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PROPOSAL FOR AN EXPERIMENT AT THE PS *)

MEASUREMENTS OF THE PARAMETERS A AND R IN $\pi^{\pm}p$ SCATTERING BETWEEN 5 AND 18 GeV/c

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ABSTRACT

We propose to scatter pions off the protons in a target polarized in the scattering plane, and to measure the polarization of the recoil proton. The measurements would be made between 5 and 18 GeV/c, in the interval $0.15 \leq |t| \leq 0.55$ $(\text{GeV/c})^2$. In this interval the predictions for the parameters A and R vary considerably according to the model used.

The apparatus consists of a polarized proton target, a superconducting magnet, scintillator hodoscopes and a total absorption spark chamber to measure the polarization of the protons.

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1. INTRODUCTION

At present there exist experimental results from pion-nucleon interaction for the unpolarized differential cross-sections $\pi^{\pm}p \to \pi^{\pm}p$[1] and $\pi^- p \to \pi^0 n$[2], for the polarization p in $\pi^- p \to \pi^- p$[3], and in the very near future they will be available for p in the charge exchange $\pi^- p \to \pi^0 n$[4].

The scattering matrix for these reactions is composed of spin-flip terms g and non-spin-flip terms f in the direct channel

$$M = f(s,t) + i g(s,t)\vec{\sigma}\cdot\hat{n} \quad \text{with} \quad \hat{n} = \frac{\vec{q}_i \times \vec{q}_f}{|\vec{q}_i \times \vec{q}_f|}$$

($\vec{q}_i$, $\vec{q}_f$ are the momenta of the incident pion and the scattered pion). For each of the channels $\pi^{\pm}p \to \pi^{\pm}p$, $\pi^- p \to \pi^0 n$ there is a corresponding amplitude $M_{\pi^{\pm}p}$, $M_{\pi^0 n}$. These amplitudes are related to the amplitudes M_0 and M_1 for the isotopic spin T = 0 and T = 1 in the crossed channel

$$M_{\pi^{\pm}p} = M_0 \pm M_1$$

$$M_{\pi^0 n} = \sqrt{2}\, M_1 = \frac{1}{\sqrt{2}}\left(M_{\pi^+ p} - M_{\pi^- p}\right) .$$

In the general case of scattering off a target with arbitrary polarization $\vec{P}_i$, where both the differential cross-section I and the polarization $\vec{P}_f$ of the recoil proton are measured, the following relationships between I, $\vec{P}_f$ and f, g are obtained[5]

$$\boxed{\begin{aligned} I &= |f|^2 + |g|^2 + 2\,\mathrm{Im}\, f g^* \vec{P}_i\cdot\hat{n} \\ I\vec{P}_f &= (|f|^2 - |g|^2)\vec{P}_i + 2|g|^2(\vec{P}_i\cdot\hat{n})\hat{n} + 2\,\mathrm{Re}\, f g^*(\vec{P}_i\times\hat{n}) + 2\,\mathrm{Im}\, f g^*\hat{n} \end{aligned}} \quad . \qquad (1)$$

The quantities which have been measured so far[1-4] are differential cross-sections with unpolarized targets $I_0 = |f|^2 + |g|^2$, and differential cross-sections with a target polarized perpendicularly to the scattering plane $I = I_0(1 + P_0 P_i)$, where

$$P_0 = \frac{2\,\mathrm{Im}\, fg^*}{|f|^2 + |g|^2}$$

is equal to the polarization of the recoil proton from an unpolarized target in the case of invariance with respect to parity and time reversal.

The moduli and the relative phase of f and g cannot be determined by these experiments, but only by a measurement of the polarization $\vec{P}_f$ with a target polarized in the scattering plane. One usually relates the components of the polarization proportional to $|f|^2 - |g|^2$ and to $2\,\mathrm{Re}\, fg^*$ to the quantities A and R. These quantities correspond to a measurement, in the lab. system, of the transverse component of the recoil proton polarization in the scattering plane, with a target which is polarized in a direction either parallel or perpendicular to the direction of the incident pion[6].

If Φ and Φ_L are the angles between the recoil proton and the incident pion in the c.m. system and in the lab. system, one has the relations

$$R = \left[(|f|^2 - |g|^2)\cos(\Phi - \Phi_L) + 2\,\mathrm{Re}\, fg^* \sin(\Phi - \Phi_L) \right] \frac{1}{I_0}$$

$$A = \left[(|f|^2 - |g|^2)\sin(\Phi - \Phi_L) - 2\,\mathrm{Re}\, fg^* \cos(\Phi - \Phi_L) \right] \frac{1}{I_0} .$$

More generally, if the target $\vec{P}_i$ has a polarization which is given by the components $P_i \sin\alpha \cos\varphi$, $P_i \sin\alpha \sin\varphi$ and $P_i \cos\alpha$ in the frame of reference $(\hat{n} \times \hat{q}_i, \hat{n}, \hat{q}_i)$ (Fig. 1), measurement of the transverse polarization of the recoil proton in the scattering plane will determine

$$\vec{u} = (\vec{P}_f \cdot \hat{u}')\hat{u} = \frac{-(A \cos\alpha + R \sin\alpha \cos\varphi)P_i}{1 + P_0 P_i \sin\alpha \sin\varphi} , \tag{2}$$

where $\hat{u}'$ is the effective direction of analysis of the polarization, in the c.m. system. $\hat{u}'$ is the transform of $\hat{u}$ through rotation by an angle of $(2\Phi_L - \Phi)$ around the $\hat{n}$ axis[7].

For our target the angle α can be chosen close to either 18°, or 87°, or 39°, φ will be between ± 15° (or between 180 ± 15°) (Fig. 2).

The recoil protons are emitted on the average at 72° (Table I) with α = 87° one therefore measures principally R (and Re fg^*) and with α = 18° one measures A (and $|f|^2 - |g|^2$); with α = 39° one obtains a combination of A and R.

The predictions for the parameters A and R are quite different according to the models used[8,9].

a) An optical model, or a Regge pole model[9] which both fit the experiments on angular distributions, predict different behaviours for A(s, t) and R(s, t) (Figs. 3 and 4).

b) R. Phillips has fitted a Regge pole model to the data on angular distribution and on polarization[1-3]. He predicts a difference of the order of 0.2 between A and R in π^+p and in π^-p, at 5 GeV/c, for $-0.15 > t > -0.40$ (GeV/c)^2. The difference vanishes at high energies.

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2. APPARATUS

The apparatus consists of the following parts (Fig. 5):

- A beam of negative or positive pions, vertical divergence < ± 3 mrad, horizontal divergence < ± 5 mrad, intensity more than $10^5 \pi$/cycle.
- A scintillator hodoscope in the beam (five horizontal elements, three vertical elements). According to the intensity, either a defining telescope or a monitor telescope. A gas Čerenkov counter to separate pions from protons.
- A polarized proton target ($L \simeq 6$ cm, $P_i \gtrsim 0.5$) within a superconducting magnet[10] (Fig. 6). The magnet is made of two Helmholtz coils which produce a stable and homogeneous field, and which have a large angular aperture (~ 90°) along the axis. A similar magnet of half the size has already been built at Saclay.
- A hodoscope along one side of the target (eight elements).
- A hodoscope in a variable position for the scattered pions (16 φ elements, 16 ϑ elements).
- A hodoscope for the scattered protons (14 φ elements, 8 ϑ elements).
- A spark chamber of transverse dimensions 80×60 cm^2, made of 32 carbon plates 1 cm thick, for the analysis of the polarization of the recoil proton.

Similar counter hodoscopes and polarized targets have been used at Saclay, in 1965 and 1966, in a proton-proton scattering experiment between 0.5 and 1.2 GeV[11]. The technique of measuring proton polarization by means of a carbon plate spark chamber has also been used before, to measure the polarization in pion-proton scattering at 410 and 490 MeV[12]. In the case of an optical spark chamber, the automatic scanning device "ARIANE"[13] would be able to measure about 100'000 photographs per week. The electronics group is also developing wire chambers. If such a chamber can be ready for the experiment, it would be preferable to the optical one because of its shorter dead-time during data acquisition.

Elastic scattering off free protons will be selected by fast coincidences between corresponding counters of the pion-hodoscope and the proton-hodoscope. This selection should lead to not more than one trigger from bound nucleons for one trigger from free protons. This estimate is based on a Monte-Carlo calculation. The analysis of the code numbers of the elements which are triggered in each hodoscope should reduce the background from bound nucleons to 10 or 20%. We intend also to measure the counting rate with a dummy target, and the polarization for the background events.

3. PRINCIPLE OF THE MEASUREMENT OF $\vec{P}_f$

The transverse polarization of the protons is measured at a distance of about one metre from the target. The protons have to travel through the magnetic field which is necessary to polarize the target. This results in a rotation of both the momentum and the polarization. The field map being known, the trajectories for momentum and spin can easily be calculated.

Prior to the second scattering we know the momentum $\vec{Q}$ of the recoil proton and the direction $\hat{N}$ which is the transform of $\hat{n}$ through the magnetic field. The transverse components of the polarization of the proton by the second scattering are measured along the two directions

$$\hat{V} = \frac{\vec{Q} \times \hat{N}}{|\vec{Q} \times \hat{N}|}$$

and $\hat{U} = \hat{Q} \times \hat{V}$. There is a small mixing of the components as they are defined at the target. But the component $\vec{U}$ is close to $\vec{u}$. The value of the component $\vec{U}$ will be obtained from the four counting rates $H_{\pm}$, $B_{\pm}$, where H and B are the rates for scattering to one side or the the other of the plane $(\vec{U}, \vec{Q})$, and where $\pm$ are the signs of the target polarization. Since $\vec{U}$ is nearly equal to $\vec{u}$, we have, according to formula (2)

$$H_{\pm} \simeq 1 \pm \left(\frac{A \cos \alpha + R \sin \alpha \cos \varphi}{1 \pm P_0 P_i \sin \alpha \sin \varphi}\right) P_i P_c$$

$$B_{\pm} \simeq 1 \pm \left(\frac{A \cos \alpha + R \sin \alpha \cos \varphi}{1 \pm P_0 P_i \sin \alpha \sin \varphi}\right) P_i P_c \ .$$

From the four rates $H_{\pm}$, $B_{\pm}$ one can determine $\vec{U}$ in four different ways, thus reducing the risk of hidden experimental bias.

Measurement of the component $\vec{V}$ yields mainly the value of Im fg*. It does not depend very much on the target polarization (Eq. 1). This measurement can be done only in one way, namely by measuring the difference of scattering rates to the left and to the right of the plane $(\vec{V}, \vec{Q})$.

The error on the measured value of $\vec{u}$ depends mostly upon the error on the target polarization P_i, upon the error on the analyzing power of carbon P_c, and upon the statistical error on the scattering rates. We have estimated that with a total of 2000 double scattering events (H + B) the error may reach about 0.1. At each energy we propose to measure simultaneously six points within the interval of t. This corresponds to 12'000 double scattering events for a measurement of either A or R, at one energy and for one charge state.

4. NUMBER OF EVENTS AND OF TRIGGERS

The number of events N is calculated from the formula

$$N = n_p \epsilon_{ch} L \frac{\Delta\varphi}{2\pi}\left(1+k\right) n_\pi \int_{-0.15}^{-0.55} \frac{\partial\sigma}{\partial t} dt$$

n_p number of free protons per cm^3 = 3.8×10^{22} protons/cm^3;

ϵ_{ch} geometrical efficiency of the chamber, estimated by a Monte-Carlo programme for α = 87°, ϵ_{ch} = 0.85 (the effective solid angle is not the one given by $\Delta\varphi$ and Δt);

L = 6 cm, length of the target;

$\frac{\Delta\varphi}{2\pi}$ azimuthal dimension of the spark chamber for the existing optical chamber[12]) $\Delta\varphi$ = 28°; for a possible wire chamber $\Delta\varphi$ = 21.5°;

k background ratio from bound nucleons k = 1.

The number of triggers n depends upon the dead time τ of the data acquisition system, and upon the length T of the beam spill according to the formula

$$n = \frac{N}{1 + \frac{\tau}{T} N} .$$

In Table II are given the number of triggers per cycle for the two types of spark chamber (optical chamber with two fast cameras, three tracks per photograph, τ = 12 msec; wire chamber, τ = 4 msec) and for two types of beam "D" and "E".

Beam "D" 10^5 to 2×10^5 pions/2.3 sec, T = 250 msec;

Beam "E" 5×10^5 to 10^6 pions/2.3 sec, T = 100 msec

(estimated performance of beams from experimental targets).

5. BEAM AND MACHINE TIME

The following beam characteristics are requested:

$\pi^{\pm}$ at 5, 10, 15 and 18 GeV/c,

$\Delta p/p = \pm 0.01$,

0.8 cm image diameter,

beam divergence $\epsilon_H < \pm 5$ mrad, $\epsilon_V < \pm 3$ mrad,

beam intensity greater than 10^5 pions/cycle.

The machine time is estimated for 600'000 triggers, including a "safety factor" of 2, and an average efficiency of 0.04 for useful double scatters. This leads to 2000 double scatters for each of the six intervals in t. With an optical spark chamber this number of triggers corresponds to 200'000 photographs and a measuring time of two weeks using "ARIANE" (Table II).

We are considering starting with a measurement of R at high energy ($p_\pi \gtrsim 14$ GeV/c). Once the apparatus is installed the requested time is divided in the following manner:

2 weeks parasitic operation for electronic tests;

1 week for tests with hydrogen, crystal and dummy crystal;

1 week for final test and for the first measurements with the polarized target.

Following this first part we would like to request an interval of one month, in order to analyse the results.

We would then ask for:

1 or 2 weeks (depending on beam intensity) for a first measurement of R.

The amount of machine time requested to complete the experiment would be at most four or twelve weeks, depending on beam intensity. This would be used to measure A and R for π^+ and π^- at two energies. With the optical chamber this represents 1.6×10^6 photographs or sixteen weeks of measurement with "ARIANE"

The apparatus will be tested at SATURNE. It could be installed at the PS early in 1967.

We want to stress the point that the experiment would lose much of its interest if measurements were made for only one charge state. Since we do not want to be at CERN for more than one year, it would be necessary to be able to make the measurements with π^+ and with π^- without moving the apparatus, that is in a beam from an external target.

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Figure captions

Fig. 1 : Definition of momentum and polarization of the particles ($\hat{u}$ is the unit vector of direction $\vec{u}$).

a) c.m. frame

$\vec{q}_i$, $\vec{q}_f$ momenta of the incident and the scattered pion

$\hat{u}'$ effective direction of analysis of the polarization

$\hat{n} = (\hat{q}_i \times \hat{q}_f)/|\hat{q}_i \times \hat{q}_f|$

$\cos\vartheta = \hat{q}_i \cdot \hat{q}_f$

$\cos\Phi = -\hat{q}_i \cdot \hat{q}_f$.

b) Lab. frame, first scattering

$\vec{P}_i$ polarization of the target protons

$\vec{u}$ transverse component of the recoil proton polarization in the scattering plane

$\vec{q}$ momentum of the recoil proton

$\cos\Phi_L = \hat{q}_i \cdot \hat{q}$

$\cos\alpha = \hat{q}_i \cdot \hat{P}_i$

φ angle between the axis $\hat{u}\times\hat{q}_i$ and the projection of P_i in the plane $(\hat{n}, \hat{n}\times\hat{q}_i)$.

c) Lab. frame, second scattering

$\vec{Q}$ momentum of recoil proton prior to second scattering

$\hat{N}$ transform of $\hat{u}$ through the magnetic field

$\hat{U} = (\hat{Q}\times\hat{N})/|\hat{Q}\times\hat{N}|$

$\hat{V} = \hat{U}\times\hat{Q}$

$\vec{U}$, $\vec{V}$ measured transverse components of the polarization of the recoil proton.

The second scatterings are defined with respect to the two planes $(\hat{Q}, \hat{V})$ and $(\hat{Q}, \hat{U})$. H and B correspond to scatterings towards the $\pm\hat{V}$ axes, G and D towards the $\mp\hat{U}$ axes.

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Fig. 2 : Positions of the superconducting coils, compatible with πp reaction kinematics and with the shape of the coils. Two positions are sufficient to measure A and R.

Fig. 3 : Behaviour of A and R at 20 GeV/c according to the optical model with the assumptions[9]:

a) (dotted line): zero spin-flip amplitude $g(s,t) = 0$

b) (full line) : spin-flip amplitude proportional to non spin-flip amplitude $g(s,t) = \sqrt{(-t)/(4m_p^2)}\ f(s,t)$, where m_p is proton mass.

Fig. 4 : Behaviour of A and R according to the Regge pole model proposed by R. Phillips[9] fitted to the experimental results of the angular distributions $\pi^{\pm}p \rightarrow \pi^{\pm}p$, $\pi^{-}p \rightarrow \pi^{0}n$, and the polarization $\pi^{-}p \rightarrow \pi^{-}p$.

Fig. 5 : Apparatus.

Fig. 6 : Polarized target in a superconducting magnet. The cryostats for the target and coils are independent of each other.

Table captions

Table I : Angular intervals calculated from the kinematics at 4, 10 and 16 GeV/c.

Table II : Time necessary to measure one parameter (A or R) at one energy and for one charge state.

The time is expressed in numbers of shifts of six hours each. It is calculated for two types of beam. It includes a "safety factor" $K_{sec} = 2$. The following figures were used for the two possible spark chambers:
Optical chamber: $80 \times 60 \times 64$ cm^3, dead time 12 msec with three tracks per photograph and with two cameras of 36 msec dead time.
Wire chamber : $80 \times 60 \times 96$ cm^3, dead time 4 msec. The times are calculated for 1000 double scatterings of recoil protons from "free proton" scatters (one trigger from free protons for one trigger from bound nucleons), two signs of the initial polarization $\pm P_i$, six intervals of t, and an efficiency of 0.04 for useful second scatterings within the chamber. This leads to a total number of $1000 \times 2 \times 2 \times 6 \times 25 = 6 \times 10^5$ triggers.

The optical chamber would take 2×10^5 photographs. The measuring time with "ARIANE" would be two weeks.