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# NUCLEAR PROPERTIES OF ANTINUCLEONS

Emilio Segrè

(Nobel Lecture)

December 10, 1959

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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 I naturally thought of means for hunting the elusive antiproton. Although its existence was very probable, a definite experimental proof was lacking and,

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[*]Lecture given in Stockholm before the Royal Swedish Academy of Sciences in ceremonies accompanying presentation of the Nobel Prize in Physics.

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 in the preceding lecture by Dr. Chamberlain.[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]

Dr. Chamberlain has described to you what an antiproton is and how it was found, and I have nothing to add to his lecture on these matters.

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 will direct the rest of my speech.

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 to say that now it is possible to have at Berkeley beams with about 10 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 more difficult and complicated experiments and the developments 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 as 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, expect 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, Piccinoni, and Wenzel did demonstrate the existence of the antineutron some time ago.[5] Their method was based on a counter technique and uses the reaction

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

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 anti-neutron is recognizable by its annihilation properties. Namely, an anti-neutron 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 by the joint efforts of Professor 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 some of the nucleonic properties of the antinucleons--specifically the spin, I-spin, third com-ponent of the I-spin, and parity--to be those shown in Table I.

Table I

| Spin, parity, and I-spin of nucleons and antinucleons | | | | |
|---|---|---|---|---|
| | Proton | Neutron | Antiproton | Antineutron |
| Spin, S | 1/2 | 1/2 | 1/2 | 1/2 |
| I-spin, T | 1/2 | 1/2 | 1/2 | 1/2 |
| Third component of I-spin, $T_3$ | 1/2 | -1/2 | -1/2 | 1/2 |
| Parity | + | + | - | - |

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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 g/cm$^3$.  Real distance between
charge exchange and origin of star, 9.5 cm.  $T_{\bar{p}}$ at charge
exchange, ~ 50 Mev.  (From Agnew et al.[6])

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.

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 a radius of about 1/3 of the Compton wave length of the pion ($0.45 \cdot 10^{-13}$ 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
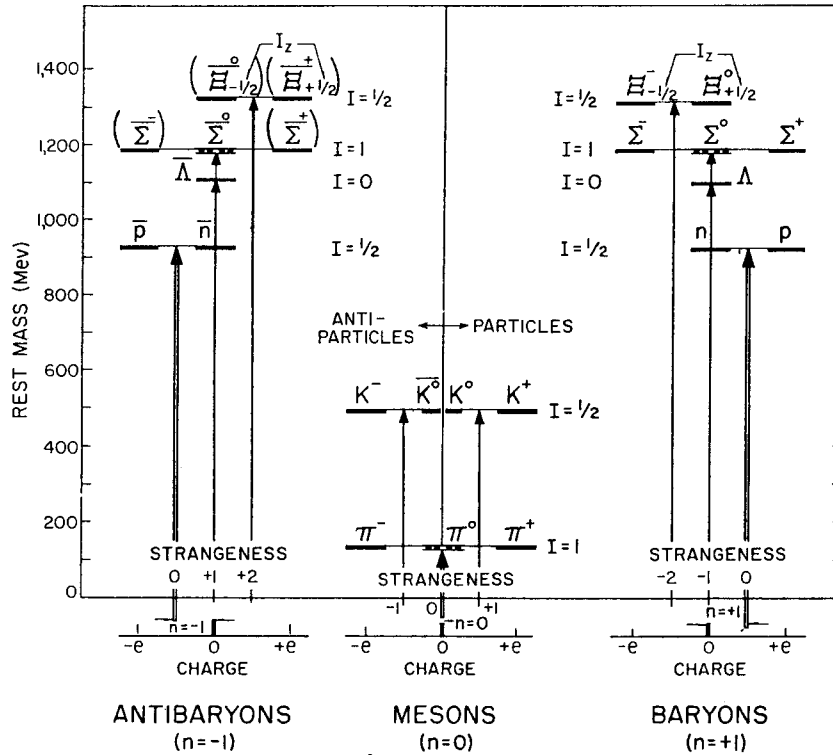
Fig. 2. A diagram showing all strongly interacting particles as
known or predicted today. The particles still unobserved
are in parenthesis. The weakly interacting particles not
reported in this diagram are the $\mu^{\pm}$ meson, the electron and
positron, the neutrino and antineutrino, and the light quanta.
(From Gell-Mann and Rosenfeld, Ann. Rev. Nuclear Sci.
7, 407 (1957).)
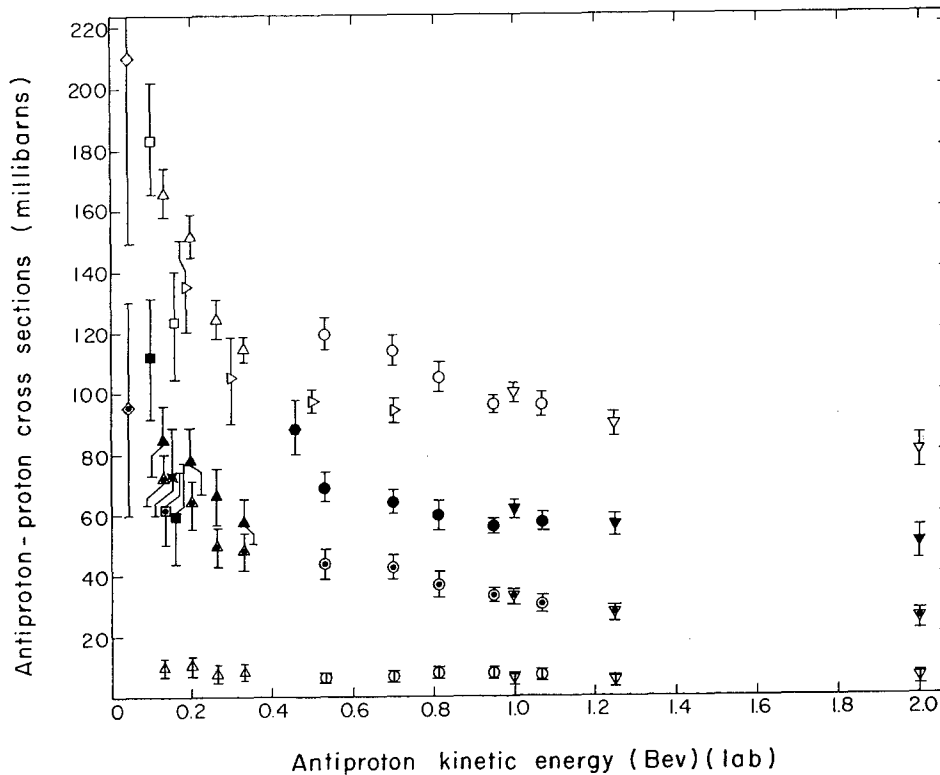
Fig. 3. All p̄-p cross sections published up to November, 1959.
The open symbols are total cross sections; closed symbols
are inelastic cross sections (which are due to annihilation only
for $T_{\bar{p}} < 290$ Mev); open symbols encircling a dot are elastic
cross sections; open symbols crossed by a 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, and Ypsilantis, Bull. Am. Phys. Soc.
  Series II, 4, 357 (1959).

▽ Armenteros, Coombes, Cork, Lambertson, and Wenzel, Bull.
  Am. Phys. Soc., Series II, 4, 356 (1959).

⬡ Chamberlain, Keller, Mermod, Segrè, Steiner, and Ypsilantis,
  Phys. Rev. 108, 1553 (1957).

△ Coombes, Cork, Galbraith, Lambertson, and Wenzel, Phys.
  Rev. 112, 1303 (1958).

○ Elioff, Agnew, Chamberlain, Steiner, Wiegand, and Ypsilantis,
  Phys. Rev. Letters 3, 285 (1959).

▷ Cork, Lambertson, Piccioni, and Wenzel, Phys. Rev. 107, 248
  (1957).

◊ Horwitz, Miller, Murray, and Tripp, Phys. Rev. 115, 472 (1959).

✕ Emulsion results of many authors compiled and averaged by
  Baroni et al., Nuovo cimento 12, 564 (1959).

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 has been first investigated with 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 errors.  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-$\bar{\text{p}}$ 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 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.

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 Dr. 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 USA 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 is expected to be rare and thus far has never been observed with certainty.
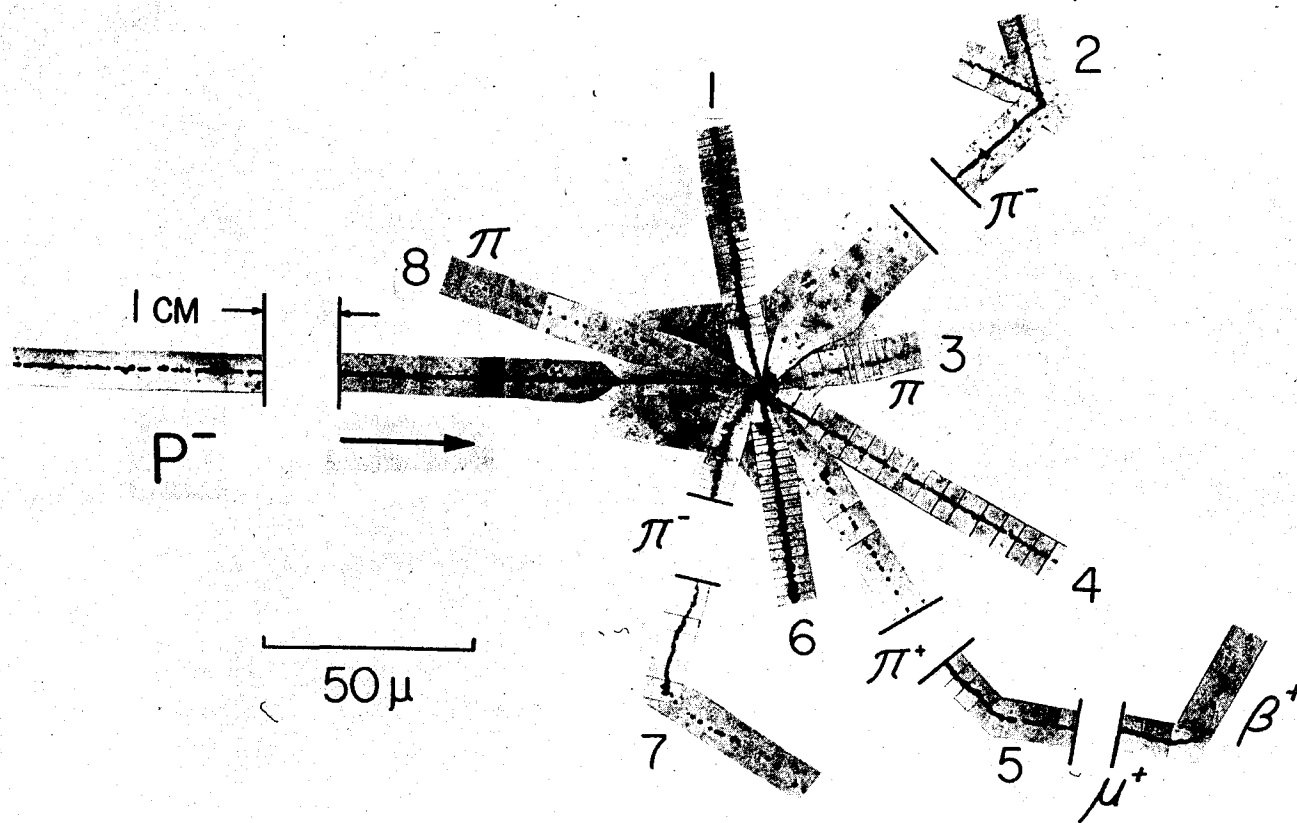
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Fig. 4. An annihilation star, showing the particles as numbered.

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

Total visible energy 1300 Mev.  Total energy release 1400 Mev.

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 giving 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 its effects 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 annihilation 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% 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 is also found among the particles emitted on annihilation. Sometimes the relatively rare K-mesons interact, producing a $\Lambda$-hyperon, and even more complicated hyperfragments have been observed (Ekspong).

In hydrogen the multiplicity of the prongs (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 | Total |
|---|---|---|---|---|---|---|
| Number of stars | 10 | 89 | 109 | 14 | 0 | 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

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Fig. 5.   Annihilation of an antiproton in carbon giving rise to a
$K^0$ meson and a $\Lambda^0$ hyperon.

of the radius equal to 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.

And now let me say some words on the popular subject of the "anti-
world." Already Dirac in his Nobel lecture of 1933 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.

We can now add that the proved existence of the antinucleons has very
strongly corroborated this possibility, although we also know that the sym-
metry 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 anti-
neutrinos coming from a pile or from our sun by performing an inverse
beta-decay experiment. If it should turn out that they are neutrinos, i. e.,
different from those coming from the sun, then the star is of antimatter.

Let me finish this lecture with a remark and some acknowledgments.
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 con-
tributors, I shall limit myself to a few. Dr. Oreste Piccioni helped
materially in the early planning of the experiment, especially by suggesting
the use of magnetic quadrupole lenses. Dr. Edward J. Lofgren most ably
directed the operation of the Bevatron. Dr. Herbert M. Steiner supplied
invaluable help during the whole experiment. Dr. Tom J. Ypsilantis, our
colleague and co-author, also worked with us all the time. Above all,
however, our co-author and comrade of 20 years of work, Dr. Clyde Wiegand,
was indispensable and deserves a major part of the credit for the success
of our investigation.

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