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Author
Chew, Geoffrey F.

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PIONS AND ANTINUCLEONS

Geoffrey F. Chew*

I propose here to review certain experiments in high-energy nuclear physics which demonstrate that at least some aspects of quantum field theory, when applied to strong as well as to electromagnetic interactions, actually correspond to nature.

I use the term "strong interaction" for the short-range forces which, for example, operate between pairs of nucleons as well as between pions and nucleons. The strange particles also have strong interactions, but I exclude these particles from my discussion. Photons, electrons, mu mesons, and neutrinos do not have strong interactions.

The first example of quantum field theory resulted from the straightforward application of quantum mechanics to the classical electromagnetic equations of Maxwell. This theory successfully described the emission and absorption of photons. Later, after the discovery of electron-pair creation and annihilation, it was realized that a natural way to describe changing numbers of any particles is to associate with each kind of particle a field, just as the electromagnetic field is associated with the photon. The Dirac description of the electron in interaction with the electromagnetic field was modified in this way, and the resulting theory, which contains two fields—one for photons and one for electrons, has been extremely successful in describing the results of experiments involving these particles.

It was a natural step to associate fields with other known particles, such as neutrons and protons and later, π-mesons. For many years it was not possible to test experimentally the theoretical predictions following from such an association, but with the postwar development of high-energy accelerators, we now are in possession of many experimental facts which confirm the general validity of the field theoretical description of matter. I propose here to review some important experiments of this kind, recently carried out in the United States, which relate, in particular, to pions and nucleons.

One may distinguish between aspects of field theory that have to do with the separate noninteracting fields and those that relate directly to interactions. Among the predictions that flow from the field concept itself, perhaps the most spectacular is that relating to antiparticles. As soon as one attempts in terms of fields to make a relativistic description even of noninteracting

*Radiation Laboratory, University of California, Berkeley, California.

particles, one is led to the necessity for antiparticles. If the particle in question is neutral it may be its own antiparticle (although such is not necessarily the case), but if it is charged the antiparticle must have the opposite charge. It is possible also to prove that the particle and antiparticle must have the same mass, spin, and lifetime.

These predictions were obeyed by the π-meson, discovered just after the war, which exists in three forms–positive, negative, and neutral. The positive and negative particles have the same mass and lifetime, while the neutral is lighter and decays in an entirely different way. A big question, however, ever since the Dirac theory was put forward, has been: Where is the antiproton? According to theory, this particle should be stable and have the same mass and spin as the proton but a negative charge. It should also be capable of annihilating a proton, together with itself, with a total energy release of about 2 Bev.

This large energy is of course also required to produce an antiproton in the first place and accounts for the rarity of these particles. Multi-Bev energies are available in cosmic radiation, but many years of search by cosmic-ray physicists failed to produce any convincing example of an antiproton. The first accelerator to have a sufficiently high energy to do the job was the Bevatron at the University of California Radiation Laboratory in Berkeley. I am not going to describe here the famous experiment in 1955 of Chamberlain, Segrè, Wiegand, and Ypsilantis,[1] which by a rigorous set of criteria established the existence of the antiproton. Suffice it to say that they found this particle to have the theoretically predicted mass and charge and to be stable. Later the antineutron was found by Cork, Lambertson, Piccioni, and Wenzel[2] and also observed to have the expected properties. (Neutron and antineutron, even though they are both neutral, are not the same particle, in contrast to the situation with the neutral pion which is its own antiparticle.)

After it was found that antiproton beams could be produced at the Bevatron, many experiments were undertaken to determine the interactions of these particles. 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 are emitted per annihilation, a number that some theorists find surprisingly large but that depends on so many complicated considerations that no clean-cut interpretation has yet been possible.

Further experiments have given detailed cross sections for nucleon-antinucleon scattering and annihilation, but I want to postpone discussion of these results until we have considered certain properties of pions, the agents responsible for the main interaction between nucleon and antinucleon.

Yukawa conjectured the existence of the π-meson more than 20 years ago in an attempt to understand nuclear forces by analogy with electromagnetism. The π meson was to play the same role with respect to nucleons that photons play with respect to charged particles; in particular, the force between two nucleons was to come about by the exchange of virtual pions. Yukawa successfully predicted the order of magnitude of the pion mass on this basis as well as many other qualitative properties; but the question I want to consider

now is to what extent the Yukawa theory has been quantitatively verified. If we are in a position of really understanding the force between two nucleons in terms of the exchange of pions, then we must be able to say a good deal about the corresponding nucleon-antinucleon force, since according to quantum field theory, the probability of emission and absorption of pions by antinucleons is exactly the same as for nucleons.

The first question that arises in a quantitative consideration of the Yukawa theory is the value of the pion-nucleon coupling constant, the quantity analogous to the fine-structure constant in electrodynamics. The Yukawa theory has no classical limit, so the definition and measurement of this constant, which I shall call $f^2/\hbar c$, is not a straightforward question. In fact it has only been within the last three years that theorists have agreed on a suitable definition. The now accepted choice, however, can be independently measured by many different methods, and I list some of these now:

a. The most reliable determination of $f^2/\hbar c$ is based on the dispersion relations for pion-nucleon scattering in the forward direction. These relations were formulated in 1955 by Goldberger[4] and later shown to be derivable from quantum field theory on the basis of microscopic causality. Microscopic causality is the property, inherent in quantum field theory, that signals never propagate faster than the velocity of light, no matter how short the distance involved. The dispersion relations for forward pion-nucleon scattering, which can be derived from this principle, are relations between the real and imaginary parts of scattering amplitudes; these relations contain the coupling constant as a parameter but otherwise involve only physically measurable quantities. For example, one uses the total cross sections for π^+ and π^- mesons on protons all the way from zero kinetic energy up to 5 Bev, a range that has now been covered by the collective efforts of laboratories all over the world. The largest contribution to the total cross section problem has come from the Cosmotron at the Brookhaven National Laboratory. Angular distributions are also needed for dispersion relations; these have come largely from the synchrocyclotrons at Chicago and Carnegie Institute of Technology.

There had been some question as to whether the dispersion relations are precisely satisfied by the experimental data, but a review at the High Energy Physics Conference here in Geneva during July 1958 led to the conclusion that no significant discrepancies have been established. On the contrary, the verification of microscopic causality is impressive, and the value of the pion-nucleon coupling constant thus derived is

$$f^2/\hbar c = 0.080 \pm 0.008 .$$

b. The process of photo-pion production,

$$\gamma + p \rightarrow \pi^+ + n ,$$

can be used, together with appropriate dispersion relations, to give a value for $f^2/\hbar c$. The most useful data here has come from the betatron group at the University of Illinois, under the leadership of Professor Bernardini, and leads to

$$f^2/\hbar c = 0.07?$$

As a parenthetical illustration of the current state of photopion physics, Figs. 1 and 2 show angular distributions for photopion production from protons recently obtained at the University of California synchrotron, compared to predictions based on field theory. These theoretical curves are calculated on the basis of the known nucleon magnetic moments and pion-nucleon phase shifts, but contain no free parameters. They are supposed to be accurate to an order $(\omega/Mc^2)^2$, where ω is the photon energy and Mc^2 the nucleon rest energy, about 1 Bev. Thus we expect errors of the order of 10%, which increase as the energy increases, and this is roughly what seems to happen. The coupling constant determination is made at the threshold for photopion production, where the error should be minimized.

c. A third method for measuring f^2 is based directly on Yukawa's original idea that the nuclear force is due to the exchange of pions. It can be shown that single-pion exchange dominates the force at distances larger than the pion Compton wavelength, $\hbar/m_\pi c = 1.4 \times 10^{-13}$ cm. At shorter distances two-pion exchange becomes important, at still closer separations three-pion, and so on. It can be shown that the single-pion-exchange part of the nuclear force is a direct measure of f^2, just as the coulomb force between two particles is a measure of their charge. Thus if one can somehow measure the outer fringe of the nucleon-nucleon force, one has a determination of f^2.

Recently a precise formulation of this notion has been achieved. It has been shown that according to field theory the angular distributions for nucleon-nucleon scattering should be analytic functions of the cosine of the scattering angle, and, if they are sufficiently well determined experimentally, they can be extrapolated to values of cos θ greater than +1, i.e., "beyond" the forward direction. Extrapolation to a certain definite point in this nonphysical region leads to a direct determination of f^2. This point moves closer and closer to cos θ = +1 as the energy increases, so one may say that the forward nucleon-nucleon scattering at very high energy measures f^2. Such a procedure corresponds to a measurement of the outside fringe of the force. Using data from the University of Chicago synchrocyclotron on charge-exchange neutron-proton scattering at 400 Mev, one may in this way find

$$f^2/\hbar c = 0.08 \pm 0.02 .$$

New measurements of this kind are being undertaken at Berkeley to improve the value.

Unfortunately, although we can make precise statements about the nuclear force due to single-pion exchange, we cannot do the same for the multiple-pion contributions. Nevertheless the collective efforts of many theorists have now produced a nucleon-nucleon potential which satisfies experimental requirements up to about 150-Mev energy and which has a semifield theoretical basis.[5] In particular its outer part is the correct Yukawa one-pion potential:

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

where $\vec{\tau}_1$, $\vec{\tau}_2$ are the nucleon isotopic-spin operators, $\vec{\sigma}_1$ and $\vec{\sigma}_2$ the corresponding

Pauli spins, and r the separation distance. Here μ is the reciprocal pion Compton wavelength, $\mu = m_\pi c/\hbar$.

The intermediate-range part of the potential is based on two-pion exchange and is much more complicated and less reliable than the one-pion part. Furthermore a spin-orbit coupling is added without direct theoretical justification in order to fit experiment. This spin-orbit term may well arise in the meson theory from nucleon-recoil effects that so far have been too difficult to calculate. The final important feature of the potential is a short-range hard core, which is almost completely phenomenological.

If one believes that pion exchange is really responsible for this nucleon-nucleon interaction, then field theory makes some rather definite statements about the corresponding nucleon-antinucleon interaction. The parts due to exchange of an odd number of pions should reverse sign, while those due to exchange of an even number should not. In other words one may say, just as for electric charge, that the pionic "charge" of the antiparticle is opposite to that of the particle. Thus one should reverse the sign of the one-pion potential, and if one believes that most of the remainder, outside the hard core, is due to two pions, one should leave that unchanged.

At very short distances, of course, the process of annihilation can occur for the nucleon-antinucleon system but not for the nucleon-nucleon. It is plausible that the radius for annihilation is roughly the nucleon Compton wavelength and so not far from the radius of the hard core in the nucleon-nucleon force. Because a large number of pions are observed to result from annihilation, it seems that once the process is begun it is unlikely to be reversed. For this reason, James Ball and I at Berkeley proposed replacing the hard core in the nucleon-nucleon potential by a "black hole" for the nucleon-antinucleon system.[6] In other words, we assumed that once the two particles reach a critical separation they certainly annihilate. Outside this distance they interact through pion exchange according to the standard prescription.

This model leads to cross sections for scattering and annihilation that at moderate energies are independent of the annihilation radius, provided this radius is small. There are, therefore, no free parameters. The model cannot be used in any case for very high energies because, like all potential models, it does not take proper account of nucleon recoil.

Ball and Fulco have calculated scattering and annihilation cross sections as well as angular distributions predicted by the model and their curves are plotted for comparison with experiment in Figs. 3 through 5.

Figure 3 shows the total, elastic, and exchange proton-antiproton cross sections as a function of energy.

Angular distributions at two different energies for nucleon-antinucleon elastic scattering are shown in Figs. 4 and 5.

Preliminary measurements at 450 Mev suggested a very small scattering cross section, compared to annihilation, and led some theorists to propose a much larger radius of annihilation than in the model discussed here. It now appears, however, that there is nothing abnormal about the scattering, and that

the central black-hole model is satisfactory. A crucial test of this point will come when annihilation cross sections are measured in the multi-Bev range. It is hard to see how the concepts I have discussed today can lead to large annihilation cross sections at really high energies. Our model leads to strong annihilation at low energies by having the pion cloud deflect the antinucleons inward so that they fall into the small black hole at the center. But antiprotons in the Bev range will have too much momentum to be deflected appreciably by the pion cloud. Fringe collisions will lead only to multiple meson production; so the annihilation cross section should shrink to the size of the black hole--that is, it should not be more than about 10 mb.

A good deal of attention has been given to the fact that the nucleon-antinucleon cross sections are several times larger than the nucleon-nucleon. According to the approach described here this circumstance is associated with a kind of Ramsauer effect in nucleon-nucleon scattering which makes both the S- and P-wave phase shifts abnormally small. The effect does not occur in the nucleon-antinucleon system because of the reversal of sign of the one-pion exchange potential and the replacement of the hard core by a black hole.

In this short time I have been able to touch on only a few highlights in strong-interaction high-energy physics. The impression I hope to have given is not that everything is understood, but that quantum field theory has had a certain amount of at least superficial success in this domain. The great question of why pions and nucleons occur in the first place, with their particular masses and particular coupling strength remains totally unanswered.

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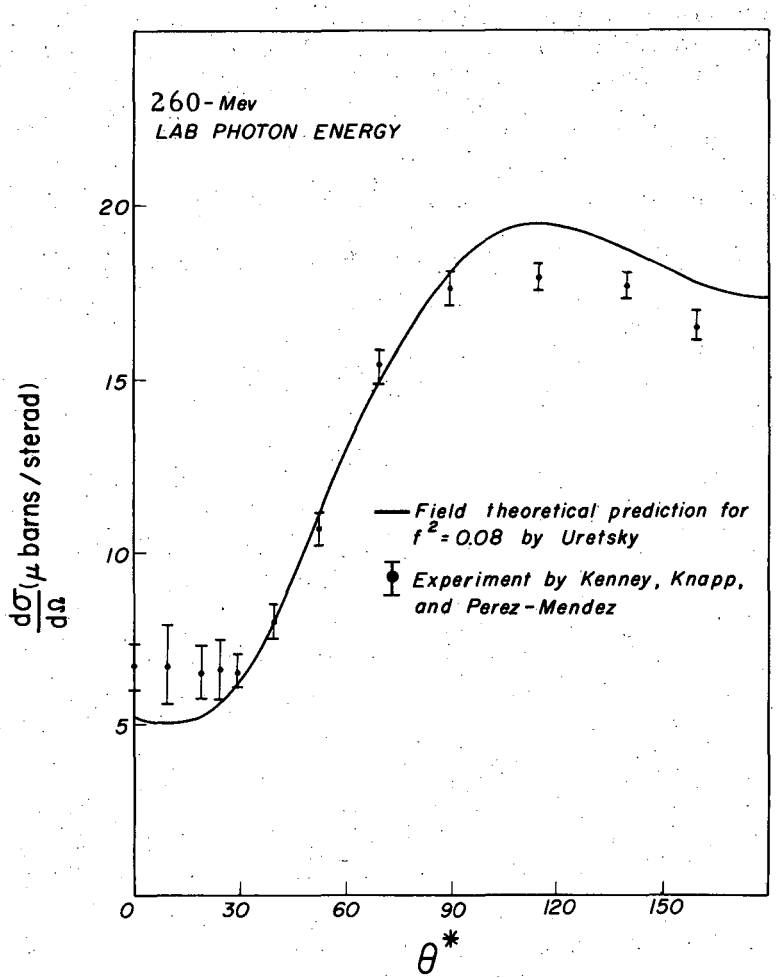


Fig. 1. Angular distribution for 260-Mev pion photoproduction.

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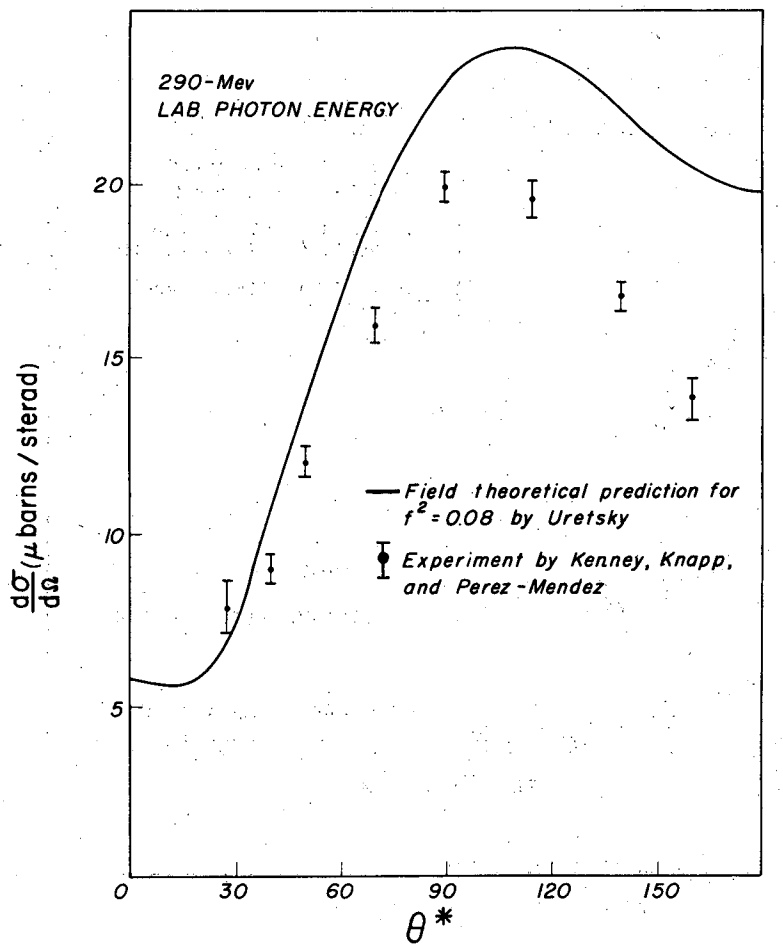


Fig. 2. Angular distribution for 290-Mev pion photoproduction.

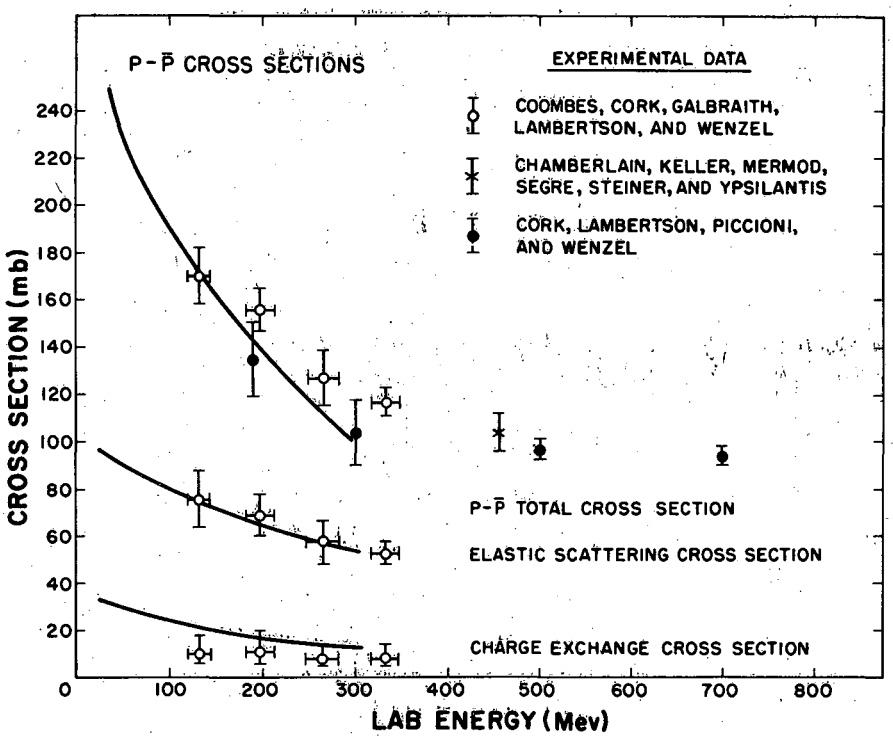


Fig. 3. Antiproton-proton cross sections as a function of energy.

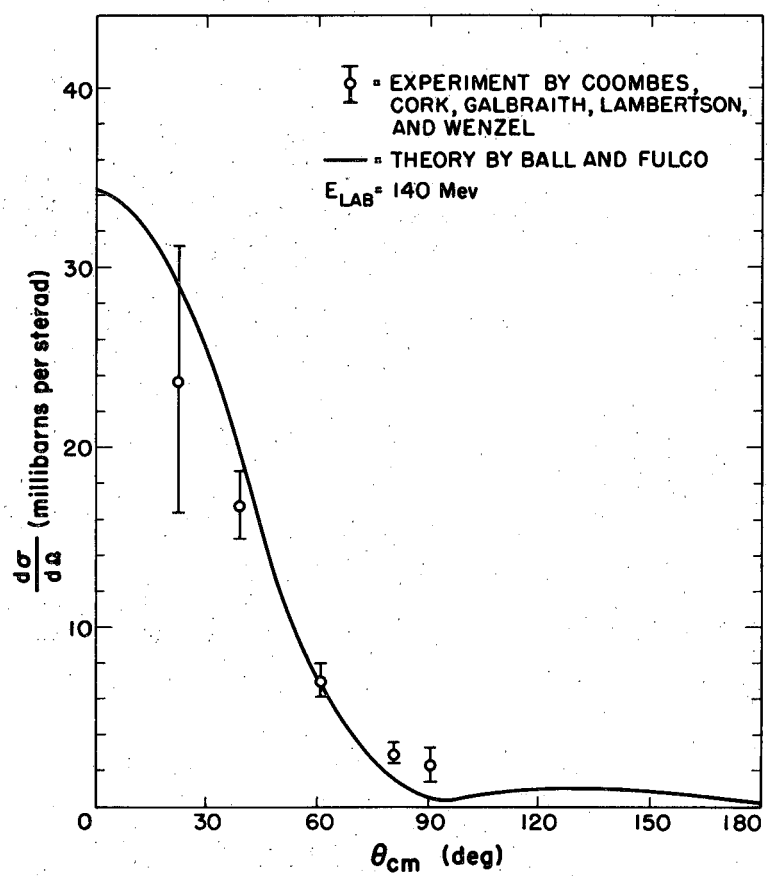


Fig. 4. Antiproton-proton elastic-scattering angular distribution at 133 Mev.

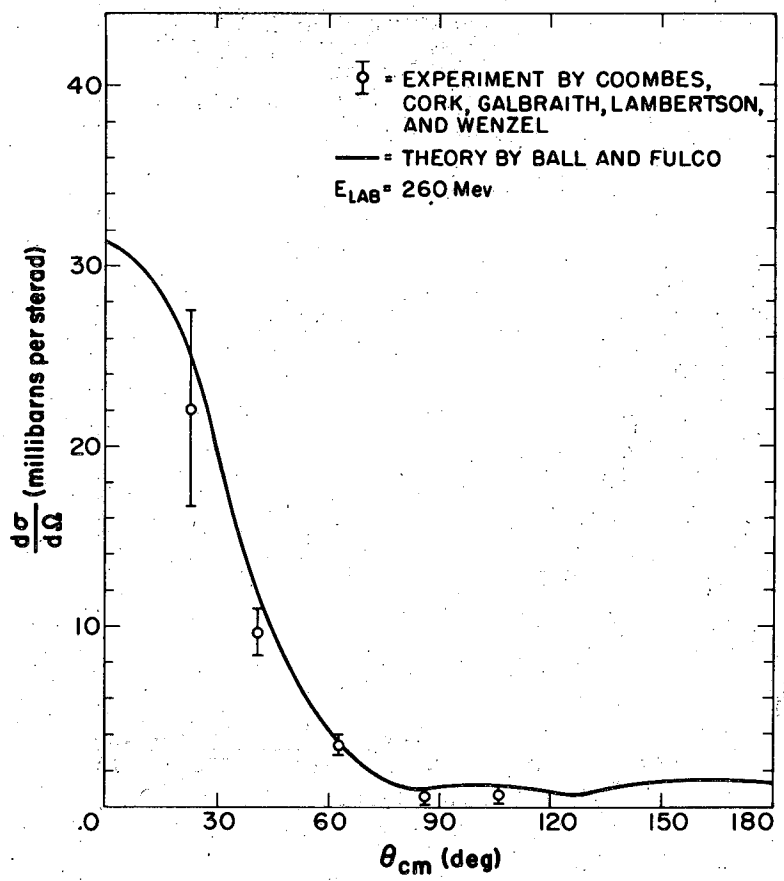


Fig. 5. Antiproton-proton elastic-scattering angular distribution at 265 Mev.