Title
FORCES BETWEEN NUCLEONS AND ANTINUCLEONS

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ABSTRACT

Existing experimental information about the nucleon-antinucleon interaction is reviewed and a description is given of a theoretical model, based on the Yukawa theory, which seems able to explain the experimental results.

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I.

In 1955, Chamberlain, Segrè, Wiegand, and Ypsilantis, working with a beam of particles from the Bevatron, established the existence of the antiproton.[1] As theoretically expected, they found this particle to have a mass equal to that of the proton and a charge equal but opposite in sign. Later the antineutron was found by Cork, Lambertson, Piccioni, and Wenzel and also observed to have the expected properties.[2] (Neutron and antineutron, even though they are both neutral, are not the same particle. For example, they are capable of mutual annihilation, a process that cannot occur for two neutrons.)

Many experiments were then undertaken to determine the interactions of antiprotons, and the first important fact established was that annihilation actually occurs when proton and antiproton come sufficiently close to each other. This experiment was carried out with emulsions in a collaboration between a group in Rome under Professor Amaldi and a large Berkeley group.[3] It was found that on the average about five pions were emitted per annihilation, a number that some theorists find surprisingly large, but which depends on so many complicated considerations that no clean-cut interpretation has yet been possible.

Further experiments have given the detailed cross sections for proton-antiproton scattering and annihilation at intermediate energies, that is between about

100 and 400 Mev. The processes involved and the corresponding cross sections are as follows:

Process	Cross section
$p + \bar{p} \rightarrow p + \bar{p}$	σ scat (scattering)
$p + \bar{p} \rightarrow n + \bar{n}$	σ ex (charge-exchange)
$p + \bar{p} \rightarrow$ annihilation	σ ann (annihilation)

Ordinary inelastic scattering, with pion production, is negligible at these energies. The total cross section is, then,

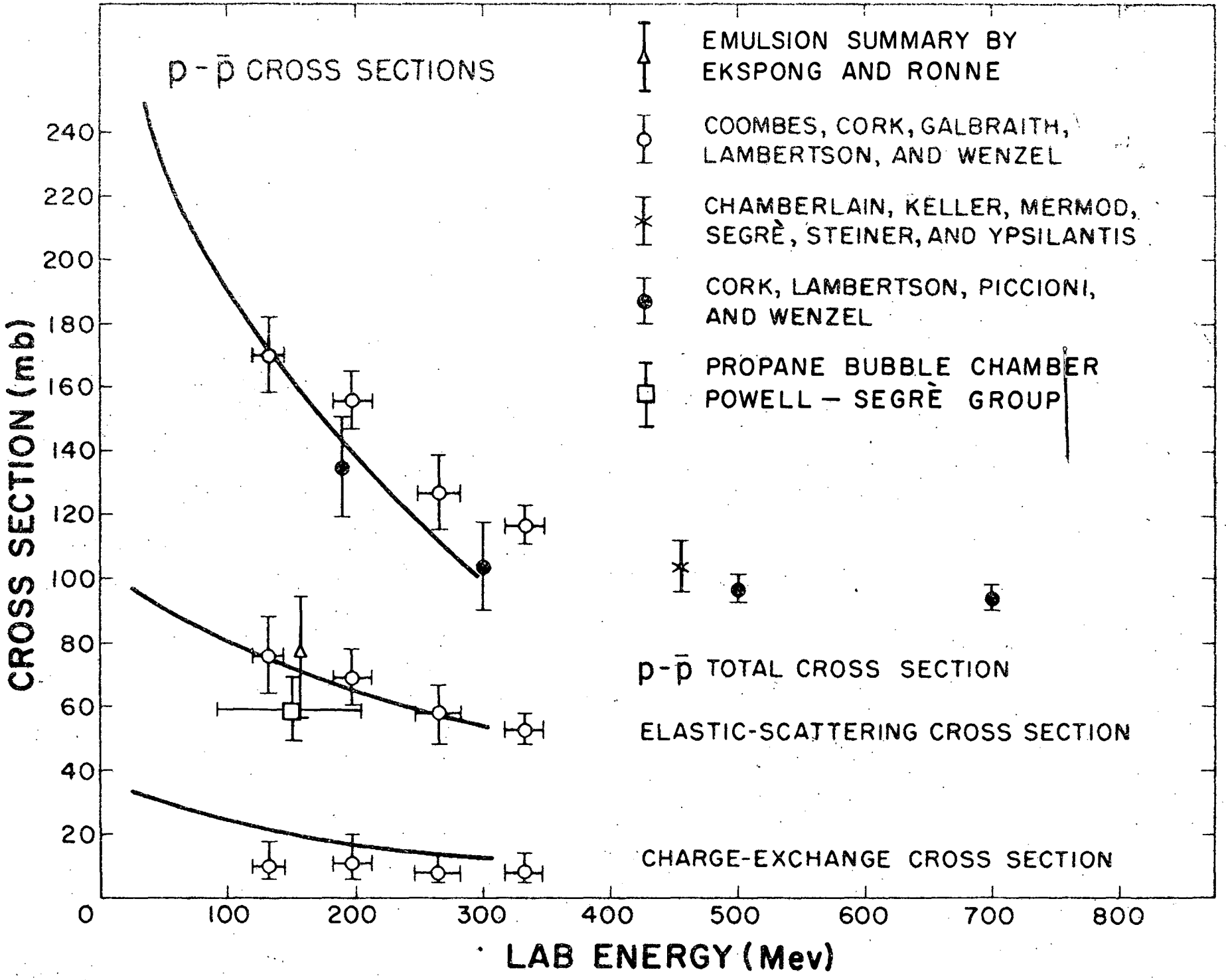
$$\sigma_{total} = \sigma_{scat} + \sigma_{ex} + \sigma_{ann} .$$

In Fig. 1 a compilation of many different experimental results for these cross sections is shown, and it is seen that good agreement exists between the various measurements. Angular distributions for elastic scattering have also been measured; examples are shown in Figs. 2 and 3.

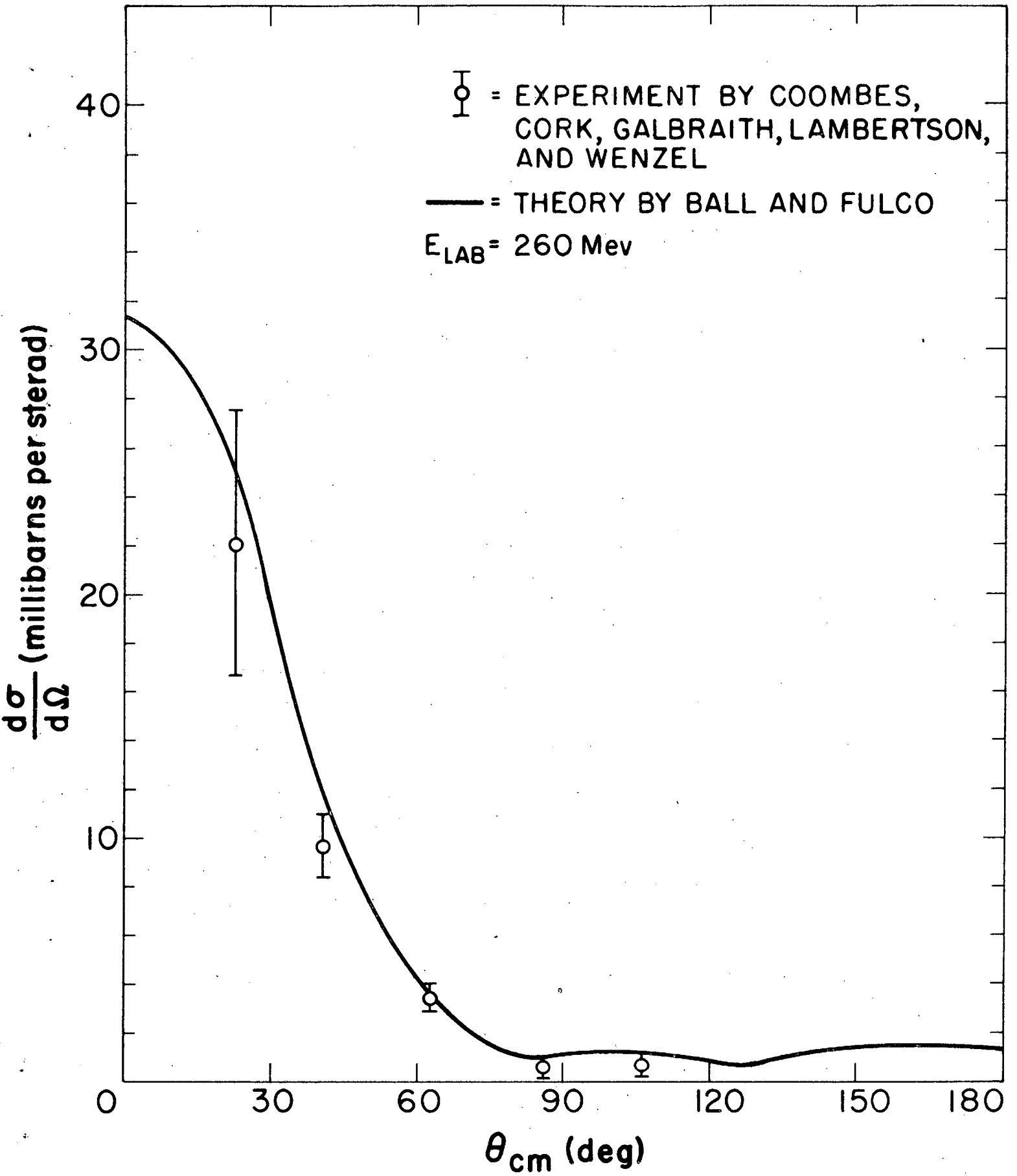
The most striking aspect of these experimental results is the magnitude of the total proton-antiproton cross section, which at these energies is two to three times as large as the corresponding nucleon-nucleon cross sections. This difference led people at first to suppose that the forces acting between nucleon and antinucleon must be quite different from those between two nucleons. Let us consider now what field theory has to say about this question.

II.

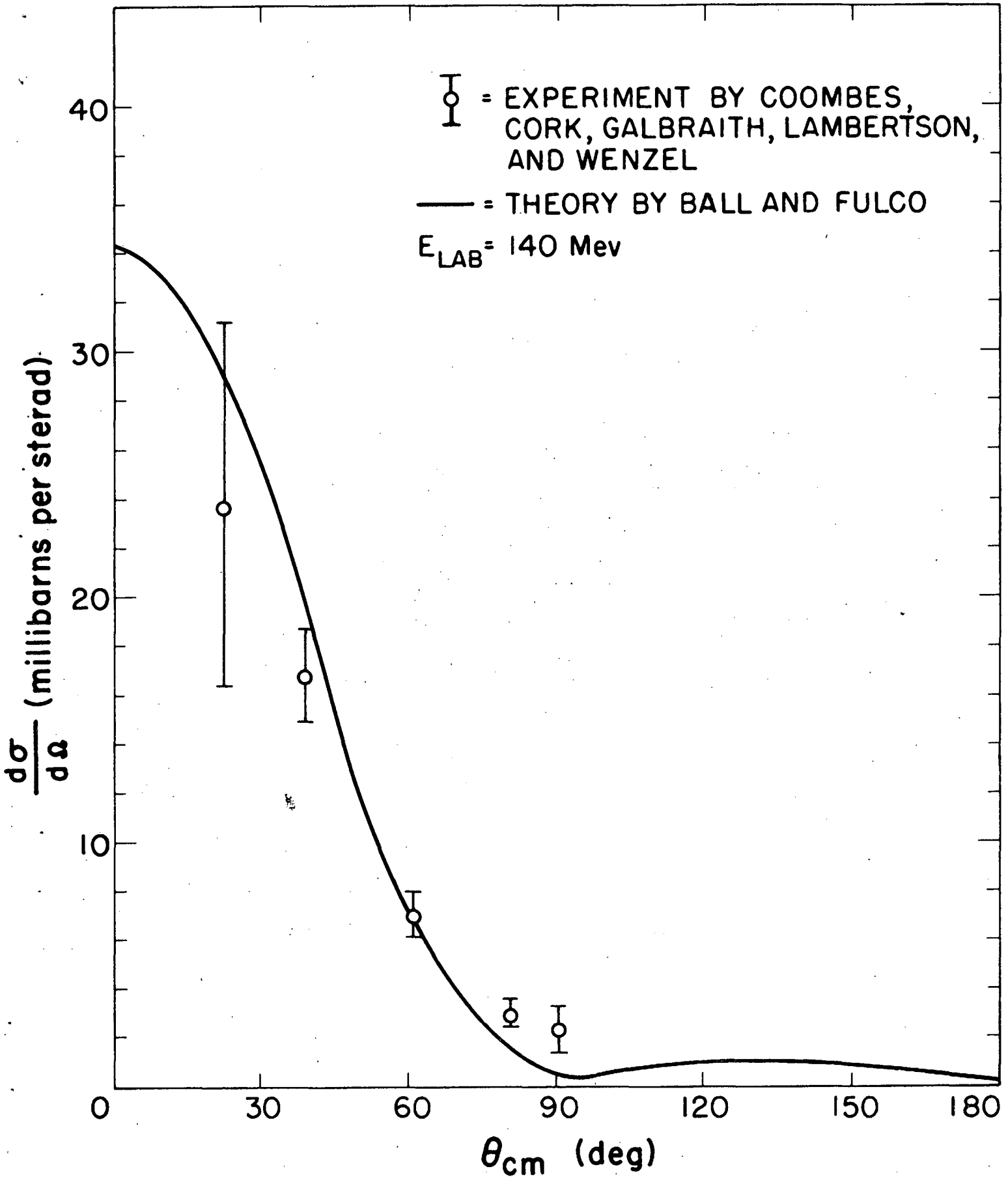
It has been possible to understand many properties of the nucleon in terms of the Yukawa hypothesis that the nucleon is a source of the π-meson field in the same sense that a charged particle is a source of electromagnetic field. The


p - p̄ CROSS SECTIONS
EMULSION SUMMARY BY EKSPONG AND RONNE
COOMBES, CORK, GALBRAITH, LAMBERTSON, AND WENZEL
CHAMBERLAIN, KELLER, MERMOD, SEGRÈ, STEINER, AND YPSILANTIS
CORK, LAMBERTSON, PICCIONI, AND WENZEL
PROPANE BUBBLE CHAMBER POWELL – SEGRÈ GROUP
p - p̄ TOTAL CROSS SECTION
ELASTIC-SCATTERING CROSS SECTION
CHARGE-EXCHANGE CROSS SECTION
CROSS SECTION (mb)
0
20
40
60
80
100
120
140
160
180
200
220
240
100
200
300
400
500
600
700
800
LAB ENERGY (Mev)

50,918-1


= EXPERIMENT BY COOMBES, CORK, GALBRAITH, LAMBERTSON, AND WENZEL
= THEORY BY BALL AND FULCO
E_{LAB} = 260 Mev
40
30
20
10
0
30
60
90
120
150
180
$\frac{d\sigma}{d\Omega}$ (millibarns per sterad)
θ_{cm} (deg)

50,917-1


= EXPERIMENT BY COOMBES, CORK, GALBRAITH, LAMBERTSON, AND WENZEL
= THEORY BY BALL AND FULCO
E_{LAB} = 140 Mev
40
30
20
10
0
30
60
90
120
150
180
$\frac{d\sigma}{d\Omega}$ (millibarns per sterad)
θ_{cm} (deg)

50,916-1

Yukawa picture of the physical nucleon is divided roughly into three regions:

(1) An outer "fringe" at distances larger than or of the order of the pion Compton wavelength, $\lambda\!\!\!^{-}_{\pi} = \hbar/m_{\pi} c = 1.4 \times 10^{-13}$ cm. Here single virtual pions occur in a well defined distribution, with a strength characterized entirely by the pion-nucleon coupling constant, $f^2/\hbar c = 0.08 \pm 0.01$. General considerations--such as conservation laws and the uncertainty principle--give us confidence that we understand this region. If the pion is indeed the lightest particle that interacts strongly with the nucleon, then according to the uncertainty principle it must dominate the outer parts of the nucleon structure; and if we believe that strong interactions conserve parity and isotopic spin and are essentially local in nature, then the distribution of virtual pions at large distances is determined entirely by symmetry considerations. Experiments on the long-range parts of the nucleon-nucleon force and on the zero-energy limits of pion-nucleon scattering and photopion production give quantitative confirmation of these conclusions. By any ordinary standards, then, we can claim to have a rather complete understanding of the "fringe" of the nucleon.

(2) The intermediate structure of the nucleon, at distances smaller than $\lambda\!\!\!^{-}_{\pi}$ but greater than the nucleon Compton wavelength, $\lambda\!\!\!^{-}_{n} \simeq \lambda\!\!\!^{-}_{\pi}/7$, is by no means completely understood, but it seems still to be dominated by virtual pions, and the Yukawa theory has had semiquantitative success in describing this intermediate region. In particular, the theory seems to give a nucleon-nucleon force at intermediate distances which is remarkably close to that required by experiment. When we add the fact that the anomalous nucleon magnetic moments are fairly well understood in terms of this pion cloud, we conclude that a good deal is known, at least empirically, about the intermediate structure of the nucleon.

(3) Finally there is the "core" of the nucleon, the structure at distances smaller than the nucleon Compton wavelength. Almost nothing is understood about this region theoretically although we expect it to contain virtual strange particles and antinucleons. Empirically it gives rise to a strong repulsive force between two nucleons, the famous "hard core" of the potential.

What relevance do these considerations have to antinucleons? Well, if the principle of charge conjugation means what we think it does, the above picture of the nucleon leads us to just as complete a picture of the antinucleon. Every virtual pion in the fringe and intermediate region is simply to be replaced by a corresponding antipion. The point I am trying to make is that if we claim to understand the nucleon-nucleon interaction at large and intermediate distances in terms of the corresponding portions of the pion cloud, then we understand exactly as much about the nucleon-antinucleon interaction. We are not in the position of being able to plead ignorance about the "mysterious" antinucleon. We cannot make ad-hoc assumptions about the $N\bar{N}$ interaction at large and intermediate distances without the danger of doing violence to well established principles.

The magnitude of the $N\bar{N}$ total cross section in itself does not imply that anything beyond the conventional Yukawa pion-exchange mechanism is involved. A classical impact parameter equal to the pion Compton wavelength corresponds to a total cross section of 130 mb. Thus the astonishing fact, if there is one, is that np and pp cross sections are so small, not that pp cross sections are so large.

The usual theoretical description of the NN interaction differs according to the region of structure involved. At large separations, where singly occurring fringe pions are dominant, the potential energy is exactly given by

$$V_{1\pi} = f^2 \vec{\tau}_1 \cdot \vec{\tau}_2 \vec{\sigma}_1 \cdot \vec{\nabla} \vec{\sigma}_2 \cdot \vec{\nabla} \frac{e^{-r}}{r} ,$$

where the length unit is the pion Compton wavelength. The constant f is the pion-nucleon coupling constant and might be called the "pionic charge" of the nucleon. The value is such that $f^2/\hbar c \simeq 0.08$. Because the pionic charge of the antinucleon is the opposite of that for the nucleon, this part of the interaction simply reverses sign in the $N\bar{N}$ system.

At intermediate distances double pion exchange becomes important, and these contributions have the same magnitude and sign in both NN and $N\bar{N}$ systems. (As a general rule, terms due to exchange of an odd number of pions reverse sign while those due to an even number do not.) Unfortunately no reliable expression exists for the interaction due to multiple pion exchange, and at intermediate distances there also are corrections to the single-pion formula due to nucleon recoil. However if one tends to be optimistic there is reason to believe that the most important parts of the interaction at intermediate distances can be and have been calculated in terms of one- and two-pion exchange. Thus we are in a position to construct, at least roughly, the $N\bar{N}$ interaction potential, except in the region of the core.

For the core we must make an assumption, but we are guided by both theory and experiment. Theoretically it is clear that there are two distinct contributors to the $N\bar{N}$ interaction. First there are pion exchanges, which are in one-to-one correspondence with pion exchanges in the NN interaction and which are represented by the long- and intermediate-range potential discussed previously. Second, however, there is the possibility of annihilation, which has no counterpart in the NN system; the annihilation mechanism corresponds in the theory to an absorptive interaction whose range is of the order of the nucleon Compton wavelength. The experimental fact of significance is the large average number of pions observed in $N\bar{N}$ annihilation.

Putting these two facts together suggests that the very-short-range part of the $N\bar{N}$ interaction should be represented not by a hard core but by a black hole.[4] That is to say, once the cores of N and $\bar{N}$ touch, annihilation is inevitable. If virtual pions are formed, there are so many that the chance of all being reabsorbed to lead back to the $N\bar{N}$ system is negligible.

Before describing the detailed quantum treatment of this model, let me emphasize its classical significance. We have a small black hole, surrounded sometimes by a repulsive "wall" (Fig. 4a) and sometimes by an attractive "well" (Fig. 4b).

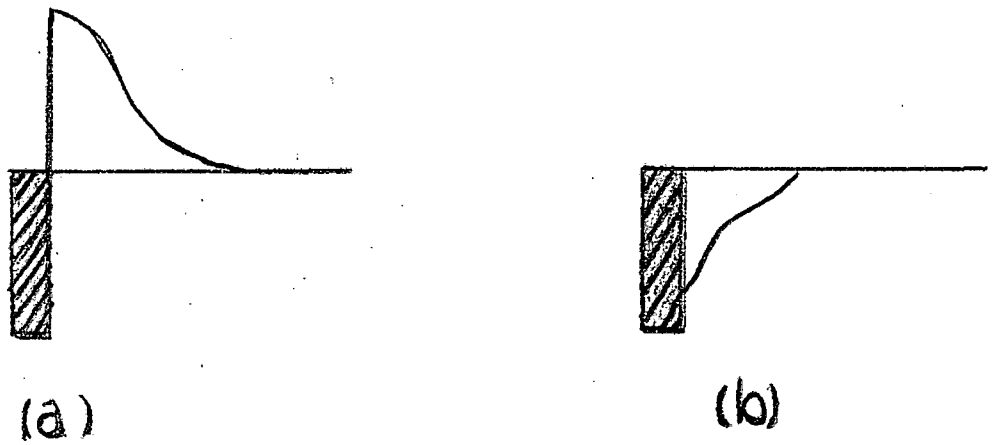


Fig. 4. The general form of the nucleon-antinucleon potential according to the Yukawa theory. In (a) the outside potential is repulsive and in (b) attractive.

Both situations occur because the nuclear force has a strong spin dependence and may be either attractive or repulsive depending on how the spins are oriented.

The cross section is clearly determined by the outer potential. With a repulsion, one gets elastic scattering, unless the kinetic energy overcomes the barrier. With an attraction, one sometimes gets scattering, but the lower-angular-momentum collisions may lead to a spiraling in, followed by absorption, that is to say, annihilation. The exact size of the black hole is clearly not important, so our model contains no free parameters and makes unambiguous predictions.

III.

Ball and Fulco[5] have made detailed calculations of the proton-antiproton cross sections on the basis of this model. Their results are shown as the solid curves in Figs. 1 to 3, and the agreement with experiment is evidently satisfactory at the energies considered. The model cannot be taken seriously above about 200 Mev, because the fast relative motion of the nucleon and antinucleon invalidates the potential concept.

We may ask at this point how the theory was able to produce the large difference between NN and $N\bar{N}$ cross sections, with such similar forces in the two cases. To answer this question we must understand the underlying reason for the small NN cross sections. First of all, the S phase shifts of the $N\bar{N}$ system are anomalously small because of a kind of "Ramsauer effect," a cancellation of the effect of the repulsive core against an attractive outside region. The NN system, with the repulsive core replaced by a black hole makes full use of the outside potential. A somewhat similar phenomenon occurs in the P states where in the NN system a repulsive long-range one-pion potential tends to counteract a short-range attractive

two-pion potential. The reversal of sign of the one-pion part in the $N\bar{N}$ system removes this cancellation, giving a strong over-all attraction that accounts for a large part of the total plane-wave cross section.

A final word about what to expect at very high energies, i.e., in the multi-Bev range. It is very hard to see how the concepts discussed here can lead to large annihilation cross sections in this region of energy. We have been depending on the pion cloud to deflect the antinucleons inward so that they strike the nucleon core and are annihilated. But for antiprotons in the Bev range the pion cloud cannot do much deflecting. Fringe collisions will lead only to multiple meson production, and the annihilation cross section should shrink to the size of the black hole that we have been talking about. Exactly what this size is we do not know but it must be closer to 10 than to 60 mb. Experiments to determine the very-high-energy proton-antiproton cross sections are now being planned.

ACKNOWLEDGMENT

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FOOTNOTES

1 Chamberlain, Segrè, Wiegand, and Ypsilantis, Phys. Rev. 100, 947 (1955).

2 Cork, Lambertson, Piccioni, and Wenzel, Phys. Rev. 104, 1193 (1956).

3 The Antiproton Collaboration Experiment, Phys. Rev. 102, 921 (1956).

4 J. Ball and G. Chew, Phys. Rev. 109, 1385 (1958).

5 J. S. Ball and J. R. Fulco, Nucleon-Antinucleon Scattering, UCRL-8365, July 30, 1958.