Meson Experiments with Enrico Fermi

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I THOUGHT you might like to hear more about what it was like to work with Enrico Fermi, in another setting. Let me tell you about the time we decided to work together with the pi mesons.

It was just about four years ago. At Chicago, we had just completed a large synchrocyclotron which could accelerate protons to 450 Mev. Fairly intense meson beams, rather well defined in energy, could be obtained from this machine.

There was reason to believe that the pi mesons played a rather fundamental role in the nuclear interaction. Of the four interactions which are known in nature this was the strongest and yet the least understood.

Fermi's idea was that we should do scattering measurements. This was the classical way to study nuclear interactions, since Rutherford's time. Even if the method was not very novel, it had the merit of being simple and direct. From Earl Long, who had constructed a liquid-hydrogen plant, we could have ample quantities of liquid hydrogen. So we could do directly, the most fundamental of scattering experiments, pions on protons.

It was Fermi's style always to add something quite individual and original to every enterprise he entered into. For the cyclotron he volunteered to make a trolley (Fig. 1). This was an exceedingly useful device on which the cyclotron target was mounted. The trolley could be moved about the rim of the magnet pole by remote control and the target could be raised out of, or lowered into the proton beam.

These motions were powered by sending currents through appropriate coils, taking advantage of the torque which the magnetic field of the cyclotron would then exert upon them. The target was connected to a heat reservoir through a calibrated heat leak. Thus, by measuring, with thermocouples, the temperature drop across this, it was possible to record the power delivered by the beam to the target. This served as a useful monitor for our experiments.

Fermi's trolley was not a thing of beauty, but he made the whole thing himself in one weekend and it worked very well for several years. He was proud to point out how much more quickly he had finished it, than if it had been made in the shop.

No one could accuse Fermi of contributing less than twice his share of the sweat and labor that goes into every experiment. For although we were joined at this time by Darragh Nagle and Ronald Martin, two of the hardest working physicists I ever expect to meet, we must still give Fermi the major credit for laying out the meson beams, designing and calibrating the deflection magnet, assembling scintillation counters and even wiring some of the electronic circuits we had to use. He traced the orbits of the pions so relentlessly that before long we felt we knew the number of every one.

TRANSMISSION MEASUREMENTS

The transmission measurement is very simple in principle. The pion beam is made to pass first through two scintillators (Fig. 2) then through the hydrogen target, and finally through two somewhat larger scintillators. The number D of double coincidences of the pulses from the first two scintillators establishes the number of incident particles, the number Q of quadruple coincidences measured simultaneously gives the number transmitted by the hydrogen. Except for a number of small corrections which must be made, the total cross section is obtained from the relation

$$(Q/D)_{\mathrm{H}}/(Q/D)_{\mathrm{NoH}}=\exp(-\sigma N)$$

where N is the difference in the number of hydrogen atoms per cm^2 in the target when filled with the liquid (H) or with the gas (NoH).

We learned a great deal about pions from these experiments.[1] Notice, first of all, (Fig. 3) that at low energies $\sigma \sim E^2$. This is typical of a strong P-wave interaction. The cross section becomes sizeable around one unit of angular momentum. Thus,

$$\mathbf{r}\times\mathbf{p}=(\hbar/\mu c)\cdot p \simeq \hbar.$$

This seemed to fit rather nicely with the idea that the

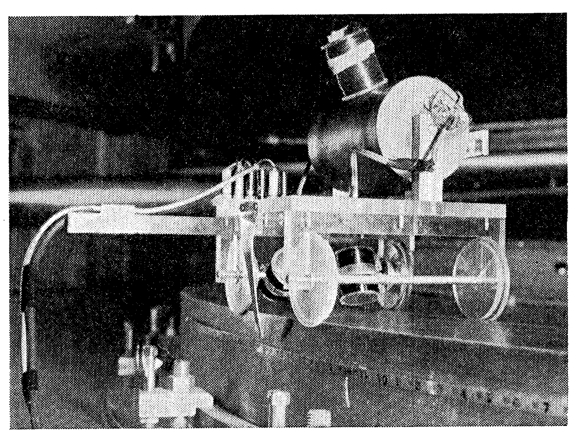

FIG. 1. Trolley for cyclotron built by Professor Fermi.

[1] Anderson, Fermi, Long, Martin, and Nagle, Phys. Rev. **85**, 934 (1952); Anderson, Fermi, Long, and Nagle, Phys. Rev. **85**, 936 (1952).

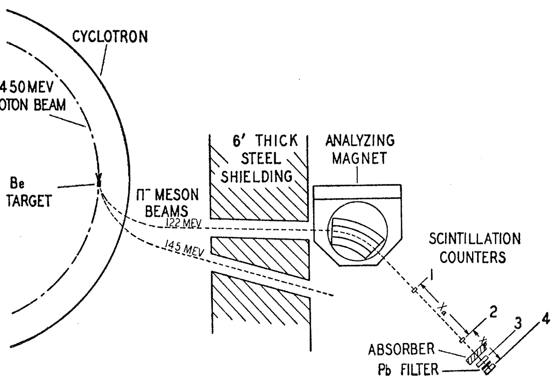

FIG. 2. Schematic diagram of scintillation apparatus.

pion was a pseudoscalar particle. It ruled out many of the possible meson theories and concentrated attention on those in which the coupling was pseudoscalar or pseudovector.

Notice, second of all, that for π^- the cross section levels off around the geometrical value

$$\sigma=\pi(\hbar/\mu c)^2=67\text{mb}.$$

This fits in with the idea that the interaction is strong and of range short and of the order of the pion Compton wavelength. This was a clear sign that pions must play a central role in nuclear behavior. Confirming Yukawa's idea, the process of emission and absorption of pions must be the major contributor to the nuclear forces.

A third feature arises from a comparison of the cross sections for π^+ and π^-. Notice $\sigma(\pi^+)=2$–3 times $\sigma(\pi^-)$. This seemed strange in view of the greater mutiplicity of reactions with π^-. For π^- we have

$\pi^-+P\to\pi^-+P$ elastic scattering,

$\pi^-+P\to\pi^0+N$ charge exchange scattering,

$\pi^-+P\to\gamma+N$ radiative capture,

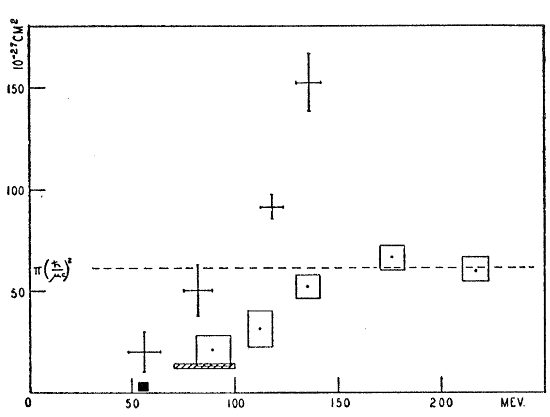

FIG. 3. Scattering cross section for pions on protons. (Squares are for π^-, crosses for π^+.)

while for π^+ only

$\pi^++P\to\pi^++P$ elastic scattering

seems possible.

This anomaly puzzled Fermi very much. I recall the day we were measuring this cross section. Fermi was running the counters. He had a stopwatch in one hand, a slide rule in the other, the desk calculator was clattering away, and his eyes were keeping a close watch on the flashing neon indicators to detect any possible misbehavior. After he recorded each count, he would calcalculate the cross section. He kept shaking his head because it kept coming out so high.

There was so little for me to do that I just sat back and began to go through my mail. On this day there was a preprint of a paper by Keith Brueckner[2] on meson nuclear scattering. "Enrico," I said after glancing at one of the curves, "here's a guy who seems to think the π^+ cross section should be higher than the π^-." Fermi was disparaging in his retort. "How should he know anything about it?".

"But Enrico," I persisted, now taking the trouble to scale off Brueckner's curve, "this fellow Brueckner says we ought to be getting about 120 millibarns for the cross section." "We're getting even more than that" admitted Fermi. "Let me have a look at that paper." Then, "Will you take over for 20 minutes while I go up to my office?"

I suppose he consulted his "Artificial Memory" for he was back in 20 minutes with a broad grin. "The cross sections will be in the ratio 9:2:1 for $\pi^+:\pi^0:\pi^-$ scattering," he announced. This would be the case if the dominant interaction which took place was for the state of isotopic spin $\frac{3}{2}$.

It was necessary to carry out, forthwith, a comparison[3] of the charge exchange cross section with the ordinary scattering for π^-. This confirmed the predictions of a 2:1 ratio in the cross section for these processes.

The importance of charge independence in nuclear processes appeared very evident in these experiments. Fermi was so taken by the simple ratios that he made them the theme song of his Richtmyer Lecture at the following New York Meeting of the American Association of Physics Teachers.

The result spurred a revival of interest in the role of the isotopic spin in the more classical variety of nuclear reactions and provided an important key to the understanding of all nuclear processes.

ANGULAR DISTRIBUTION MEASUREMENTS[4]

The next task was to obtain more detailed information about the scattering process. This could be done by making angular distribution measurements. In this case, one tries to detect the scattered particles. This is in contrast to the transmission measurement which deter-

[2] K. A. Brueckner, Phys. Rev. **86**, 106 (1952).
[3] Fermi, Anderson, Lundby, Nagle, and Yodh, Phys. Rev. **85**, 934 (1952).
[4] Anderson, Fermi, Martin, and Nagle, Phys. Rev. **91**, 115 (1953).

mines the number of particles lost. There is a check since

$$\sigma_T = \int \frac{d\sigma}{d\Omega} d\Omega.$$

At low energies we could expect s- as well as p-waves to be important so that neglecting d-waves, the angular distribution would be of the form

$$\frac{d\sigma}{d\Omega} = a + b\cos\theta + c\cos^2\theta.$$

Measurements at three angles for each of the processes $\pi^+ \to \pi^+$, $\pi^- \to \pi^0$, $\pi^- \to \pi^-$, would be sufficient to determine the a, b, c's for each, uniquely. The process $\pi^- \to \gamma$ is weak and could be estimated by detailed balance from its inverse, the photomeson production process.

Taking spin zero for the pion, this led to three angular momentum states, $s_{\frac{1}{2}}$, $p_{\frac{3}{2}}$, and $p_{\frac{1}{2}}$. These could exist in either of two isotopic spin states $T=\frac{1}{2}$ and $T=\frac{3}{2}$; six different states in all. Thus, six phase shifts should be sufficient to describe the scattering as in Table I.

Nine experimental data were available to determine six parameters, a situation which allowed some opportunity to check the assumptions.

TABLE I. Phase shifts for the pion-proton scattering.

	$s_{\frac{1}{2}}$	$p_{\frac{3}{2}}$	$p_{\frac{1}{2}}$
$T=\frac{3}{2}$	α_3	α_{33}	α_{31}
$T=\frac{1}{2}$	α_1	α_{13}	α_{11}

PHASE-SHIFT ANALYSIS

The problem of finding the phase shifts for the pion-proton scattering began to occupy the center of the stage. A least-squares type of fit was called for to make maximum use of the data. Since the relation between the phase shifts and the cross sections is not a simple one, this looked like an ideal problem for the electronic computer.

Fermi liked to spend his summers at Los Alamos. In the summer of 1952 Nick Metropolis had his wonderful computer, the MANIAC, in operation. Nothing could have worked out better. The MANIAC fascinated Fermi and he had been itching to get his hands on it. Now he had a problem to put to the machine. Metropolis would teach him how, and he could feed in his questions, watch the machine digest them, and gather the answers as they rolled out.

The machine found the phase shifts all right. The trouble was it found too many.[5] It found several sets of phase shifts which fit the experimental data equally well. The puzzle then was, which solution was the correct one?

I'm sorry that Fermi didn't wait around to see in what an interesting way this puzzle has come to be resolved. The key turned out to be the Principle of Causality.

CAUSALITY

The statement of the Principle is simple enough. It depends on the fact that signals cannot propagate faster than the speed of light. Because of this, the causality condition is that the scattered wave should remain zero until the incident wave reaches the scatterer.

A well-known consequence of this condition is the Kramers-Kronig[6,7] dispersion formula which gives a relation between the real and imaginary parts of the forward scattering amplitude for the scattering of light by atoms.

Recently, Goldberger has been able to extend the application of such a causality condition so as to apply to particles with mass. Goldberger's derivation uses the formalism of quantum-field theory. The demand that waves do not propagate faster than the velocity of light is expressed by requiring that measurements of two observable quantitities made at space-like points should not interfere. Thus, the causality condition is imposed by setting the commutator of two Heisenberg operators for the pion field equal to zero when they are taken at space-like points.[8]

The dispersion relation which is obtained thereby[9] enabled us to calculate the real part of the forward scattering amplitude from a knowledge of the total

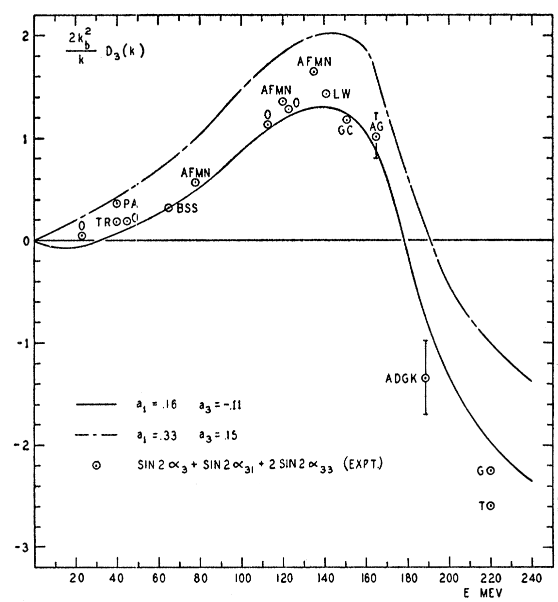

FIG. 4. $2k_b^2/kD_3$ plotted as a function of pion energy.

[5] Fermi, Metropolis, and Alei, Phys. Rev. **95**, 1581 (1954).

[6] H. A. Kramers, Atti congr intern. fisici. como. **2**, 545 (1927).

[7] R. Kronig, J. Opt. Soc. Am. **12**, 547 (1926).

[8] M. L. Goldberger, Phys. Rev. (to be published).

[9] Goldberger, Miyazawa, and Oehme, Phys. Rev. (to be published). See also Karplus and Ruderman, Fifth Annual Rochester Conference (1955).

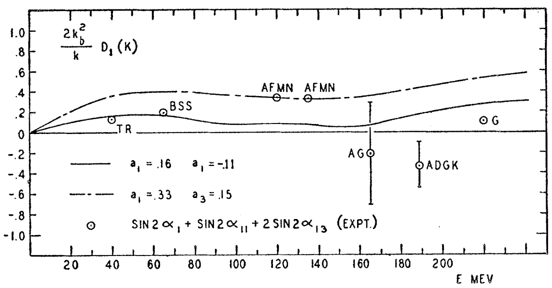

FIG. 5. $2k_b^2/kD_1$ plotted as a function of pion energy.

scattering cross sections for negative as well as positive pions by protons. These data now extend up to 1.9 Bev.[10,11]

It is a striking result of this calcualtion[12] that for the isotopic spin $\frac{3}{2}$ state the real part of the forward scattering amplitude changes sign abruptly at about 180 Mev. In Fig. 4 we have plotted

$$\frac{2k_b^2}{k}D_3 = \sin 2\alpha_3 + 2\sin 2\alpha_{33} + \sin 2\alpha_{31} + \cdots$$

as a function of pion energy (in the laboratory system). Here k_b and k are the wave numbers of the pions in the center of mass and laboratory systems, respectively.

The dispersion relations give the real part of the forward scattering amplitude (in the laboratory system) for the isotopic spin $\frac{3}{2}$ state D_3 positive and in good agreement with experimentally determined phase shifts below 180 Mev. Above 180 Mev, D_3 becomes abruptly negative in agreement with the solution recently found at 189 Mev[13] in which $\alpha_{33}=98.5°$, $\alpha_3=-11.3°$ and $\alpha_{31}=-11.6°$. Alternative solutions with $\alpha_{33}=81.5°$, $\alpha_3=+11.3°$, and $\alpha_{31}=+11.6°$ or one with $\alpha_3=-44.5°$ give the wrong sign for D_3. A fourth solution at 189 Mev which is of the Yang type has $\alpha_3=-11.6$, $\alpha_{33}=126°$, and $\alpha_{31}=236°$. This is in agreement with causality but must be compared with the analogous solution at 165 Mev[14] in which $\alpha_3=-20°$, $\alpha_{33}=34°$, and $\alpha_{31}=94°$. This seems unlikely in view of the large jump in phase shift which is called for. For the $T=\frac{1}{2}$ state the experiments give D_1, close to zero, (Fig. 5) and so do the dispersion relations provided proper account is taken of the bound state which is the neutron.

This choice of phase shifts coincides with that taken by de Hoffmann, Metropolis, Alei, and Bethe[15] on less convincing evidence.

Fermi had recognized that a good way to decide the choice of sign of the forward scattering amplitude was to study the Coulomb interference with it. In this way, one of Fermi's students Jay Orear, established the positive sign of by such a study at 113 Mev.[16] Just the other day, another of his students, Horace Taft,[17] was able to demonstrate the change in sign of D_3 by detecting an augmentation of the small angle scattering at 216 Mev due to Coulomb interference.

Looking back now at all the wonderful experiences we had in this adventure with the pi mesons, with their pseudoscalar nature, their strong coupling, their short range interaction, their charge independence, and their causal behavior, I wish there were a better way to say "Thanks Enrico, for taking me along!"

[10] Ashkin, Blaser, Feiner, Gorman, and Stein, Phys. Rev. **96**, 1104 (1954).
[11] S. J. Lindenbaum and L. C. Yuan, Fifth Annual Rochester Conference (1955); Cool, Clark, and Piccioni, Fifth Annual Rochester Conference (1955).
[12] Anderson, Davidon and Kruse, Phys. Rev. (to be published).
[13] Anderson, Davidon, Glicksman, and Kruse, Phys. Rev. (to be published).
[14] H. L. Anderson and M. Glicksman, Phys. Rev. (to be published).
[15] De Hoffmann, Metropolis, Alei, and Bethe, Phys. Rev. **95**, 1586 (1954).
[16] J. Orear, Phys. Rev. **96**, 1417 (1954).
[17] H. Taft (to be published).

Dr. Bethe:

Thank you Dr. Anderson.

You have heard the story of thirty years of physics and of thirty years of research of Fermi on physics. You have heard the story of Fermi's influence on physicists, how, by his example and by his knowledge, he inspired his collaborators and many generations of students. The main quality in Fermi was his simplicity, the simplicity of his person and the simplicity of his approach to the problems of physics. It was his ability to take a complicated problem, to take it apart, resolve it, and then having taken it apart, find the solution to the parts and find it elegantly. Many times, many of us had problems that we were too stupid to solve and we came to Fermi for advice. He was always ready to give it. We would tell him our problems, and, having listened attentively and carefully for a few minutes, he would relate our problem in a completely different form. Either he gave us the solution, or more often he had made the problem so clear that it was then possible for us to solve it, and at the same time have the fun of doing it ourselves. There is no other physicist like Fermi. His life was a full one. His work will live on and so will his spirit, but we shall always miss Enrico Fermi.

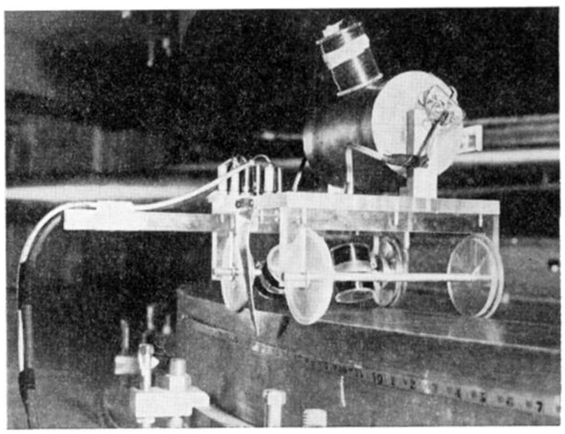

FIG. 1. Trolley for cyclotron built by Professor Fermi.