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Nuclear Properties of Antinucleons

The study of antiprotons reveals other antiparticles previously predicted and also unpredictable aspects of the scattering and annihilation process.

Emilio Segrè

I must begin by thanking the Swedish Academy for the great honor they have bestowed on me. The names of the previous recipients of the Nobel award lend such great prestige to the award, that I feel very humble in joining the company. At the outset I must also mention the names of two people who have had, in different ways, a very great influence upon all my work. Of Enrico Fermi I would only say, quoting Dante as he himself might have done,

Tu se' lo mio maestro e il mio autore
Tu se' solo colui da cui io tolsi
Lo bello stilo che mi ha fatto onore.

(Thou art my master and my author;
Thou alone art he from whom I took
The good style that hath done me
honor.)

I learned from him not only a good part of the physics I know but, above all, an attitude of constant devotion to science which has affected all my work. Ernest Orlando Lawrence created the instruments with which most of my work was done. Although I belong scientifically to a different tradition and outlook, it was only through the instruments developed at his instigation and under his leadership that most of my own researches became possible. This is especially true for the most recent one: the antiproton.

By 1954 the bevatron had been developed and tested. It had been purposely planned for an energy above the threshold for forming nucleon-antinucleon pairs, and many physicists, including my colleagues and me, naturally thought of means for hunting the elusive antiproton. Although its existence was very probable, a definite experimental proof was lacking, and being aware of the crucial importance of the problem for the extension of Dirac's theory from the electron to the nucleon, we tried to design an experiment which would give a definite answer (*1*). The final apparatus has been described elsewhere (*2*).

Other experiments involving photographic detection were also planned at that time and came to fruition soon after the success of the first experiment (*3*).

The properties used for the identification of the antiproton were predicted by Dirac long ago and were used as a guide in finding the particle. However, once it was found, we faced a host of new problems, and it is to those that I direct this discussion.

Systematics of Particles

I will be very brief concerning the experimental developments. Here, great emphasis has been put on the development of better antiproton beams. By "better" I mean beams in which there are more antiprotons per unit time and in which the ratio of the number of antiprotons to unwanted particles is higher. Suffice it to say that now it is possible to have, at Berkeley, beams with about ten antiprotons per minute instead of one every 15 minutes as in 1955, and beams in which antiprotons are about one in ten particles instead of one in 50,000, as in 1955. The improved beams allow us to make more difficult and complicated experiments, and the development of electronics and bubble chambers has kept pace with the increased possibilities. I may add that the complications in which we are entering now are by no means a cause of joy to the experimenters who have to cope with them, and that they are properly considered the heavy price to be paid in order to obtain more detailed physical information.

Some of the problems raised by the very existence of the antiproton have a predictable solution, although the prediction does not derive from anything as solid as Dirac's theory. We could, for instance, predict with complete confidence the existence of the antineutron and of all the antiparticles of the baryons, although it might require considerable skill to find them. In fact, antineutrons are certainly formed copiously at the Bevatron, but the primary antineutrons are very difficult to identify. For this reason, immediately after the discovery of the antiproton it was suggested that the antineutron should be found by investigating the charge-exchange reaction in which a proton and an antiproton give a neutron and an antineutron (*4*). In a very ingenious and elegant counter experiment, Cork, Lambertson, Piccioni, and Wenzel did demonstrate the existence of the antineutron some time ago (*5*). Their method was based on a counter-technique and used the reaction

$$p + \bar{p} \rightarrow n + \bar{n},$$

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Table 1. Spin, parity, and I-spin of nucleons and antinucleons.

	Proton	Neutron	Antiproton	Antineutron
Spin, S	½	½	½	½
I-spin, T	½	½	½	½
Third component of I-spin, T_3	½	−½	−½	½
Parity	+	+	−	−

which is called charge exchange because we can interpret it as the passage of the electric charge from the proton to the antiproton. The product antineutron is recognizable by its annihilation properties. Namely, an antineutron on annihilation forms an annihilation star extremely similar to an antiproton star. Instead of reproducing their experimental arrangement, I will show (Fig. 1) a graphical picture of these phenomena as observed in a bubble chamber through the joint efforts of Wilson Powell and his group and my own group (*6*).

Similarly, the antilambda was found by Baldo-Ceolin and Prowse (*7*) in photographic emulsions exposed to a pion beam and was confirmed in the hydrogen bubble chamber. Also the antisigma-zero has been recently seen in a hydrogen bubble chamber by the Alvarez group in Berkeley (*8*).

It is also possible to predict with certainty that some of the nucleonic properties of the antinucleons—specifically the spin, I-spin, third component of the I-spin, and parity—are those shown in Table 1.

But in addition to these interesting questions of systematics of particles, which can be summarized by the diagram shown in Fig. 2, there are problems for which we know much less what to expect because they involve more than general symmetry properties. They require a fairly detailed knowledge of interactions and subnuclear structure, which at present we do not have. Indeed these are the most interesting and challenging problems.

For instance, we know that a nucleon and an antinucleon may annihilate each other, but what are the products of the annihilation? What is their energy? What are the collision cross sections? It is in this direction that we are working now, and here we must be guided mainly by experiment, at least for the time being, and also be prepared for surprises.

Fig. 1. An antiproton enters a propane bubble chamber, and at the point marked with the arrow undergoes charge exchange. The antineutron originates the annihilation star (directly below). Density of propane, 0.42 gm/cm³. Real distance between charge exchange and origin of star, 9.5 cm. $T_{\bar{p}}$ at change exchange, ~ 50 Mev. [From Agnew *et al.* (*6*)]

Collision Cross Sections

The first surprise came immediately after the discovery of the antiproton, when we found that this particle has an unusually large collision cross section. This fact has now been studied intensively for some time. The simplest situation occurs in the case of proton-antiproton collisions. There, in addition to the charge-exchange process mentioned above, there are two other possibilities, elastic scattering and annihilation, at least until we reach energies such that inelastic processes (pion production) also become possible. Thus we have three cross sections: for scattering, for annihilation, and for charge exchange. All three have been measured for a wide energy interval, and the results are shown in Fig. 3.

The magnitude of these cross sections is striking when we compare them with those obtained in proton-proton collisions. A tentative theory of this phenomenon has been put forward by Chew (*9*) and his associates and also by Koba and Takeda in Japan (*10*).

The model is based on the Yukawa theory of nuclear interactions in such a way as to stress the analogy between the nucleon-nucleon and the nucleon-antinucleon system. For the nucleon-nucleon system a model consisting of a hard repulsive core of radius about one-third the Compton wavelength of the pion (0.45 · 10^{-13} cm) surrounded by a pion cloud has been reasonably successful in explaining the experimental results of the scattering and polarization experiments. The pion cloud, which is involved in the interactions at moderate distance, can be treated from first principles of pion theory. The hard repulsive core, on the other hand, is unaccounted for from a pion theoretical point of view and must be introduced *ad hoc* as a phenomenological hypothesis, although the existence of heavier mesons such as the K-mesons may have something to do with it. For a nucleon-antinucleon system the pion cloud of the antinucleon is substituted by its charge conjugate according to the expectations of meson theory, and the medium-range interactions are treated on the basis of this theory. The overlap of the cores, however, is now supposed to bring annihilation instead of strong repulsion. On the basis of this model it has been possible to account for most of the observations made thus far—which, however, do not extend to energies above 1 Bev, where some critical tests of the theory will become possible.

In addition to the total cross sections for scattering, annihilation, and charge exchange mentioned above, the angular distribution on scattering has been measured. Here a large diffraction peak in the forward direction has been found. It is directly related to the annihilation.

The extension of the cross-section studies to complex nuclei has been started. The deuteron was first investigated in the hope of finding information on the neutron-antiproton interaction. Here the data are still very rough, mainly because the subtraction techniques which we were forced to use introduce considerable error. The qualitative feature seems to be that there is not much difference between proton-antiproton and neutron-antiproton collisions.

For heavier nuclei the data from the nucleon-antinucleon collision have been fed into an optical-model treatment, and the results agree with the experimental data as far as they are available. This gives a consistent picture connecting the more complicated case to the simpler one.

There are, however, still some crucial tests to be performed on the p-$\bar{p}$ case in order to validate the Chew model. At high energy, say 2 Bev, the annihilation cross section should be essentially the cross section of the core, and hence considerably smaller than the one observed at lower energy: 10^{-26} cm^2 would

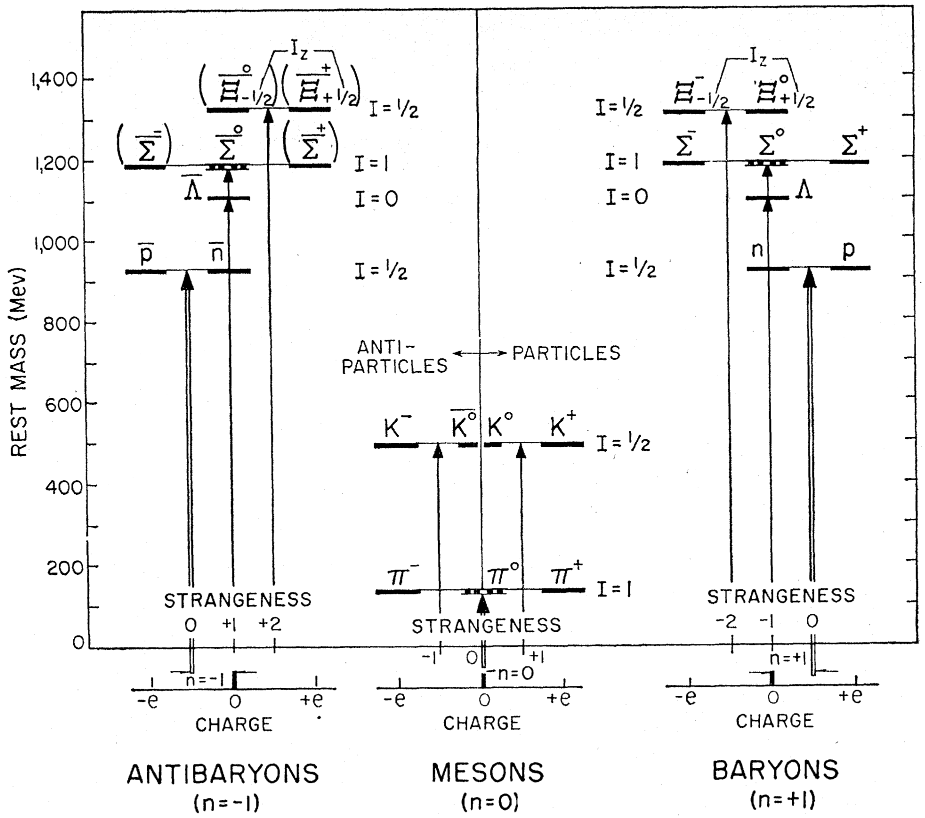

Fig. 2. A diagram showing all strongly interacting particles as known or predicted today. The particles still unobserved are in parentheses. The weakly interacting particles not reported in this diagram are the $\mu^{\pm}$ meson, the electron and positron, the neutrino and antineutrino, and the light quanta. [From Gell-Mann and Rosenfeld, *Ann. Rev. Nuclear Sci.* **7**, 407 (1957)]

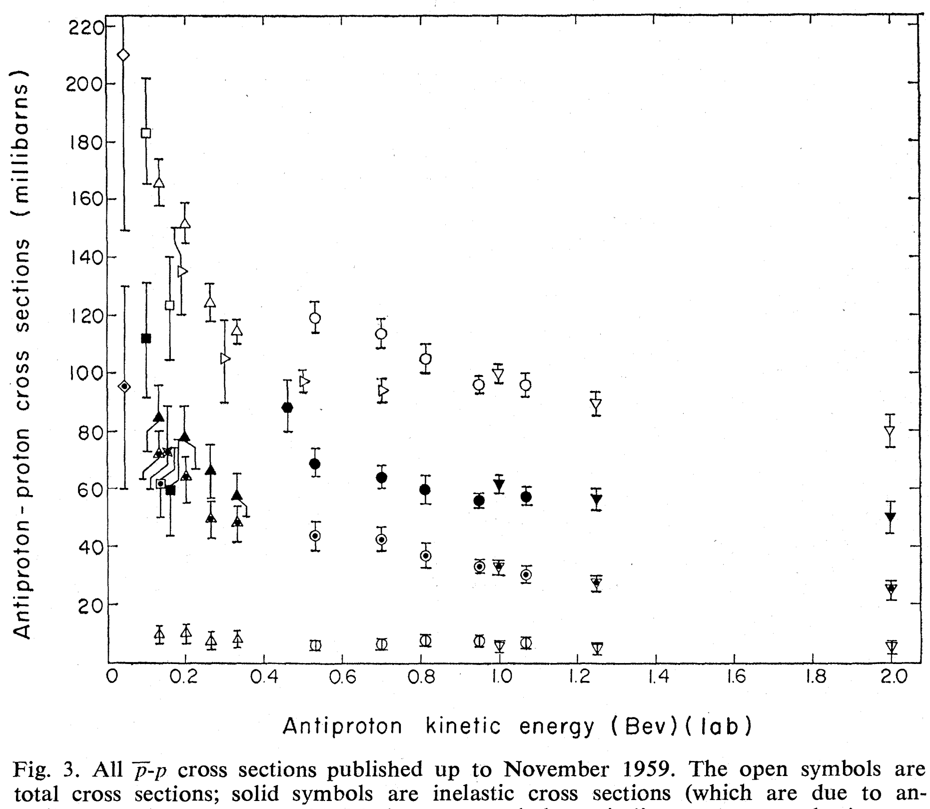

Fig. 3. All $\bar{p}$-p cross sections published up to November 1959. The open symbols are total cross sections; solid symbols are inelastic cross sections (which are due to annihilation only for $T_{\bar{p}} < 290$ Mev); open symbols encircling a dot are elastic cross sections; open symbols crossed by a vertical line at the bottom of the figure are charge-exchange cross sections. [The various symbols are referenced as follows: (□) Agnew, Elioff, Fowler, Gilly, Lander, Oswald, Powell, Segrè, Steiner, White, Wiegand, Ypsilantis, *Bull. Am. Phys. Soc.* **4**, 357 (1959); (▽) Armenteros, Coombes, Cork, Lambertson, Wenzel, *ibid.* **4**, 356 (1959); (⬡) Chamberlain, Keller, Mermod, Segrè, Steiner, Ypsilantis, *Phys. Rev.* **108**, 1553 (1957); (△) Coombes, Cork, Galbraith, Lambertson, Wenzel, *Phys. Rev.* **112**, 1303 (1958); (○) Elioff, Agnew, Chamberlain, Steiner, Wiegand, Ypsilantis, *Phys. Rev. Letters* **3**, 285 (1959); (▷) Cork, Lambertson, Piccioni, Wenzel, *Phys. Rev.* **107**, 248 (1957); (◇) Horwitz, Miller, Murray, Tripp, *ibid.* **115**, 472 (1959); (☆) Emulsion results of many authors compiled and averaged by Baroni *et al.*, *Nuovo cimento* **12**, 564 (1959).]

be a generous guess. If this expectation is not fulfilled it will be necessary to look for some other model. I will not go further into the numerous problems connected with cross-section studies and will turn now to the annihilation.

Annihilation

The annihilation process itself has been fairly well investigated experimentally, but the theoretical situation leaves much to be desired. Initially the effort was mainly directed toward establishing the fact that the energy released was $2mc^2$, thus furnishing a final proof of the annihilation. In the early investigations with photographic emulsions carried out in my group (especially by Gerson Goldhaber) and by a group in Rome led by Amaldi, we soon found stars showing a visible energy larger than mc^2 (m is the mass of the proton, c the velocity of light), giving conclusive evidence of the annihilation in pairs of proton and antiproton (*11*).

The observations on annihilation have been performed with many techniques. Initially, immediately after the identification of the antiproton, these particles were stopped in a block of heavy glass, and the showers due to the gamma rays resulting from the decay of neutral pions were observed by Moyer and his co-workers (*12*). This method was not, however, very quantitative.

Photographic emulsions were also exposed to antiprotons at the earliest possible moment. Here we see only the charged annihilation products, although much detailed information is obtainable (see Fig. 4). The great observational effort needed here was shared in a large cooperative experiment in which many laboratories in the United States and in Europe participated (*13*).

Bubble chambers have also been used, both of the propane and of the hydrogen type.

By now we know a good deal about annihilation. It gives rise prevalently to pi-mesons. These, in a time of the order of 10^{-8} second, decay into mu-mesons and neutrinos. The mu-mesons, in a time of the order of microseconds, decay into electrons or positrons and neutrinos, and the electrons and positrons finally recombine to give gamma rays. In a few microseconds the total rest mass of the nucleon-antinucleon pair degrades to particles with rest mass zero, traveling away from the spot of the annihilation with the velocity of light.

Direct annihilation into photons may occur, but this is expected to be rare and thus far has never been observed with certainty.

The reason for this difference between the behavior of electron-positron and nucleon-antinucleon pairs is, of course, that the latter can annihilate not only through the electromagnetic interaction that gives rise to light quanta but also through the specific nuclear interaction whose quanta are the pions. This last interaction is much stronger than the electromagnetic one, and when both are simultaneously present, the effects of the specific nuclear interaction overwhelm those of the electromagnetic interaction, which is the only one available to the electron-positron pair.

The most significant result of the annihilation studies is that the annihila-

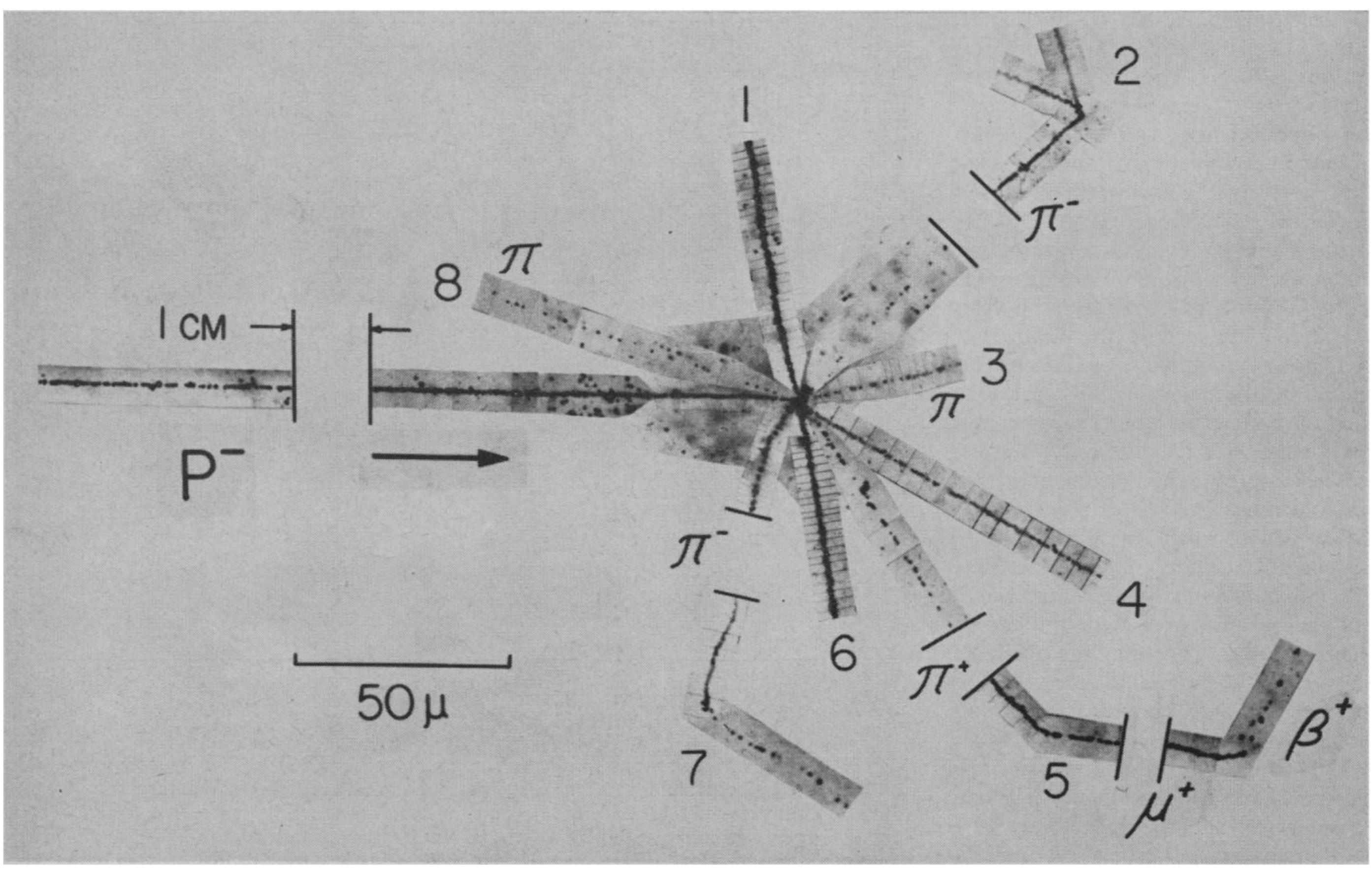

Fig. 4. An annihilation star, showing the particles as numbered. Total visible energy, 1300 Mev; total energy release, 1400 Mev.

No.	1	2	3	4	5	6	7	8
Identity	p(?)	π^-	π(?)	p	π^+	H^3(?)	π^-	π(?)
T (Mev)	10	43	175	70	30	82	34	125

tion process gives rise to an average of 4.8 pions per annihilation, about equally divided among positive, negative, and neutral pions. These pions escape with a continuous energy distribution, the average kinetic energy being about 200 Mev. In about 4 percent of the cases of annihilation at rest, strange particles, K-mesons, are emitted (see Fig. 5).

The escaping pions give rise in complex nuclei to secondary processes, and thus a number of nucleons or light nuclei are also found among the particles emitted on annihilation. Sometimes the relatively rare K-mesons interact, producing a Λ-hyperon, and even more complicated hyperfragments have been observed (Ekspong).

In hydrogen, the multiplicity of the prongs (I am referring of course only to charged particles) for annihilations at rest is given in the following little table:

Charge multiplicity	0	2	4	6	8
Number of stars	10	89	109	14	0
(Total, 222)					

Naturally, only even numbers of charged prongs may appear because the total charge of the proton-antiproton system is zero.

From the theoretical point of view, we don't yet have an entirely satisfactory picture of the annihilation process. It has been mostly analyzed on the basis of a statistical theory put forward many years ago by Fermi, which does not take into account any detailed mechanism, but only the obvious and necessary features determined by phase space. This theory contains only one free parameter—namely, the volume into which the energy released on annihilation is concentrated at the beginning of the phenomenon. Naturally, this volume is supposed to be the one corresponding to a sphere of radius equal to the radius of action of nuclear forces. If one calculates what is to be expected on this basis one finds a result which is in rather poor agreement with experiment—namely, the multiplicity of pions produced is larger than that predicted by the model. Clearly the average energy and the multiplicity are connected, and hence the average energy also disagrees with the naive statistical prediction. The model can be made to yield correct results by increasing beyond what seems plausible the volume in which the energy comes to equilibrium. Many attempts have been made to refine Fermi's theory and to bring it into agreement with facts. Some of these attempts are very ingenious, and one would wish that there were more success than there is. The ratio between K-mesons and pions is another element of the puzzle that has to be taken into account and seems rather intractable for the time being.

It is, however, hardly to be expected that a purely statistical theory should explain quantitatively the annihilation process, inasmuch as selection rules, strong interactions of the escaping particles, and other important factors completely omitted in the theoretical picture are at work. I think that the future study of the annihilation process, with its bearing on the core of the nucleon—a region of which we know so little—will give some important results. Antinucleons are especially suited for this study because they will exhibit more clearly than other particles the effects of the core.

Antimatter

And now let me say some words on the popular subject of the "antiworld." As early as 1933 Dirac, in his Nobel lecture, said:

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of nature, we must regard it rather as an accident that the earth (and presumably the whole solar system) contains a preponderance of negative electrons and positive protons. 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 would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

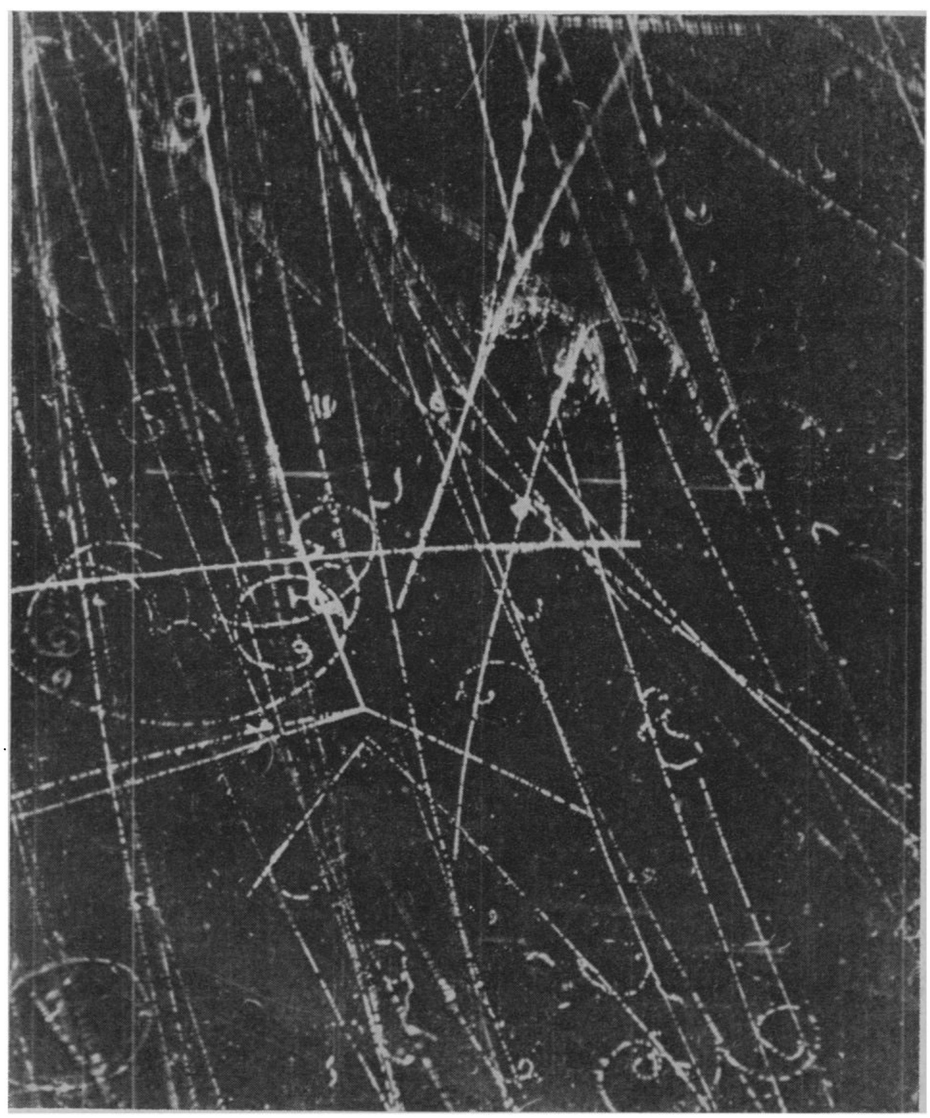

Fig. 5. Annihilation of an antiproton in carbon, giving rise to a K^0 meson and a Λ^0 hyperon.

We can now add that the proved existence of the antinucleons has very strongly corroborated this possibility, although we also know that the symmetry between electric charges breaks down for weak interactions. As far as astronomical means are concerned, a verification seems impossible in principle, because they depend on electromagnetic phenomena, which are invariant under charge conjugation. It is, however, interesting that the recent important discoveries about beta decay and the neutrino now give a method for looking for antimatter which, while still impossible in practice, is sound in principle, being based on weak interactions which are *not* invariant under charge conjugation. This method, if it could be executed, would solve unambiguously the question of the existence of antiworlds. If we observe a star and from its astronomical characteristics can decide that most of its energy comes from a known cycle, as for example the carbon cycle, which is dominated by beta decays, we can see whether the antineutrinos coming from it are or are not of the same kind as the antineutrinos coming from a pile or from our sun by performing an inverse beta-decay experiment. If it should turn out that they are neutrinos —different from those coming from the sun—then the star is of antimatter (*14, 15*).

References and Notes

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14. As in many investigations in high-energy physics in recent times, this experiment is the result of a large cooperative effort. The credit for the success is shared by many individuals and even by a machine, which was obviously necessary to produce particles above the threshold for nucleon pair production. Since it is impossible to mention all the numerous contributors, I shall limit myself to a few. Oreste Piccioni helped materially in the early planning of the experiment, especially by suggesting the use of magnetic quadrupole lenses. Edward J. Lofgren most ably directed the operation of the Bevatron. Herbert M. Steiner supplied invaluable help during the whole experiment. Tom J. Ypsilantis, our colleague and coauthor, also worked with us all the time. Above all, however, our coauthor and comrade of 20 years of work, Clyde Wiegand, was indispensable and deserves a major part of the credit for the success of our investigation.
15. This article was prepared as an account of work sponsored by the U.S. Atomic Energy Commission.

General Theory of Mortality and Aging

A stochastic model relates observations on aging, physiologic decline, mortality, and radiation.

Bernard L. Strehler and Albert S. Mildvan

Although statistics on human mortality furnish one of the most extensive and reliable collections of biological data, general theories to account for the quantitative relationships between age and death rate have not been completely satisfactory. The essential observations which must be taken into account in any general theory of mortality are as follows:

1) The death rate at any age (of most adult human populations and of many populations of animals) may be expressed as the sum of an age-dependent term (Gompertz, *1*) and an age-independent term (Makeham, *2*)—that is, $R = A + R_0 e^{\alpha t}$).

2) In certain environments the Makeham term (A) predominates (for example, wild birds, *3*), while in most human populations (between ages 35 to 85) and in certain animal populations, the Gompertz term predominates (see Fig. 1). The Gompertzian period is followed by a gradual reduction in the rate of increase of the mortality rate (*4*).

3) The rate of decrease of most physiological functions of human beings is between 0.5 and 1.3 percent per year after age 30, and is fit as well by a straight line as by any other simple mathematical function (*5, 6*) (see Fig. 2).

4) Death rates due to certain important specific causes (for example, cancer, tuberculosis, and heart disease) increase exponentially with age similarly to the total death rate (*7, 8*).

5) Continuous exposure of experimental animals to high-energy radiation tends to increase the Gompertz slope (α) by an amount proportional to dose rate, whereas exposure to a single dose of ionizing radiation does not appreciably affect α, but does increase $\ln R_0$ proportionally to dose (*9–11*).

Among the recent attempts to postulate mechanisms underlying the Gompertz function or the other generalities given above, or both, are the theories of Jones (*8*), Failla (*12*), Sacher (*13*), Yockey (*14*), and others (*15, 16*). Each theory has certain attractive features but either fails to account for all of the above observations, possesses internal inconsistencies, or makes incorrect predictions. A detailed critique of these and other theories is in press (*17*).

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