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Destructive interference of s and p waves in 180° $\pi^- p$ elastic scattering

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Abstract

The differential cross section for π^-p elastic scattering shows a pronounced dip at 180° and incident pion laboratory energies around 57 MeV. This is due to the cancellation of the real parts of the s- and p-wave hadronic scattering amplitudes. The first observation of this dip is reported and the potential of exploiting the destructive interference phenomenon is discussed.

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1 Motivation

A challenging problem in strong-interaction physics is the determination of the (current) quark masses and the coupling constant, which are free parameters in the QCD Lagrangian. The main experimental input used to determine the light quark masses m_u, m_d and m_s are the pseudoscalar meson masses [1]. An alternative new approach to the problem of the up and down quark masses is the comparison of the low energy pion-nucleon (π-N) scattering amplitudes determined from experiments with theoretical predictions from heavy baryon chiral perturbation theory [2, 3, 4]. High precision experimental data (and a good understanding of the electromagnetic corrections) are needed to measure effects of the strong π-N interaction proportional to the symmetry breaking parameters (m_u+m_d) for chiral and (m_u−m_d) for isospin symmetry. At threshold, precise data from pionic hydrogen and deuterium [5, 6] are now available.

In the following, we present a new experiment which also has high precision capability, namely the measurement of the differential cross section of π^-p elastic scattering at angles close to 180° for pion laboratory energies around 57 MeV [7]. Here, the cross section, as a function of energy, exhibits a very narrow dip with a vanishingly small (<1 μb/sr)[1] minimum value. This is due to a cancellation of the real parts of the hadronic s- and p-wave scattering amplitudes at this particular energy. From the energy corresponding to the minimum and the shape of the dip precise information on the energy at which the cancellation occurs and the slope difference of the s- and p-wave amplitudes can be obtained. Moreover, the fact of a nearly vanishing cross section is a unique feature in the search for exotic interactions or the investigation of corrections to the main part of the interaction (e.g. effects of isospin breaking).

2 Destructive interference in π-N-scattering

In the energy region considered here, we can safely concentrate on the s- and p-wave components, neglecting the small higher partial waves. The most general centre of mass (c.m.) hadronic scattering amplitude, respecting rotational symmetry, parity conservation and isospin invariance, can then be derived from

$$\begin{aligned} f_{\pi N} &= \left[b_0(\varepsilon) + b_1(\varepsilon)\vec{\tau}\cdot\vec{t}\right] + \left[c_0(\varepsilon) + c_1(\varepsilon)\vec{\tau}\cdot\vec{t}\right]\vec{k_f}\cdot\vec{k_i} \\ &+ \left[d_0(\varepsilon) + d_1(\varepsilon)\vec{\tau}\cdot\vec{t}\right] i\vec{\sigma}\cdot(\vec{k_f}\times\vec{k_i}) \ , \end{aligned} \quad (1)$$

[1]Calculated within the framework of a new analysis of π-N data [8].

where ε is the c.m. pion kinetic energy, $\vec{k_i}$ and $\vec{k_f}$ are the c.m. momenta of the incident and outgoing pion, $\vec{t}$ denotes the pion isospin operator and $\frac{1}{2}\vec{\tau}$ and $\frac{1}{2}\vec{\sigma}$ are the nucleon isospin and spin operators respectively. The coefficients $b_0(\varepsilon), \ldots, d_1(\varepsilon)$ are complex functions of ε but their *imaginary parts are small* in the energy region of interest.

For backward (scattering angle $\theta = \pi$) or forward scattering ($\theta = 0$), the third (spin-flip) term in eq. 1 vanishes. Very close to threshold, the s-wave part (first term in eq. 1) dominates over the spin non-flip p-wave part (second term in eq. 1). As ε increases, the real p-wave part rises monotonously – due to the $\vec{k_f} \cdot \vec{k_i}$ term – faster than the s-wave part. At a certain energy both amplitudes are of the same magnitude and their relative sign is determined by the scattering angle. Therefore, there exists a "magic" energy $\varepsilon = \varepsilon_0$ for which the real parts of the hadronic s- and p-wave amplitudes cancel for scattering angles $\theta = 0$ or π. Provided that all other contributions to the amplitudes (e.g. imaginary and electromagnetic) are small at these energies, one expects a characteristic dip in the cross section, due to the destructive interference of the hadronic s- and p-wave amplitudes [7].

The above consideration holds for any of the low-energy π-N reactions: $\pi^{\pm}p$ elastic scattering and single-charge exchange (SCX) [7, 9]. The interference dip in the SCX reaction has been observed previously in the forward region by an experiment performed at LAMPF [10]. In the case of π^+p scattering under zero degree, the interference effect is masked by the Coulomb interaction. In elastic π^-p backward scattering, the imaginary part of the hadronic s- and p-wave amplitudes has also a zero crossing close ($\approx$5 MeV) to the zero crossing of the real parts. Therefore, the minimum is very deep and narrow and thus, makes the measurement of the cross section an ideal tool to study the π-N interaction.

3 Experiment

In the following we are going to present the results of a first run that demonstrates the interference phenomenon in π^-p elastic scattering. The data was collected during a period of one week.

The layout of the experimental set-up is shown in figure 1. The experiment was performed in the πE1-area of the Paul Scherrer Institute (PSI). The initial high electron contamination of the beam was reduced to a pion-to-electron ratio of $\approx$3:1 by ranging out the electrons with a 6 mm thick graphite plate upstream in the beam line. After passing a bending magnet, the electrons were dumped into a lead collimator located at an intermediate focus. Immediately downstream of the collimator, which had an opening of

2 cm, was a 1 mm thick beam counter S1. By means of a quadrupole triplet the beam spot at the collimator was imaged onto the active scattering target, T. The latter consisted of an organic scintillator NE102A with an area of 2×2 cm^2 and was 2.79 mm thick. A triple coincidence between the signals of the beam counter S1, the target counter T and the radio frequency of the machine (50 MHz) defined an incoming pion (π_{clean}). The pion laboratory energies at the target centre were 43.6, 50.3, 57.3, 64.5 and 72.0 MeV respectively and were determined to ±1.7% by time-of-flight measurements. The size of the beam spot at the target was measured to 1.2 cm (vertical) and 1.8 cm (horizontal) FWHM; the corresponding beam divergences were determined to 50 mrad and 20 mrad FWHM. The π_{clean} rate varied between 0.2 and 1.6 MHz at a total momentum bite of 1% in the above energy range.

The AEE magnet, which was used to separate the scattered particles from the incoming beam, was a modified beam line magnet [11]. It has circular shaped tapered poles at the entrance side for a field-strength-independent effective field boundary. Detailed field maps have been taken.

Back-scattered pions were detected in the c.m. angle interval of about 170° - 180° by a 5 mm thick organic scintillator counter (S_π: 15.8 × 15.8 cm^2). The flight path for scattered pions was ≈1.1 m. The proton counter S_p consisted of a 1 cm thick and 20 × 20 cm^2 organic scintillator counter. It was placed ≈0.9 m downstream of the target.

Requiring for a good event a triple coincidence between an incoming π_{clean} and a hit in S_π and S_p for the scattered pion and the recoil proton, together with the pulse height information and the time of flight from the scattering target to the detectors, resulted in a clean sample of pions scattered elastically off the proton. From dedicated measurements with carbon foils added to the target scintillator, we conclude that the contribution to the event sample from pions scattered off the carbon in the scintillator is negligible.

The effective solid angle acceptance was obtained by a detailed Monte Carlo simulation based on the GEANT [12] code. The calculations included the definition of the geometry of the whole apparatus, field maps of the bending magnet, the measured initial distribution of the pion beam on the target and decay of scattered pions in flight. The resulting c.m. solid angle varies between 13 and 15 msr. The systematic uncertainties related to absolute normalization were estimated as follows: A 10% error was assumed for both, the integrated pion flux N_π and the total acceptance, independent of the beam momentum. For the determination of the number of protons in the target, the literature value of the scintillator material (NE102A) [13] was used and an uncertainty of 5% was assumed. Adding all three contributions in quadrature yields an overall systematic error of 15%.

The differential cross sections measured at the five energies (c.f. table 1) are shown in fig. 2. They are compared with three predictions from analyses of π-N data for a c.m. angle of 175° where the total acceptance of the experimental set-up was biggest. Those predictions are the most recent analysis by Arndt et al. [14] and the Karlsruhe solution (KA85) [15] which is based on measurements done mostly prior to 1980 (in both analyses no uncertainties are given by the authors); the shaded band has been obtained from all low-energy $\pi^- p$ elastic scattering data with the help of the most general isospin-symmetric π-N interaction model [8].

4 Conclusions

We have observed, for the first time, the phenomenon of destructive interference in $\pi^- p$ 180° elastic scattering. The precision capability of this experiment lies in the destructive interference phenomenon which is responsible for the very deep and narrow minimum in the 180° differential cross section. The precision reached in this first run is comparable to the width of the band of fig. 2 [8], which is representative of our present knowledge on the $\pi^- p$ amplitude in the kinematic region of interest. An improved experiment, which is under way, should therefore lead to a considerable improvement of our knowledge on the $\pi^- p$ hadronic amplitude around the magic energy. In addition, it may be mentioned that destructive interference in 180° $\pi^- p$ elastic scattering is a beautiful textbook experiment for demonstrating interference in quantum mechanics.

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References

[1] H. Leutwyler, Phys. Lett. B 378 (1996) 313.

[2] S. Weinberg, "Strong Interactions at Low Energies", in Chiral Dynamics: Theory and Experiment, proc. ed. by A. M. Bernstein and B. R. Holstein, Springer 1995, p. 3.

[3] D. Wyler, private communication (1995).

[4] V. Bernard, N. Kaiser and U.-G. Meißner, Phys. Lett. B 309 (1993) 421; Int. J. Mod. Phys. E 4 (1995) 193; Phys. Rev. C 52 (1995) 2185.

[5] D. Sigg *et al.*, Nucl. Phys. A 609 (1996) 269 and Phys. Rev. Lett. 75 (1995) 3245.

[6] D. Chatellard *et al.*, Phys. Rev. Lett. 74 (1995) 4157.

[7] P. F. A. Goudsmit *et al.* , "Interference Destruction in π^-p Elastic Scattering: a New Experiment", ETHZ-IPP preprint, PR-95-2 (May 1995).

[8] E. Matsinos, "Isospin violation in the πN system at low energies", ETHZ-IPP preprint, PR-97-02 (June 1997); submitted to Phys. Rev. C.

[9] W. R. Gibbs *et al.*, "Isospin breaking in the pion-nucleon interaction", in proc. of the International Conference on Mesons and Nuclei at Intermediate Energies, Dubna, 1994.

[10] D. H. Fitzgerald *et al.*, Phys. Rev. C 34 (1986) 619.

[11] J.-P. Egger *et al.*, Nucl. Instr. and Meth. 154 (1978) 437.

[12] GEANT 3.21, Detector Description and Simulation Tool, CERN Program Library Long Writeup W5013, edition March 1994.

[13] Nuclear Enterprises Limited, Product Catalog.

[14] R. A. Arndt *et al.*, Phys. Rev. C 52 (1995) 2120; data from on-line computer programme SAID (http://clsaid.phys.vt.edu/ CAPS/).

[15] R. Koch, Nucl. Phys. A448 (1986) 707.

6 Figure Captions

Figure 1: Sketch of the experimental set-up. Shown are the positions of the detectors and the magnet AEE which separated the scattered particles from the incoming beam. A few pion and proton trajectories are also indicated.

Figure 2: Measured differential cross sections as a function of the pion laboratory energy for an average c.m. scattering angle of 175°. The vertical errors shown contain statistical and an overall systematic uncertainty of 15% added in quadrature; the horizontal ones indicate the uncertainty in the beam energy. The lines are predictions by ref. [14] (solid) and ref. [15] (dashed). The shaded band is the prediction of ref. [8] based on all available low-energy π^-p elastic scattering data.

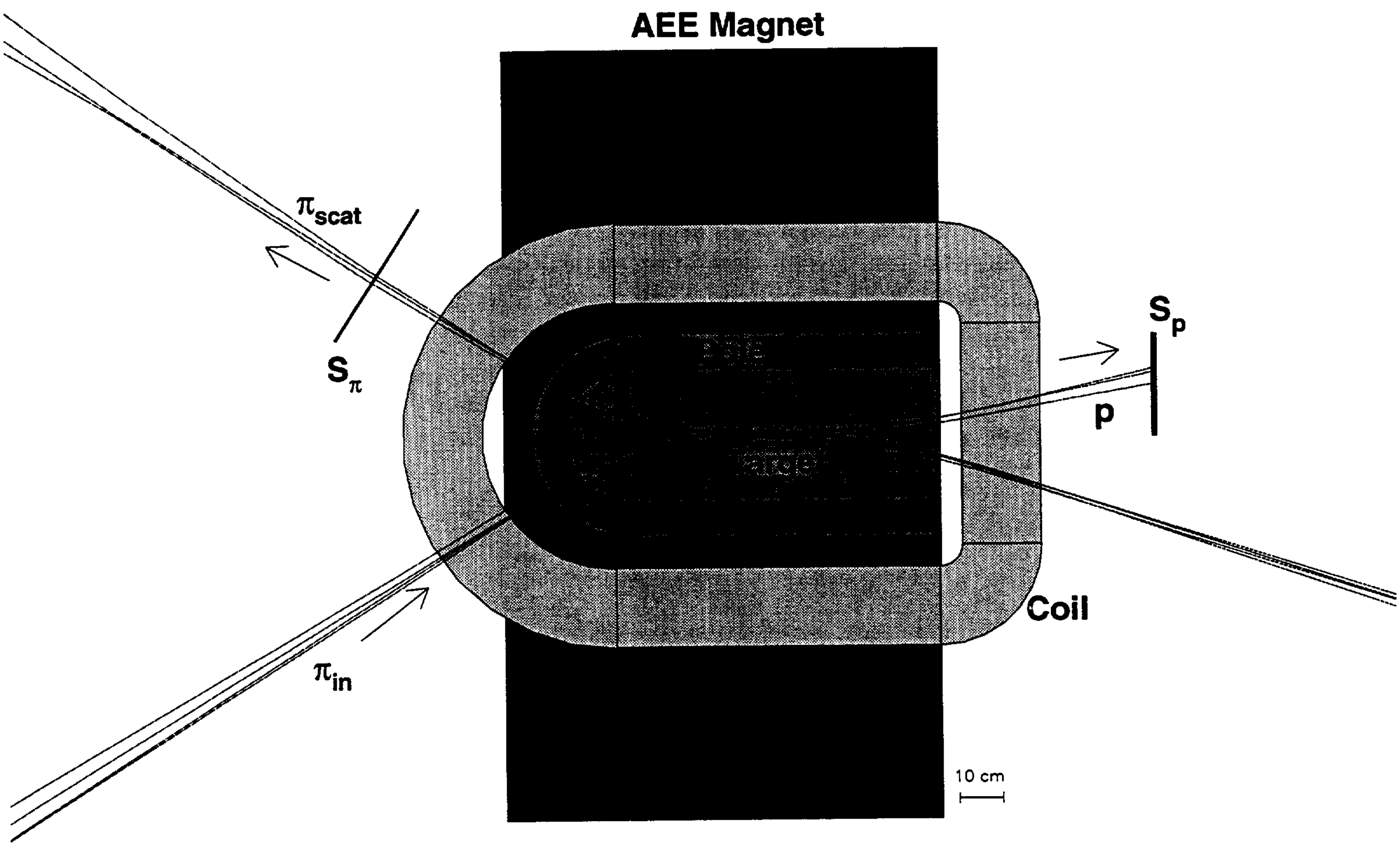
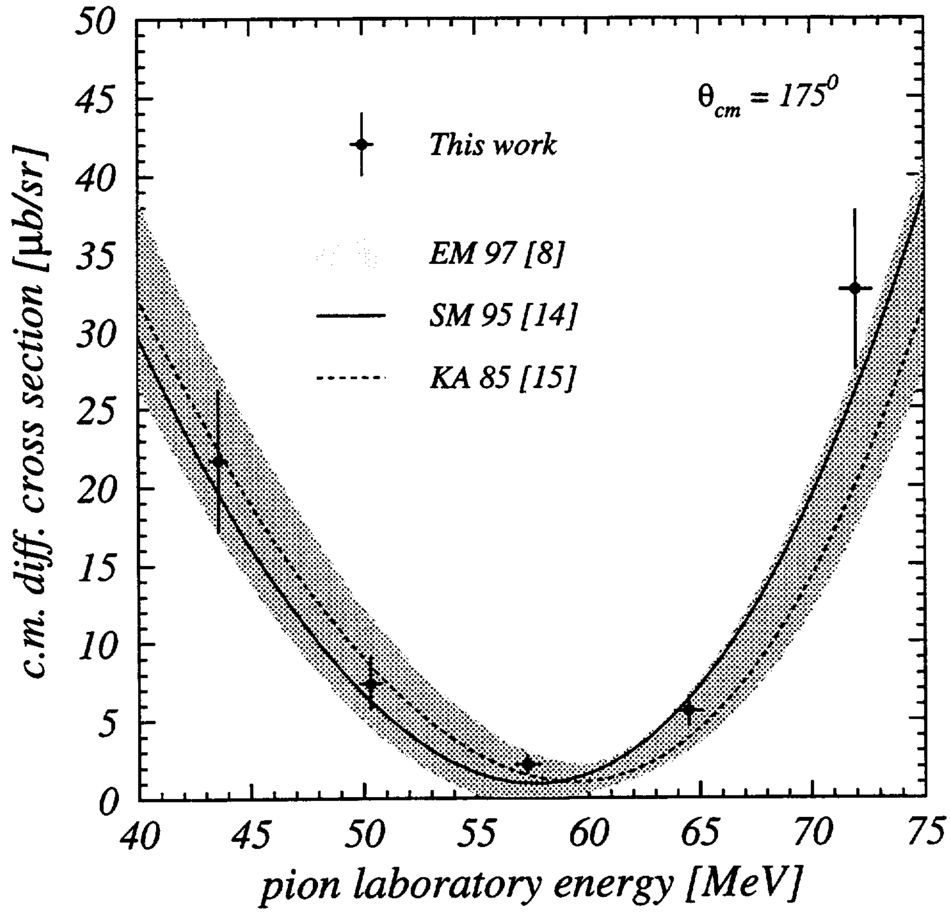


Figure 1



θ_cm = 175°
This work
EM 97 [8]
SM 95 [14]
KA 85 [15]
c.m. diff. cross section [μb/sr]
0
5
10
15
20
25
30
35
40
45
50
40
45
50
55
60
65
70
75
pion laboratory energy [MeV]

Figure 2

T_π [MeV]	N_{scat}	N_π [10^{10}]	$\left(\frac{d\sigma}{d\Omega}\right)_{cm}$ [$\mu b/sr$]
43.6	46	1.12	21.7±3.2
50.3	31	2.05	7.4±1.3
57.3	16	3.53	2.16±0.54
64.5	95	7.96	5.56±0.57
72.0	469	6.75	32.6±1.5

Table 1: Shown are the number of scattered pions (N_{scat}), the integrated pion flux (N_π) and the measured c.m. differential cross section at a scattering angle of 175° with its statistical error for the five beam kinetic energy values. An overall systematic error of 15% has to be added to the statistical error (see text).