An example is a Mössbauer transition in which one measures the rate of absorption by a detector moving at a velocity $\vec{v}$ relative to the emitter. The absorber and emitter are in magnetic fields $\vec{H}_1$ and $\vec{H}_2$, respectively; $\vec{H}_1$, $\vec{H}_2$, and $\vec{v}$ are not coplanar. The equality of the above rate with that situation in which $\vec{H}_1 \leftrightarrow -\vec{H}_2$, $\vec{v} \rightarrow -\vec{v}$ is assured by *PT* invariance. For this to be a true test, the environments of the emitting and absorbing nuclei should be identical.

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STRUCTURE IN π^-p ELASTIC SCATTERING AT 180°*

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We have measured the differential cross section for π^-p elastic scattering at 180°. We studied this fixed-angle cross section, in steps of 100 MeV/*c* or less, in the region from 1.6 to 5.3 GeV/*c*. The cross section shows considerable structure which gives information about the properties of various N^* resonances.

The experiment was done at the Argonne zero-gradient synchrotron. The 12.5-GeV/*c* internal beam of 5×10^{11} protons/2.25 sec was made to impinge upon a 3.85-in. copper target during 150 msec. This target was placed from 3 to 5 feet back into the field of the ZGS ring magnet. The π^- mesons of the appropriate momentum, which were produced at 0°, were bent through 17° by this magnetic field and made to go down the 17° beam.

The beam is shown in Fig. 1. It consists of three quadrupole doublets acting as lenses and two bending magnets for momentum analysis. There is an intermediate focus at the 1-in.× 1-in. beam collimator and a second focus at the H_2 target. The beam had a momentum bite of $\Delta p/p = \pm\frac{3}{4}\%$ and subtended a solid angle of 1×10^{-4} sr. This gave the beam particles an angular divergence of less than 3 mrad at the target. The beam intensity was 3.5×10^5 π^- mesons/5×10^{11} protons in the region 2.0-4.0 GeV/*c*. At higher and lower momenta the intensity dropped off.

We counted the beam with 1-in. diameter, $\frac{1}{8}$-in. thick scintillation counters, B_1, B_2, B_3, in coincidence with a gas threshold Cherenkov counter containing 100 psi of ethane. The Cherenkov counter discriminated against K^- mesons and antiprotons which comprised only a few percent of the beam. We tuned

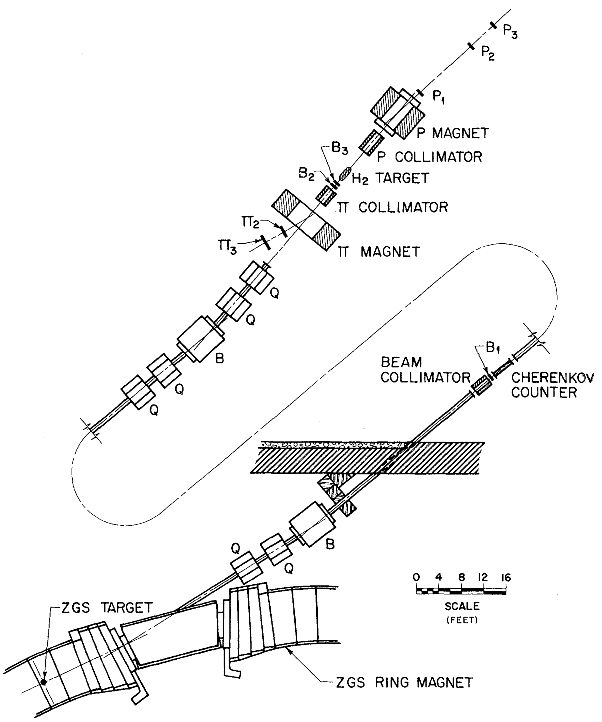

FIG. 1. Experimental layout. The ZGS ring, the 17° beam, and our double spectrometer are shown.

the beam by maximizing the ratio of B_1, B_2, B_3, $\check{C}$ coincidences to the internal beam intensity. The second bending magnet in the beam was calibrated using nuclear magnetic resonance. The momentum was known to ±30 MeV.

The liquid H_2 target was 12 in. long by $1\frac{1}{2}$ in. in diameter. However, the interaction region was defined by the 1-in. diameter beam counters (B_2, B_3).

Our detection system for the scattered particles was a double spectrometer in coincidence. The backward-going π^- always had momentum around 400 MeV/c, and the forward-going proton had momentum about 400 MeV/c greater than the π^- beam. These particles were made to pass through the π and p collimators which were considerably oversized. The π^- then passed through a 30-in., large-gap (84-in. × 14-in.) bending magnet, which deflected the π^- by about 15°. The positively charged proton went through a standard 72-in. bending magnet which deflected it by some 8°, and cleanly separated it from the π^- beam.

The π^- and proton were detected by telescopes of scintillators which were optically connected to RCA 7746 photomultiplier tubes. The signals from these counters were fed into a Chronetics coincidence logic system. The number of coincidences between the two π counters, the three p counters, and the four beam counters ($\pi pB\check{C}$) was double scaled on TSI 100-Mc/sec scalers. The number of beam particles ($B\check{C}$) was also double scaled. The cross section is proportional to the ratio $(\pi pB\check{C})/(B\check{C})$. The counters were timed in on πp coincidences at 1.6 GeV/c where the counting rate was high. The delays were then calculated for other energies.

One of the interesting features of the experiment was that the only physical change in going from one incident momentum to the next was to move the π counters by about an inch. The current in the π magnet was increased so that the higher momentum incident beam still passed through the H_2 target. The current in the p magnet was increased so that the higher momentum protons still passed through the p counters. Not having to move the H_2 target, the magnets, and the p counters removed possible systematic errors due to misalignment.

The solid angle subtended in the center of mass was defined by the (16-in. × 16-in.) π_3 counter at a distance of 200 in. from the H_2 target. The p_3 counter (~9 in. × 9 in.) was 500 in. from the H_2 target and was overmatched to subtend a somewhat larger solid angle in the center of mass. The overmatching was calculated to allow for such things as the angular divergence and momentum spread of the beam, multiple scattering of the scattered particles, a 1% variation in the magnetic fields of the π and p magnets, and the H_2 target size. Because of this overmatching, no correction to the data was necessary for these effects.

The solid angle in the center-of-mass system, defined by the π counter, varied from 1.5 to 0.5 msr as we increased the energy. The momentum bite of the π telescope was about $\Delta p/p = \pm 30\%$, while for the p telescope $\Delta p/p$ was about ±10%. At 1.6 GeV/c a test was run which consisted of a p-magnet curve. When we detuned by 10% or more the πp coincidence rate went away. This may be regarded as evidence that we were indeed seeing elastic scattering.

We had two methods for studying possible background due to accidental coincidences.

The first method involved using two independent πp coincidence circuits; one (πp fast) had a resolving time of 5 nsec and the other (πp slow) had a resolving time of 30 nsec. Both circuits gave essentially the same number of coincidences. This indicated that none of the coincidences were accidental. This was not surprising since the single telescope rates were very low; π was typically 50 counts/pulse and p was about 1 count/pulse.

The alternative method was to feed the signals from the π_3 and p_2 counters directly into a time-to-amplitude converter (TAC). This gave out a pulse whose amplitude in volts was proportional to the overlap time of the π_3 and p_2 pulses. This output was fed into a TMC 400-channel pulse-height analyzer (PHA), which gave us a plot of number of events against the π-p time-of-flight difference. The peak was was typically about 3 nsec wide due to the 12-in. length of the H_2 target. Any significant accidental background would have shown itself as a broad region under the peak. This could be subtracted from the peak.

We wanted to show that there was no contamination due to inelastic events of the type

$$\pi^- + p \to \pi^- + p + \pi^0. \tag{1}$$

This was done by taking data runs with a carbon target in place of the H_2 target. Suppose our constraints on angle and momentum were sufficiently lax that with the H_2 target we were observing $\pi^- p$ events that were in fact smeared by π^0 production. Then the additional smearing of angle and momentum introduced by the Fermi momentum of the protons in the carbon nucleus would not remove the counting rate. But if our kinematic constraints were sufficiently tight that the smear of the Fermi momentum removed most of our event rate, then we have evidence that π^0 production smears things too much to be detected much by our double spectrometer. This is true because the π^0 production introduces a greater smear than the Fermi momentum for any reasonable distribution of π^0 mesons. We took several runs with a carbon target and obtained one event. In equivalent runs with a H_2 target we obtained over a hundred events. This is conclusive evidence for a 2% upper limit on inelastic contamination. It also showed that we had no accidental events. The carbon runs simultaneously served as empty-target runs.

The differential cross section was calculated from the formula

$$\frac{d\sigma}{d\Omega} = \frac{(\pi p B\check{C})/(B\check{C})}{N_0 \rho t\, \Delta\Omega / A}. \tag{2}$$

The quantity N_0 is Avogadro's number, 6.023×10^{23}, while ρ is the density of liquid hydrogen which is taken to be 0.071. The quantity t is the length of the H_2 target which was 30.5 cm, while A is the atomic weight of hydrogen, taken to be 1.01. The quantity $(\pi p B\check{C})/(B\check{C})$ is the ratio of events to beam particles.

The following corrections to the above calculation were made. A correction of (1.25 ± 2.5)% was made for the absorption of the π meson and the proton by the H_2 target, the air, and the scintillators. A correction of (9 ± 5)% was necessary to allow for the decay of the 400-MeV/c π mesons into μ mesons which miss the π_3 counter. There is also a (6 ± 2)% correction for μ^- and e^- contamination in the π^- beam. This was determined experimentally. A (2 ± 1)% subtraction was made for counting losses in the beam counters. A 2% subtraction was necessary because our system detected interactions which occurred in the hydrogen in the polystyrene of the B_2 and B_3 scintillators. We also made a (1 ± 1)% correction for possible inelastic contamination. Combining all the errors and corrections, we get a net correction to the raw data of 1.25 with a maximum error of ±12%.

The above systematic error appears primarily as a normalization uncertainty. We used essentially the same layout in measuring the cross section at adjacent energies. Changing from one energy to the next consisted of moving the π_2 and π_3 counters only a few inches and increasing all the magnet currents. In view of this there should be no relative systematic errors. Thus in Fig. 2 we plot only statistical errors. However, in addition to the 12% normalization uncertainty, there may be an energy-dependent uncertainty of 3% in going from 1.6 to 5.3 GeV/c. The statistical errors are mostly 10 to 15%. The uncertainty in the momentum is ±30 MeV. The angle subtended by our counters goes from 179° to 180° in the center-of-mass system.

The 180° differential cross section is plotted in Fig. 2 as a function of π beam momentum. The statistical errors are shown. The line is a freehand fit to the data. The positions of the known[1] N^* resonances are shown. Given below

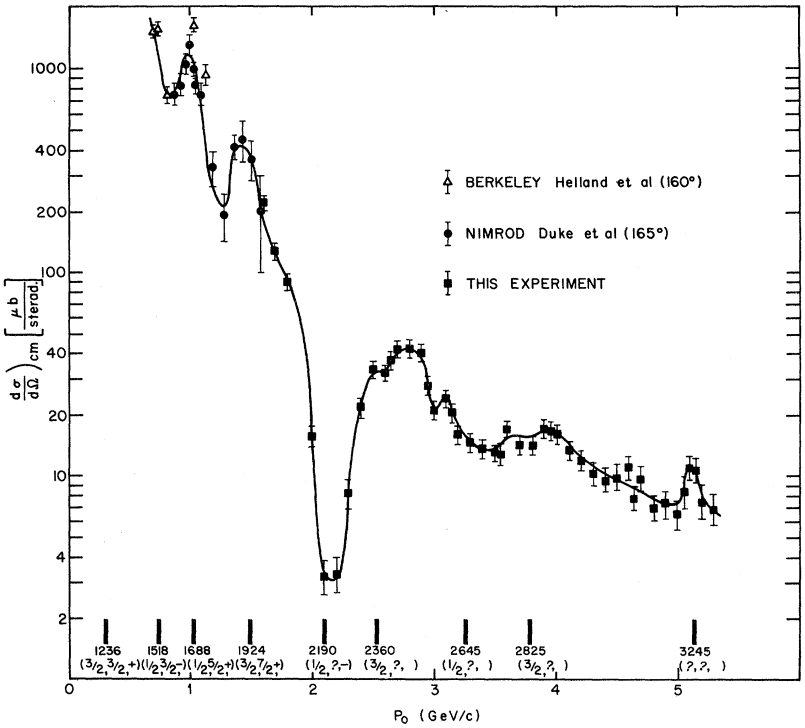

FIG. 2. Plot of $d\sigma/d\Omega$ against P_0, the incident π laboratory momentum, for π^-p elastic scattering at 180°. The positions and properties of the N^* resonances are shown. The line drawn is a freehand fit to the data. The error bars shown are statistical. There is also a 12% normalization uncertainty.

them are the N^* masses and (T, J, P). The data are also tabulated in Table I. Other groups[2-8] have measured π^-p cross sections at angles between 160° and 180° in the center-of-mass system.

The fixed-angle cross section shows considerable structure.[9] We believe that this structure is associated with the various N^* resonances. This method of probing resonances appears to be more sensitive than Kycia's method[10] of looking for bumps in the total cross section.

In elastic scattering each resonance shows up as an intermediate state in the process

$$\pi^- + p \rightarrow N^* \rightarrow \pi^- + p. \tag{3}$$

The amplitude for this type of elastic process may interfere constructively or destructively with the nonresonant elastic amplitude, or it may not interfere at all. The dramatic destructive interference at $P_0 = 2.15$ GeV/c is especially interesting. The cross section drops almost two orders of magnitude in this region. This is clearly associated with the $N^*(2190)$.

We are able to determine the parity of various resonances by using the idea first suggested by Ross and Heinz.[11,12] The point is to see whether the resonant amplitude interferes constructively or destructively with the nonresonant amplitude. It is assumed that the nonresonant amplitude does not rapidly change sign as a function of energy. Then we can determine the sign of the nonresonant amplitude by observing that the $N^*(1688)$ and the $N^*(1924)$ both interfere constructively with it. They are known[1] to have positive (+) parity. This indicates that the $N^*(2190)$ has negative (−) parity because it interferes destructively.

One of the more interesting features of the experiment is the large narrow peak in the cross section at $P_0 = 5.12$ GeV/c. We believe that this is firm evidence for the existence of a nucleon resonance with mass 3245 ± 10 MeV. This $N^*(3245)$ has a full width at half-maximum of $\Gamma < 35$ MeV and rises about 4 μb/sr above the nonresonant cross section. It seems remarkable that such a massive particle should be so stable. The width of the particle is less than 1% of its mass.

We are especially grateful to Professor M. H. Ross for his many suggestions in the early stages of the experiment. We would also like to thank Professor C. T. Coffin, Professor

Table I. Cross sections for $\pi^- p$ elastic scattering at 180°.

P_0[a] (GeV/c)	S (GeV)^2	$d\sigma/d\Omega$ (μb/sr)	$d\sigma/dt$ [μb/(GeV/c)^2]	Error[b] (%)
1.60	3.91	220	1200	7
1.70	4.10	127	643	10
1.80	4.29	89.8	424	10
2.00	4.66	15.5	64.5	12
2.10	4.85	3.15	12.4	23
2.20	5.04	3.29	12.2	23
2.30	5.22	8.04	28.3	18
2.40	5.41	21.6	72.4	11
2.50	5.60	33.3	106	9
2.60	5.79	31.9	97.4	9
2.65	5.89	36.9	110	11
2.70	5.98	41.3	121	10
2.80	6.16	42.1	118	11
2.90	6.35	40.1	108	11
2.95	6.45	27.5	72.7	12
3.00	6.54	20.8	53.9	11
3.10	6.73	23.7	59.2	10
3.15	6.82	20.1	49.3	12
3.20	6.91	15.9	38.3	11
3.30	7.10	14.5	33.7	12
3.40	7.29	13.5	30.4	12
3.50	7.48	13.0	28.3	9
3.55	7.57	12.6	27.0	15
3.60	7.66	16.9	35.6	10
3.70	7.85	14.2	29.1	11
3.80	8.04	14.0	27.8	12
3.90	8.23	16.9	32.6	12
3.95	8.32	16.6	31.6	12
4.00	8.41	16.0	30.0	12
4.10	8.60	13.2	24.1	12
4.20	8.79	11.9	21.1	13
4.30	8.98	10.1	17.5	14
4.40	9.16	9.44	15.9	15
4.50	9.35	9.60	15.8	16
4.60	9.54	10.7	17.2	15
4.65	9.63	7.58	12.0	12
4.70	9.73	9.50	14.9	15
4.80	9.91	6.77	10.4	15
4.90	10.10	7.07	10.6	17
5.00	10.29	6.38	9.37	18
5.05	10.39	8.21	11.9	19
5.10	10.48	10.7	15.4	15
5.15	10.57	10.4	14.8	17
5.20	10.66	7.25	10.2	22
5.30	10.85	6.73	9.28	20

[a] The laboratory momentum P_0 is known to ±0.03 GeV/c.

[b] The errors quoted are statistical. There is also a maximum normalization error of ±12%.

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