POLARIZATION PHENOMENA IN HIGH ENERGY HADRON SCATTERING

G. BELLETTINI

Until a few years ago, the assumption was frequently made that high energy hadron scattering about the forward direction was merely shadow scattering. This was motivated by the common feature for the various reactions which showed forward peaks, with slopes roughly characteristic of the total cross-sections. It was natural to assume that a scalar quantity was sufficient to describe the scattering process throughout the region of these forward peaks. This assumption was also supported by the fact that the excess of the forward cross-section above the optical value was small, thus implying most naturally that the scattering amplitude in the forward region was purely imaginary, as it should be in case of pure diffraction.

However, recent experiments on pion and proton scattering in the forward direction(1) and of pion charge-exchange(2) on polarised protons have proved that spin dependent effects are appreciable also in the 10 GeV energy region. These results opened us the question of measuring (and predicting theoretically) the spin-dependent part of the hadron scattering amplitude at high energies.

What has to be measured in the π - p case.

Most of the work is being done for the π - p case, which we shall discuss in some detail. It is customary to write the scattering amplitude as

$$F(s,t) = f(s,t) + ig(s,t)\ \vec{\sigma}\cdot\vec{n} \qquad (1)$$

f(s,t) is called the non-spin-flip, and g(s,t) the spin-flip part of the amplitude. g(s,t) contains as a factor the sine of the scattering angle, and is zero in the forward direction. $\vec{n}$ is the normal to the scattering plane. Similar expressions can be written for π^+, π^- elastic, and π^- charge-exchange scattering.

To measure f(s,t) and g(s,t) for any of the above reactions one has to measure four scalar quantities (at each s and t), i.e. to perform four independent experiments (when all reactions are measured, however, the amplitudes are over-determined due to isospin invariance).

The easiest experiments to be performed are

a) an elastic scattering experiment on unpolarised protons, to measure

$$\frac{d\sigma}{d\Omega}(s,t) = |f(s,t)|^2 + |g(s,t)|^2 \qquad (2)$$

The recoil proton from this reaction has a polarisation normal to the scattering plane which is given by

$$P_o = \frac{2\,\mathrm{Im}(fg^*)}{|f|^2 + |g|^2} \qquad (3)$$

b) a scattering experiment on the above recoil proton, to measure P_o. The target acts as a polarisation analyser, i.e. it must have the property of scattering differently depending on whether the proton spin is "up" or "down", with a known analysing power at the useful proton energies and scattering angles. A typical analyser is carbon for energies of a few hundred MeV and at angles between 20° and 30°. From the left and right counting rates, N_L and N_R, and from the analysing power P_C, one obtains P_o as

$$P_o P_c = \frac{N_R - N_L}{N_R + N_L} \qquad (4)$$

P_o can also be measured with a simpler experiment (a single scattering in place of a double one) if one has at one's disposal a polarised proton target. One can prove that if we assume invariance with respect to parity and time reversal, the differential cross-section for scattering on polarised protons is given by[(3)]

$$\frac{d\sigma_{\Uparrow}}{d\Omega} = |f|^2 + |g|^2 \pm 2\ \mathrm{im}(fg^*)\ P_T \qquad (5)$$

P_T being the target polarisation oriented "upwards", and the + sign holds for the scattering to the right, the - for the scattering to the left. From the left-right asymmetry in counting rate one can measure P_o. Indeed

$$N_R - N_L \propto 4\mathrm{Im}(fg^*)$$

$$N_R + N_L \propto 2(|f|^2 + |g|^2)$$

$$\frac{N_R - N_L}{N_R + N_L} = \frac{2\mathrm{Im}(fg^*)}{|f|^2 + |g|^2} P_T = P_o P_T \qquad (6)$$

Experimentally it is more convenient to measure the counting rate at a single laboratory angle, once for target polarisation "up" and once for target polarisation "down". The same formula (6) applies also in this case, when N_{UP} is substituted for N_R, and N_{DOWN} is substituted for N_L. The high energy experiments to measure P_o, (1) and (2), have been made in this manner.

c) The third experiment of our list is a double scattering experiment using a polarised proton target. If the target polarisation P_T is in the scattering plane, transverse to the direction of the incident pion, the recoil proton transverse polarisation P_F in the same plane is proportional to P_T.

$$P_F = A_r\ P_T. \qquad (7)$$

In the non-relativistic approximation the function $A_r(s,t)$ is given in terms of $f(s,t)$ and $g(s,t)$ by

$$A_r \approx A = \frac{2\mathrm{Re}\,(fg^*)}{|f|^2 + |g|^2} \tag{8}$$

The polarisation P_F, and thus $A \propto 2\mathrm{Re}(fg^+)$, can be measured by scattering the recoil proton on an analyser as discussed above, and recording the "up-down" asymmetry with respect to the scattering plane.

d) if the target proton is polarised along the direction of the incident pion, the recoil proton transverse polarisation in the scattering plane, P_F', is given by (in the non-relativistic approximation)

$$P_F' = RP_T = \frac{|f|^2 - |g|^2}{|f|^2 + |g|^2}\, P_T \tag{9}$$

again, P_F' can be measured as in c) above.

If relativistic formulae are used for 8) and 9)[4,5] one sees that $A \propto \mathrm{Re}(fg^+)$ and $R \propto (|f|^2 - |g|^2)$ cannot be measured independently in c) and d), a mixture of them being actually measured in both experiments. However, c) measures essentially A, and d) essentially R. By performing both experiments one can make the corrections which are required and fully separate A and R.

One can prove that P_o, A and R are not independent, since

$$P_o^2 + A^2 + R^2 = 1 \tag{10}$$

Therefore, with experiments a), b), c) and d) one parameter is left indetermined in the scattering amplitude, for example the relative phase of $f(s,t)$ and $g(s,t)$. However, if π^+, π^- elastic and π^- charge-exchange scattering are measured at the same time, the isospin 1/2 and 3/2 amplitudes are overdetermined.

The polarisation parameters to be measured in b), c), d) are illustrated in fig.1.

The experimental situation for $\pi^{\pm}$ scattering.

We shall now briefly illustrate what has been done up to now, and which measurements are planned in the nearest future, concerning-experiments b) to d) in high energy pion scattering and charge-exchange. The differential cross-section in the diffraction region is fairly well known for all reactions.

An experiment to measure P_o in $\pi^{\pm}$ - p elastic scattering between 6 and 12 GeV/c was performed at CERN last year. A lay-out of the experimental system is sketched in fig.2. The system comprises a polarised proton target, a scintillation counter hodoscopes on the incoming pion, on the scattered pion and on the recoil proton. For each angular bit as defined by the pion hodoscopes the elastic scattering events were isolated from the background by requiring the recoil proton to be coplanar and to have the correct angular correlation in the scattering plane. Elastic scattering events from free polarisable hydrogen in the target showed up as a peak on a continuous background in such correlation plots, as shown in fig.3. A typical problem in such an experiment using a polarised proton target is in fact the separation of good events from inelastic background events, and from elastic events of bound nucleons. This is because in all target crystals used up to now the content of free polarisable hydrogen was only about 3 % in weight. The results of this experiment are shown in fig.4 for negative pions, and in fig.5 for positive pions. Appreciable polarisation was found up to 12 GeV/c. In the same experiment sizeable, olarisation was also found for the proton-proton scattering case. The results are shown in fig. 6. For p-p scattering the expression of P_o in terms of spin amplitudes is complicated, because of the several spin couplings that can contribute to the scattering. At the same time, these results are very important simply because they show that spin effects are important at high energies also for p-p scattering.

This experimental research will be furthered at CERN later this year[6] (1967), and will also be extended to K^+, K^- and antiprotons, taking advantage of the high intensity of a secondary beam from the slow ejected proton beam of CERN. In the proton and pion case, angular distributions of the polarisation parameter will range over $0,15 \lesssim -t \lesssim 1,1$ $(GeV/c)^2$, at the energies up to $\simeq$ 15 GeV/c, with points spaced at about 0,05 to 0,1 $(GeV/c)^2$ and statistical errors of about $\pm$ 3 %. The forthcoming data should be good enough to answer several theoretically relevant questions which have been left open by the present data (as we shall briefly discuss later). The information is expected to be progressively more modest for kaons and antiprotons. A scheme of the new CERN experiment is shown in fig.7. This experiment uses a polarized proton target and scintillation counter hodoscopes to define particle trajectories, and aims to separate free hydrogen elastic scattering events in a similar manner as in the experiment of Borghini et al.[1]. However there are several important new features, which can be listed as follows:

a) a more intense beam of both signs will be used, which will allow one to collect data over an appreciably wider t-range, and to study for the first time K^+ and K^-, and to some extent also antiprotons.

b) a new polarised target in higher magnetic field, and hopefully containing a different crystal with a larger fraction of free polarisable compound, will be used.

c) There will be an additional check, by means of a couple of threshold Cerenkov counters, that the scattered particle be high-energy particle of the same nature as the incident one. This check should help in reducing background level.

d) A magnetic, with $\frac{\Delta p}{p} \sim \pm 5\ \%$, will be performed on the scattered protons, also aimed at reducing background.

The set of experiments on $\pi^{\pm} - p$ scattering in the diffraction region will be completed with a new experiment which is scheduled to begin this autumn at CERN[7] to measure A and R at energies between 5 and 18 GeV/c and $0{,}15 \lesssim -t \lesssim 0{,}55\ (GeV/c)^2$. A sketch of this experiment is shown in fig.8. The magnetic field at the longitudinally polarised target is obtained by superconducting coils, which leave free space for detection of both the scattered pion and the recoil proton. The experiment is done in two parts, with the polarised target longitudinal and transverse to the incident beam direction, to obtain the two required orientations of the polarisation. Scintillation counter hodoscopes define the elastic scattering events in a way similar to that used in ref.(1). Analysis of the recoil proton polarisation is made by means of a large carbon-plate spark chamber.

The experimental situation for pion charge-exchange.

The analysis of the data collected in the experiment of Bonamy et al.[2] is being completed now : as far as I know, this experiment will remain for some time the only one on polarisation in charge exchange at high energy. A perspective drawing of the lay-out is presented in fig.9. A similar target as in ref.(1) was used. Neutral pions produced about the forward direction were detected by means of a thick plate optical spark chamber. Recoil neutrons were detected in an array of plastic scintillation counters.

Elastic scattering events from free hydrogen were isolated above the background by requiring the neutron to be emitted at the kinematically correlated direction to the pion, in an analogous manner to the elastic scattering experiment[1]. However, due to the favourable condition of freedom from multiple scattering of the low energy recoil nucleon, and by making use of its time of flight, a better signal-to-noise ratio was obtained. This is seen in a typical neutron time-of-flight distribution, which is shown in fig.10. Partial results on P_0 at $0 \lesssim -t \lesssim 0{,}3$ $(GeV/c)^2$ and at 6 and 11 GeV/c are shown in fig.11. Appreciable polarisation is found at 6 GeV/c, which remains the same within the errors at 11 GeV/c. These results are obtained from about 80 % of the collected data.

Comments on open points.

Differential cross-sections and polarisation data in $\pi - p$ scattering at high energies, and the charge-exchange cross-section, have been interpreted in terms of Regge pole exchange in the crossed channel[8]. The known poles which can be exchanged in $\pi^{\pm} p$ elastic scattering are P, P' and ρ. Only the ρ can contribute to $\pi^{-} - p$ charge exchange. However also the ρ', if it exists[9], can be exchanged in all reactions. Polarisation in elastic scattering was attributed to interference between the spin-flip part of the ρ amplitude and the non-spin-flip part of the P and P' amplitudes. Two clear predictions are made in this model. First, that polarisation will be indentical in magnitude but opposite in sign in π^{-} and π^{+} scattering, simply because the amplitude enters with opposite sign in the two reactions. Second, that P_0 should vanish at $t \approx -0{,}6$ $(GeV/c)^2$, where the spin-flip part of the ρ term vanishes together with the trajectory $\alpha_p(t)$ itself. Polarisation data by Borghini et al. are in general agreement with these predictions even if they are not fitted in all details by the model (see fig. 12). In particular, in the π^+ data one may find an indication of an energy decrease which is more rapid than in the π^- case. Also, whether and at which momentum transfers P_o becomes zero and changes sign is, to a large extent, an open question. Hopefully, the new CERN experiment[6] will make these points clear.

The above model also predicts a difference of the order of 0.2 between A and R in $\pi^+ - p$ and $\pi^- - p$, at 5 GeV/c, for $0.15 \lesssim -t \lesssim 0.40$ $(GeV/c)^2$ [7]. At higher energies these differences should vanish. This prediction will be tested in the forthcoming CERN experiment[7].

Sizeable polarisation in $\pi^{\pm} p$ elastic scattering may be also present away from the forward direction. In the interpretation of backward $\pi - p$ scattering in terms of s-channel resonances and baryon Regge pole exchange in the u-channel[10], sizeable polarisation is predicted up to several GeV/c, in the region of the backward peaks. The predicted polarisation depends very much on the contribution of terms to which the differential cross-section is not very sensitive, showing in all cases a great deal of structure. Such a situation is illustrated in fig. 13. It is clear that an experimental investigation of this point would be extremely valuable. However, the problem of background discrimination looks in such an experiment extremely hard, at least until new polarized proton targets with higher content of free polarisable protons are available. The experiment demands magnetic analysis of both final state particles with large spectrometers, and has to deal with a very low counting rate, a severe limitation particularly in a polarisation experiment. It has been considered with interest at CERN, but is not on schedule for the near future.

For the p-p scattering case, the maximum polarisation at 12 GeV/c is still about 10 %, as found by Borghini et al.(fig.6). The overall situation at high energies is summarized in fig.14. Data at higher energies are needed to see wether P_0 continues to decrease above 12 GeV/c, or tends to remain appreciably different from zero (an indication of this tendency may be found in the data of Borghini et al.[1]. Since spin effects are still appreciable at 12 GeV/c, one faces the problem that previous analysis of elastic scattering data, made under the assumption of a spin-independent forward scattering amplitude, should be revised. As an example one can cite the derivation of the real part of the forward scattering amplitude with the Coulomb interference method[11]. On the other hand, this will only be possible when a complete set of polarisation experiments on the p-p system is available, and the strength of the various spin-orbit and spin-spin interactions are known separately. Some of these experiments will necessarily require the use of a polarised proton beam and such beams are not available to-day at high energies. However, it has to be observed that if spin interactions are indeed appreciable at high energies, one can in principle solve the problem of constructing a high energy polarized proton beam. To give an example, due to the results of Borghini et al., one knows that by scattering protons on hydrogen at $\sim$ 10 GeV/c and at $t \sim 0{,}3$ $(\mathrm{GeV/c})^2$ a $\sim$ 10 % polarised proton beam could be obtained. This polarisation level is certainly poor, but it is not inconceivable that one may use such a beam for spin-spin interactions experiments.

One may also hope that a beam with a higher degree of polarisation could be obtained in the coherent scattering of protons on medium and heavy nuclei. Fig.15 shows the angular distributions of protons elastically or quasi-elastically scattered off copper, lead and uranium at 19.2 GeV/c as obtained in a CERN experiment a couple of years age[12]. These data have been interpreted in an optical model by Frahn and Wiechers[13]. The proton-nucleus potential was found to be essentially the same at 20 GeV as at energies of the order of 1 GeV. The spin-orbit part of this potential should, on the other hand, cause strong polarisation maxima in the same angular region, as is actually found experimentally at low energies. To see whether such a polarisation still exists at 20 GeV/c, one would have to perform a double scattering experiment on some nucleus. Such an experiment is being considered with some interest at CERN, but there are no definite plans for the near future.

REFERENCES :

(1) M.Borghini, G. Coignet, L. Dick, L. di Lella, A. Michalowicz, P.C. Macq, J.C. Olivier - Phys. Letters 24B, 77 (1967).

(2) P. Bonamy, P. Borgeaud, C. Bruneton, P. Falk-Vairant, O. Guisan, P. Sonderegger, C. Caverzasio, J.P. Guillaud, J. Schneider, M. Yvert, I. Mannelli, F. Sergiampietri, L. Vincelli - Phys. Letters 23, 501 (1966).

(3) J.P. Merlo, J. Zsembery - Rapport LPCHE 62-18.

(4) L. Wolfenstein, Phys. Rev. 96, 1654 (1954).

(5) H.P. Stapp - Phys. Rev. 103, 425 (1956)

(6) CERN - Orsay - Pisa collaboration, M. Borghini, L. Dick, G. Gregoire, L. di Lella, P.M. Macq, J.C. Olivier, D. Kronenberger, K. Kuroda, A. Michalowicz, G. Bellettini, P.L. Braccini T. del Prete, and L. Foa.

(7) Y. Ducros, J.P. Merlo, J. Mouchet, P. Sonderegger, L. Van Rossum - Center of Nuclear Studies of Saclay, proposal for an experiment on CERN proton-syncroton.

(8) See for example C.B. Chiu, R.J.N. Phillips, and W. Rarita - UCRL report 16940 (to be published in Physical Review).

(9) See for example H. Högaasen and W. Fisher, Phys. Letters 22, 516(1966), and J. Beaupre, R.K. Logan, and L. Sertorio, University of Illinois, preprint.

(10) John D. Steck, Phys.Rev. Let. 16, 286 (1965)
V. Barger and D. Cline, Phys. Rev. Letters 16, 913 (1966), and Phys. Rev., to be published.

(11) See for example G. Bellettini, G. Cocconi, A.N. Diddens, E. Lillethun, J.P. Scanlon and A.M. Wetherell, Phys. Letters 19, 715 (1966)

(12) G. Bellettini, G. Cocconi, A.N. Diddens, E. Lillethun, G. Matthiae, J.P. Scanlon and A.M. Wetherell - Nuclear Physics 79, 609 (1966).

(13) W.E. Frahn and G. Wiechers "Partial wave analysis of 20 BeV proton-nucleus scattering", to be published in Annals of Physics.

FIGURE CAPTIONS :

Fig. 1 - Schematic reaction diagrams to illustrate the polarisation parameter P_0 (upper part), and the two proton polarisations to measure A (central part) and R (lower part).

Fig. 2 - Schematic drawing for the experimental system of Borghini et al., ref. (1).

Fig. 3 - Distribution of Coplanar events along the longitudinal coordinate (on the scattering plane) of the recoil proton hodoscope, for several angular bins (ref.(1)). The peaks correspond to elastic scattering on free polarisable hydrogen.

Fig. 4 - Polarisation parameter for $\pi^- - p$ scattering at 6, 8 and 10 GeV/c, in the diffraction region (ref.(1)).

Fig. 5 - Polarisation parameter for $\pi^+ - p$ scattering at 8 and 10 GeV/c, in the diffraction region (ref.(1)).

Fig. 6 - Polarisation parameter for p-p scattering at 6,10 and 12 GeV/c, in the diffraction region (ref.(1)).

Fig. 7 - Schematic lay-out of the forthcoming CERN experiment(6) to measure P_0 in $\pi^\pm$, $K^\pm$, $p^\pm$ scattering on protons, in the diffraction region.

Fig. 8 - Schematic lay-out of the forthcoming CERN experiment(7) to measure A and R in $\pi^\pm - p$ scattering.

Fig. 9 - Schematic lay-out of the experiment by Bonamy et al.(2).

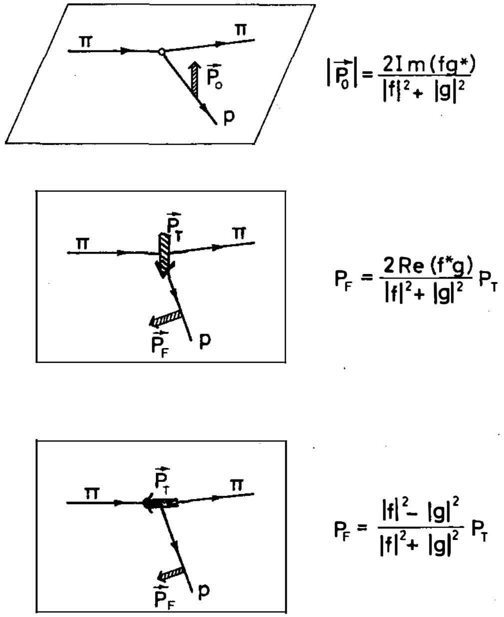


Fig. 1

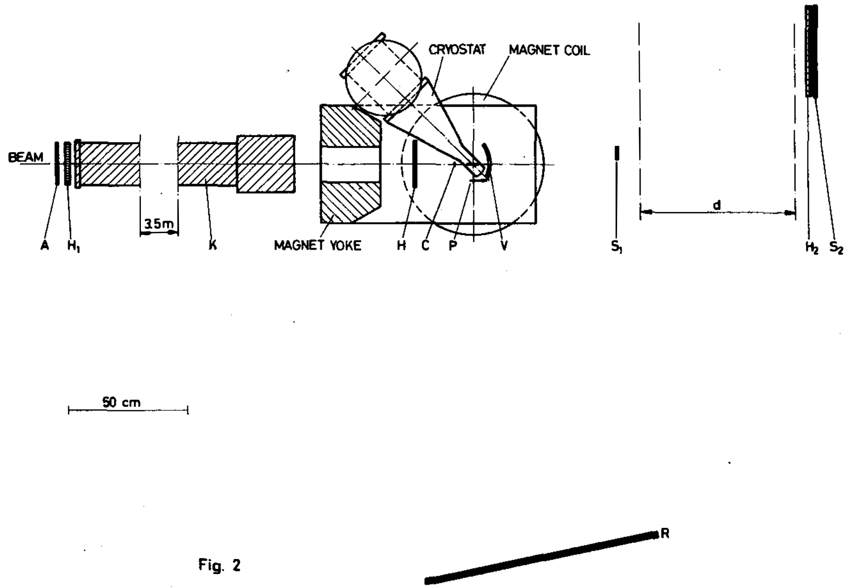


Fig. 2

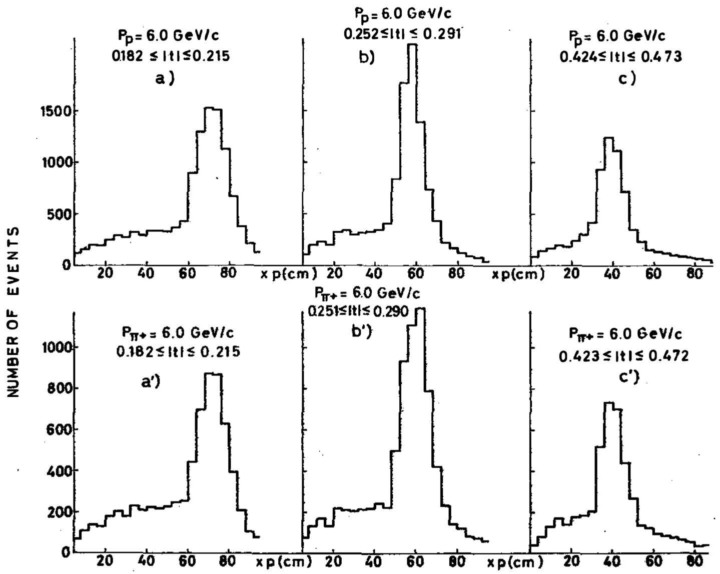


Fig. 3

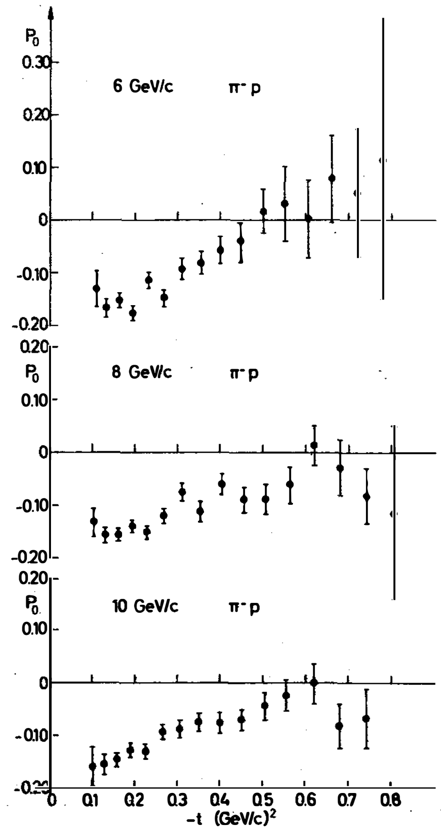


Fig. 4

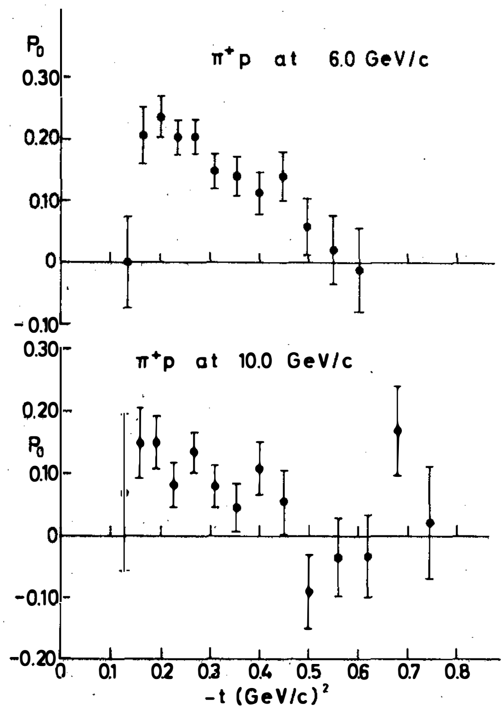

π^+p at 6.0 GeV/c
π^+p at 10.0 GeV/c
P_0
$-t\ (GeV/c)^2$

Fig. 5

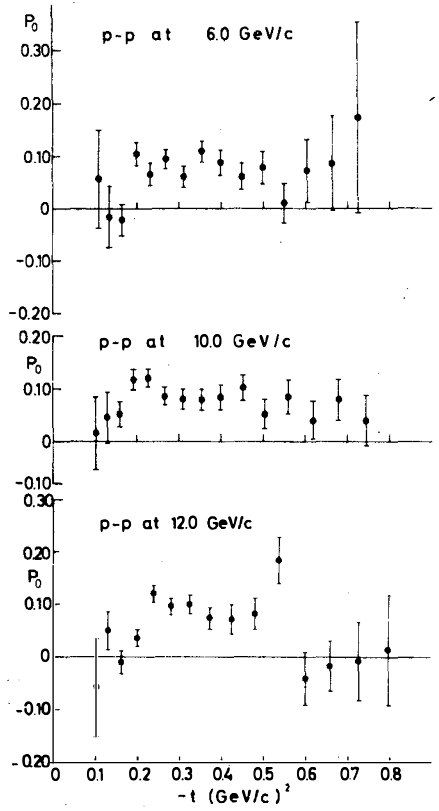
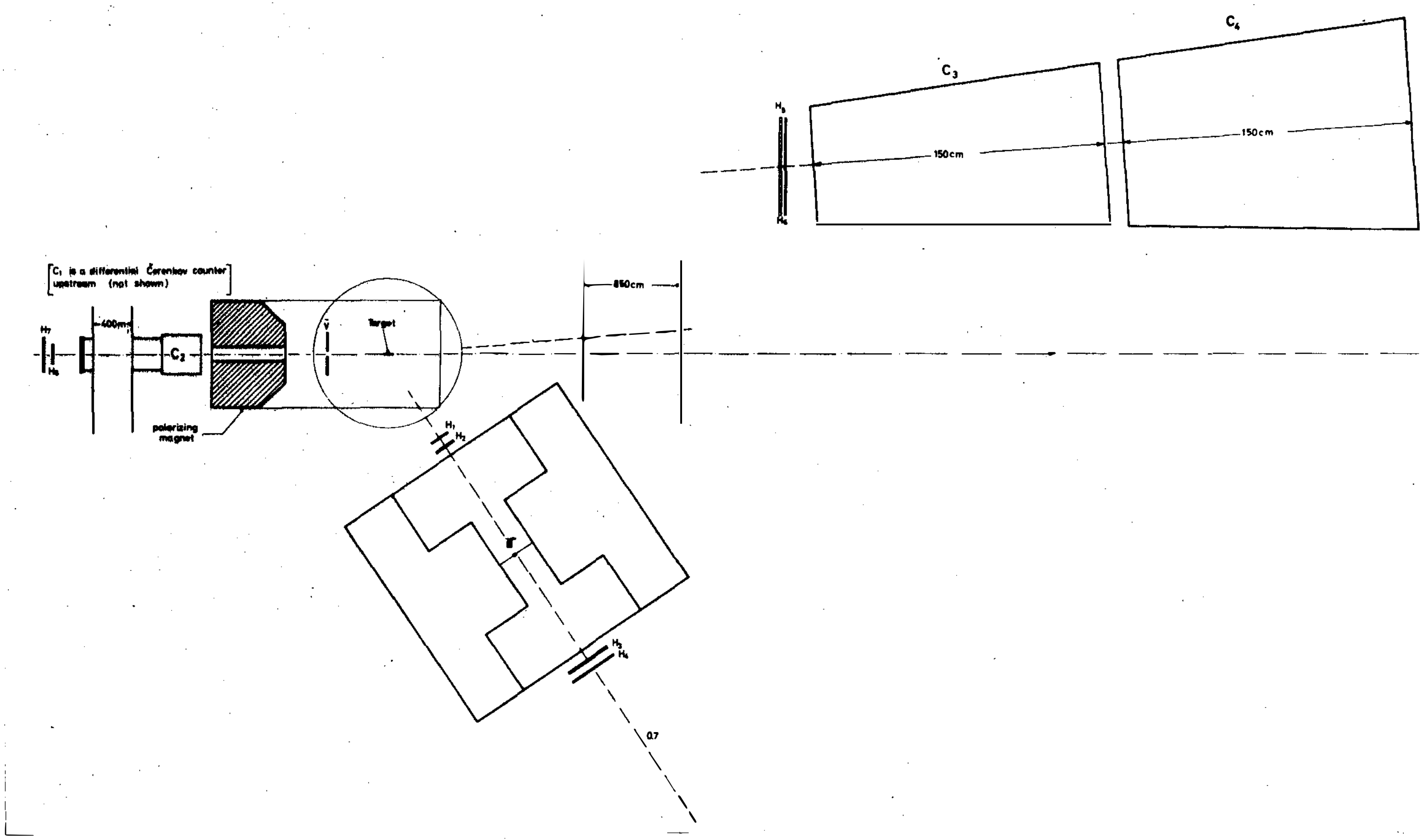

p-p at 6.0 GeV/c
p-p at 10.0 GeV/c
p-p at 12.0 GeV/c
P_0
$-t\ (GeV/c)^2$

Fig. 6


[C_1 is a differential Čerenkov counter upstream (not shown)]
C_2
polarizing magnet
Target
850cm
H_7 H_8
H_1 H_2
H_3 H_4
C_3
C_4
150cm
150cm

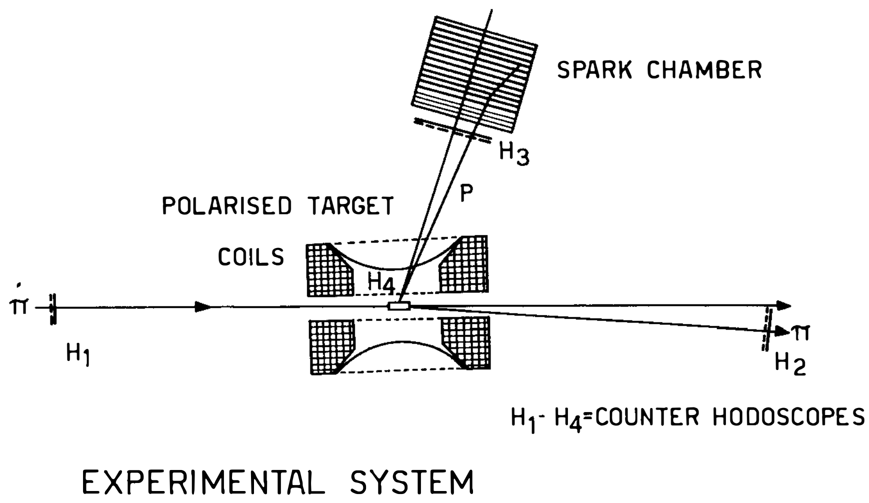


Fig. 8

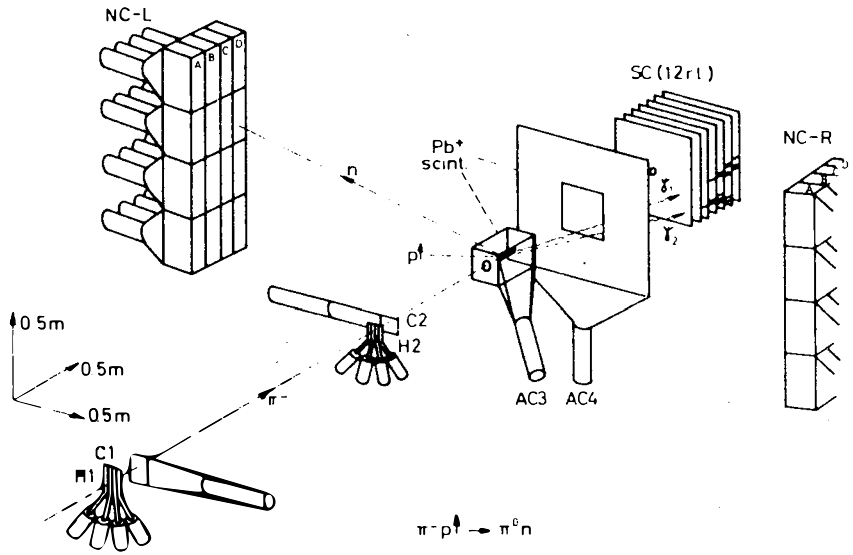


Fig. 9

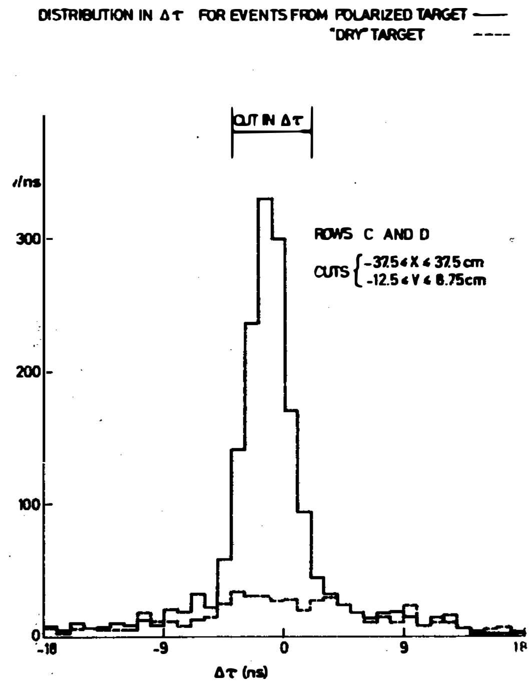


Fig. 10

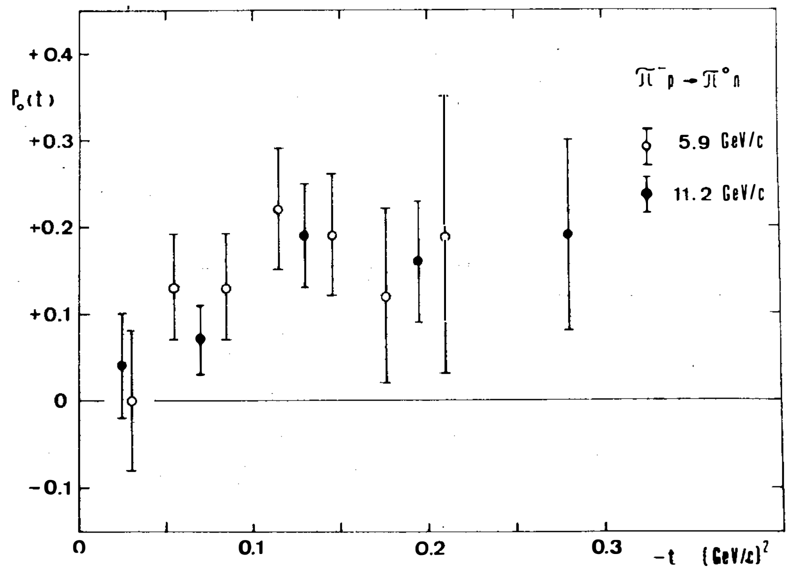


Fig. 11

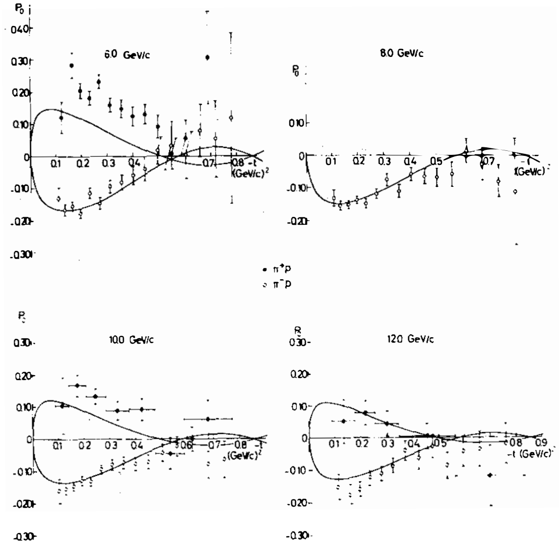


Fig. 12

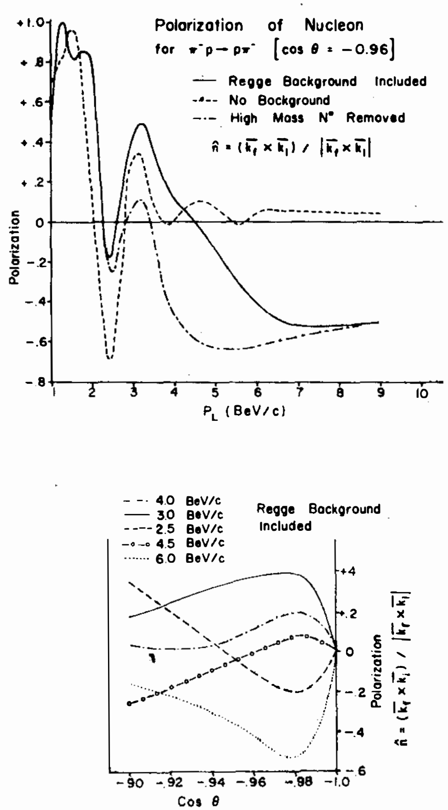


Fig.13

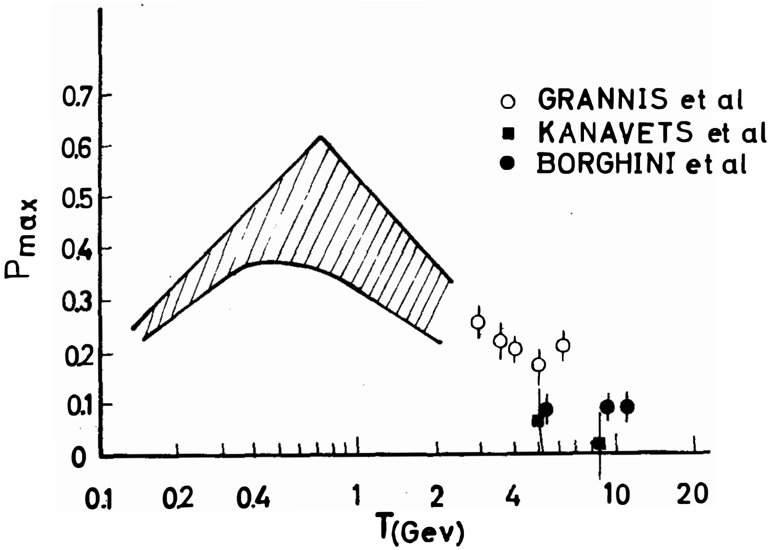


Fig. 14

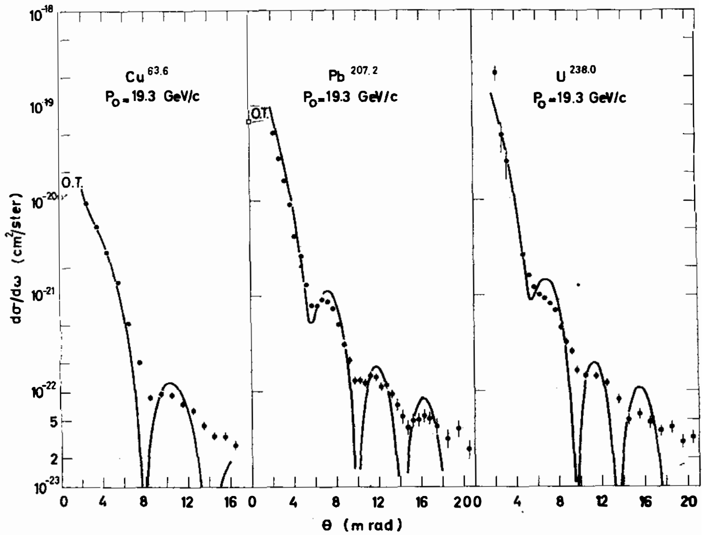


Fig.15

Fig. 10 - Recoil neutron time of flight distributions, showing the peak due to free hydrogen events, as obtained by Bonamy et al.[2].

Fig. 11 - Partial results of the experiment of Bonamy et al.[2] on the polarisation parameter at 6 and 12 GeV/c.

Fig. 12 - Polarisation data by Borghini et al.[1], fitted in the (P+P') - ρ interference model.

Fig. 13 - Predicted polarisation in the region of the backward peak, for π^- - p scattering (ref.11).

Fig. 14 - Maximum polarisation in p-p scattering.

Fig. 15 - Forward angular distributions of protons elastically or quasi-elastically scattered off natural copper, lead and uranium (ref.12).