moderators" (carbon, or heavy water) where the neutrons gradually lose their energy in collisions with other atoms. But we cannot do this in the case of anti-particles, since on passing through any moderator formed by ordinary matter they will be annihilated in the very first collision. Thus the question still remains unanswered.

In conclusion, it may be remarked that the proof of the negative gravitational mass of anti-particles would be quite useful for the solution of various cosmological problems. If both ordinary and anti-particles were created uniformly through the space of the Universe, gravitational attraction between the particles of the same kind, and the hypothetical gravitational repulsion between the particles of the opposite kind, would result in mutual separation. Large regions of space populated exclusively by ordinary matter would be formed and so would other regions populated exclusively by anti-matter. This separation would gratify our notion of the symmetry of nature. But we do not know, and we also do not know whether or not we will ever know.