EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PPE/94–191
25 November, 1994

MANIFESTATION OF THE PION POLE IN $\bar{p}p \to \bar{n}n$ CHARGE-EXCHANGE SCATTERING

F. Bradamante and A. Martin
Dipartimento di Fisica dell'Università, Trieste, and INFN, Sezione di Trieste, Trieste, Italy

Abstract

A recent experiment at LEAR, the CERN Low Energy Antiproton Ring, has provided very precise differential cross-section data for the $\bar{p}p \to \bar{n}n$ charge-exchange reaction. When performing the extrapolation procedure to the pion pole originally proposed by G. F. Chew the data exhibit the same dynamical mechanism than the np $\to$ pn line reversal reaction. The residue at the pole is consistent with the known value of the charged πNN coupling constant, as expected from charge conjugation invariance.

To be published in Physics Letters B

One pion exchange (OPE) has been shown since many years, both qualitatively and quantitatively, to be a fundamental process which dominates at large distances the nucleon-nucleon interaction [1]. Although neither the nucleons, nor the pions, are structure-less, it is a most remarkable fact that OPE with point-like nucleons and pions describes correctly the NN dynamics down to distances as small as the pion Compton wave-length. This is clearly related to the smallness of the pion mass, but it is also true that the pion, amongst all the mesons, has always played a special role, related to chiral symmetry and its identification with a Goldstone boson [2].

In order to clarify this special role of the pion it is of the greatest importance to detect clear pion manifestations in many different physical systems. In this paper we would like to draw attention over a clear evidence for pion exchange in the $\bar{\mathrm{N}}\mathrm{N}$ interaction, which is based on the $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ cross-section data from a recent experiment [3] at LEAR, the Low Energy Antiproton Ring at CERN.

The data have been taken at two values of the antiproton momentum, 601 and 1202 MeV/c. They have small statistical errors and overall normalization errors of 3 and 4% respectively. In fig. 1a we show only the low-t data, and what is plotted is the ratio of the differential cross-section to its best fitted value at $t = 0$ (the details of the fit are given below). The data have comparable quality and remarkable similarities with the line-reversed reaction $\mathrm{np} \to \mathrm{pn}$ data, two examples of which can also be seen in fig. 1b for two similar energies [4].

The most striking feature of both sets of data is the forward spike, which since long time has been interpreted as a manifestation of the nearby pion pole, and now for the first time has been precisely measured for the $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ channel. The second interesting feature is the energy dependence of the $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ differential cross-section which contrasts with the universal shape with momentum transfer exhibited by the $\mathrm{np} \to \mathrm{pn}$ reaction from a few hundred MeV to almost 10 GeV. A third point to be noticed, not apparent from the figure, is that the value of the forward differential cross-section at a given energy is about 4 times smaller for $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ than for $\mathrm{np} \to \mathrm{pn}$: this is due to the annihilation process, which is unique of the $\bar{\mathrm{N}}\mathrm{N}$ system, and is responsible of the strong absorption of the lower partial waves.

Although the very narrow width of the forward peak ($\leq$ 100 Gev^{-2}) immediately suggests a pionic phenomenon, it is not straightforward to explain the exact shape of the differential cross-section in terms of the pion propagator. Due to the lack of good $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ data, what has been scrutinized in so far is the $\mathrm{np} \to \mathrm{pn}$ cross-section and its remarkable energy-independent t-shape, but the symmetry between the two reactions demands for a common explanation.

It is well known that, due to the pseudoscalar nature of the pion, pion exchange must contribute to the cross-section with a Born term

$$\left(\frac{d\sigma}{d\Omega}\right)_{pion} = \frac{1}{s} \cdot \left(g_c^2 \frac{t}{t - m_\pi^2}\right)^2$$

where s and t are the Mandelstam variables, and

$$g_c^2 = \frac{4M^2}{m_\pi^2} \cdot f_c^2 \simeq 14.$$

is the charged pion-nucleon coupling constant (m_π and M are the pion and proton masses). The Born approximation predicts therefore a narrow dip in the forward direction, rather than the observed spike. Taking into account also the u-channel π^0 exchange gives the correct cross-section value at $t = 0$, but still fails to reproduce the measured t-dependence [5]. Agreement with the data can be obtained only assuming destructive interference between the pion- and some 'background'- term [6]. At low energy this 'background' amplitude arises naturally when subtracting the δ-function which is present in the central part of the Yukawa potential. The subtraction of this unphysical term allows to obtain excellent agreement with the data, as can be seen in fig. 1b, where the data are compared with the potential model calculation of the Paris group [7]. Several mechanisms, like the no-exchange model [8], have been proposed to motivate the subtraction of the δ-function. Recently it has been suggested that the subtraction is obtained quite naturally when correcting the OPE potential at short distances to take into account the finite size of the pion [9]. At high energy an intensive theoretical effort was dedicated in the past to the understanding of this puzzle, and several ad-hoc recipes (like conspiracy [10], or the 'poor man absorption' [11]) have been proposed. Although this problem by now is well understood, it is fair to say that a simple explanation of why the Born approximation fails to give the shape of the differential cross-section of the np $\rightarrow$ pn reaction is still lacking [12].

For these reasons we believe that the cleanest way to show up the presence of the pion pole in the scattering amplitude is the extrapolation procedure which was suggested already in 1958 by G. F. Chew [13] as a way for determining the pion-nucleon coupling constant. If in the t-interval under consideration the pion propagator is the only singularity of the scattering amplitude, by multiplying the differential cross-section by the square of the denominator of the pole term $x = m_\pi^2 - t$ one expects to obtain a smooth function of x

$$\left(m_\pi^2 - t\right)^2 \cdot \frac{d\sigma}{d\Omega} = \frac{\left(g_c^2 \cdot m_\pi^2\right)^2}{s} \cdot F(x) = \frac{\left(g_c^2 \cdot m_\pi^2\right)^2}{s} \cdot \left[a_0 + a_1 x + a_2 x^2 + a_3 x^3 + ...\right]$$

which, when extrapolated in the unphysical region to the pole position $t = m_\pi^2$, should provide the value of the coupling constant.

The quantities

$$y = \frac{s \cdot x^2}{m_\pi^4 \cdot g_c^4} \cdot \frac{d\sigma}{d\Omega}$$

are plotted as a function of x in fig. 2 for the $\bar{\text{p}}\text{p} \rightarrow \bar{\text{n}}\text{n}$ measured data at 601 MeV/c. The data at 1202 MeV/c have a very similar behavior, but have not been plotted because they fall largely on top of the ones at 601 MeV/c. For comparison we show in the same figure the same quantity for the line-reversed reaction np $\rightarrow$ pn, using precise data recently measured in this energy region, at 435 MeV/c [14], and at 1040 MeV/c [15] incident neutron momentum. We have divided by g_c^4 (assuming $g_c^2 = 13.6$, a presently agreed upon value) so that the plotted quantities should extrapolate to one at the position of the pole. Also shown in the figures are the lower order polynomial fits which best reproduce the data. The leading term of the fitted functions is parabolic, which is what one expects by assuming only the pion term in the scattering amplitude, interfering with a constant background.

It is a most remarkable fact that within errors the $\bar{\text{p}}\text{p} \rightarrow \bar{\text{n}}\text{n}$ data nicely extrapolate to the same value as the np $\rightarrow$ pn data. This means that pion exchange is a real dynamical mechanism in $\bar{\text{N}}$N physics much in the same way as it dominates the NN interaction, and it is not masked by the annihilation process. In this sense the use of π-exchange as a tool to probe the $\bar{\text{N}}$N force seems to be quite plausible, and the perspectives for measuring the long and medium-distance behavior of the $\bar{\mathrm{N}}\mathrm{N}$ meson exchange potential, and testing its physical interpretation and the G-parity rule, look promising. The fact that the data points extrapolate to the same value is also a nice confirmation of the charge conjugation independence, i.e. that the pion is coupled with the same strength to nucleons and antinucleons.

These facts clearly do not come as a surprise. The exchange of pions has always been regarded as an essential ingredient to understand the $\bar{\mathrm{N}}\mathrm{N}$ data, starting from the very early ones, i.e. the very large cross-section values as compared with those of the NN system [16]. The fact that the pionic charge of an antinucleon should be -g, and that in general from any NN meson exchange potential one can derive a corresponding $\bar{\mathrm{N}}\mathrm{N}$ potential, are clearly generally accepted, and supported by all the data which have been accumulated over the past forty years. Thus we regard fig. 2 just as a nice confirmation of our theoretical ideas and of the simplicity of physical laws. What can be considered as a nice surprise is the smooth behavior of the quantity $x^2 \cdot d\sigma/d\Omega$: the shape of the differential cross-section is very different for the $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ and $\mathrm{np} \to \mathrm{pn}$ reaction, but these differences are much less important when considering the Chew's function.

The procedure suggested by Chew has been applied successfully in the past [17] to the $\mathrm{np} \to \mathrm{pn}$ data providing fairly accurate values for the coupling constant. Other more precise methods have been implemented successively, which use dispersion relations or phase-shift analysis either of NN or of πN data, but with the advent of new precise $d\sigma/d\Omega$ data in the $\mathrm{np} \to \mathrm{pn}$ reaction very likely this reaction will again become competitive with the other methods [18]. Given the interest of knowing precisely the value of the πNN coupling constant and the recent debate stimulated by the Nijmegen group [19], which challenged the generally accepted value of $f_c^2 = 0.079$, in a separate paper [20] we describe a determination of f_c^2 which relies on the extrapolation to the pole of our $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ data.

This work stems out of a large experimental effort we have undertaken over the past ten years to study the $\bar{\mathrm{N}}\mathrm{N}$ force and we are grateful to all the members of the PS199 and PS206 collaborations, and in particular to the great enthusiasm and dedication of R. Hess. We are deeply indebted to T. E. O. Ericson, J. M. Richard and I. Shapiro for their continuous encouragement, support and enlightening discussions.

References

[1] W. Weise, *Nucl. Phys.* **A434** (1985) 685; see also T. E. O. Ericson and W. Weise, 'Pions and Nuclei', Clarendon, Oxford (1988).

[2] Y. Nambu and G. Jona-Lasinio, *Phys. Rev.* **122** (1961) 345, *Phys. Rev.* **124** (1961) 246.

[3] R. Birsa et al., 'High-precision measurement of the $\bar{\mathrm{p}}\mathrm{p} \to \bar{\mathrm{n}}\mathrm{n}$ charge-exchange differential cross-section', CERN-PPE/94-156, accepted for publication on Physics Letters.

[4] W. Hürster et al., *Phys. Lett.* **90B** (1980) 367.

[5] P. Finkler, *Phys. Rev.* **D2** (1970) 173.

[6] R. J. N. Phillips, *Phys. Lett.* **4** (1963) 19.

[7] M. Lacombe et al., *Phys. Rev.* **C23** (1981) 2405.

[8] W. M. Alberico and A. Gerstan, CERN report TH 3730-CERN, September 1983, unpublished.

[9] W. R. Gibbs and B. Loiseau, 'Neutron-proton Charge Exchange', INPO/TH 94-71, September 1994, to be published on Phys. Rev. C.
[10] D. V. Volkov and V. N. Gribov, *Sov. Phys. JETP* **17** (1963) 720; R. J. N. Phillips, *Nucl. Phys.* **B2** (1967) 394.
[11] P. K. Williams, *Phys. Rev.* **181** (1969) 1963.
[12] T. E. O. Ericson, Proceedings of the Internation School of Nuclear Physics, 'Mesons, Isobars, Quarks and Nuclear Excitations', Erice, 1983, April 6-18; edited by D. Wilkinson, p.245.
[13] G. F. Chew, *Phys. Rev.* **112** (1958) 1380.
[14] T. Rönnqvist et al., *Phys. Rev.* **C45** (1992) 496.
[15] L. C. Northcliffe et al., *Phys. Rev.* **C47** (1993) 36.
[16] J. S. Ball and G. F. Chew, *Phys. Rev.* **109** (1958) 1385.
[17] A. Ashmore et al., *Nucl. Phys* **36** (1962) 258.
[18] private communication from T. E. O. Ericson.
[19] R. A. M. Klomp et al., *Phys. Rev.* **C44** (1991) 1258, and references therein.
[20] F. Bradamante et al.,'Determination of the charged pion-nucleon coupling constant from $\bar{p}p \to \bar{n}n$ differential cross-section', accepted for publication on Physics Letters.

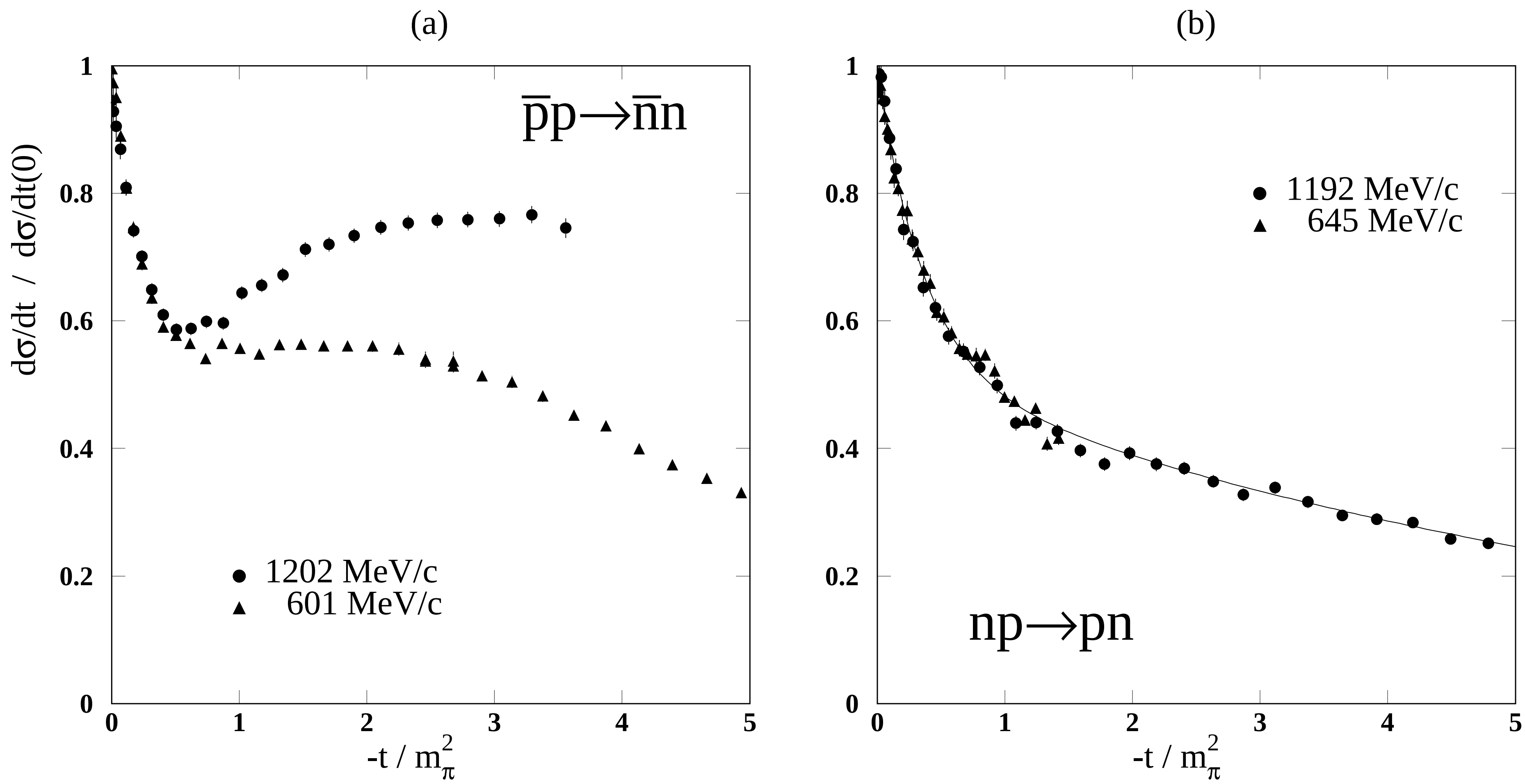

Figure 1: Ratio between the measured $\bar{p}p \to \bar{n}n$ differential cross-section data at LEAR [3] and their value at $t = 0$ (a). Ratio between the measured $np \to pn$ differential cross-section data at PSI [4] and their value at $t = 0$; the full curve is a calculation which uses the Paris potential [7] (b).

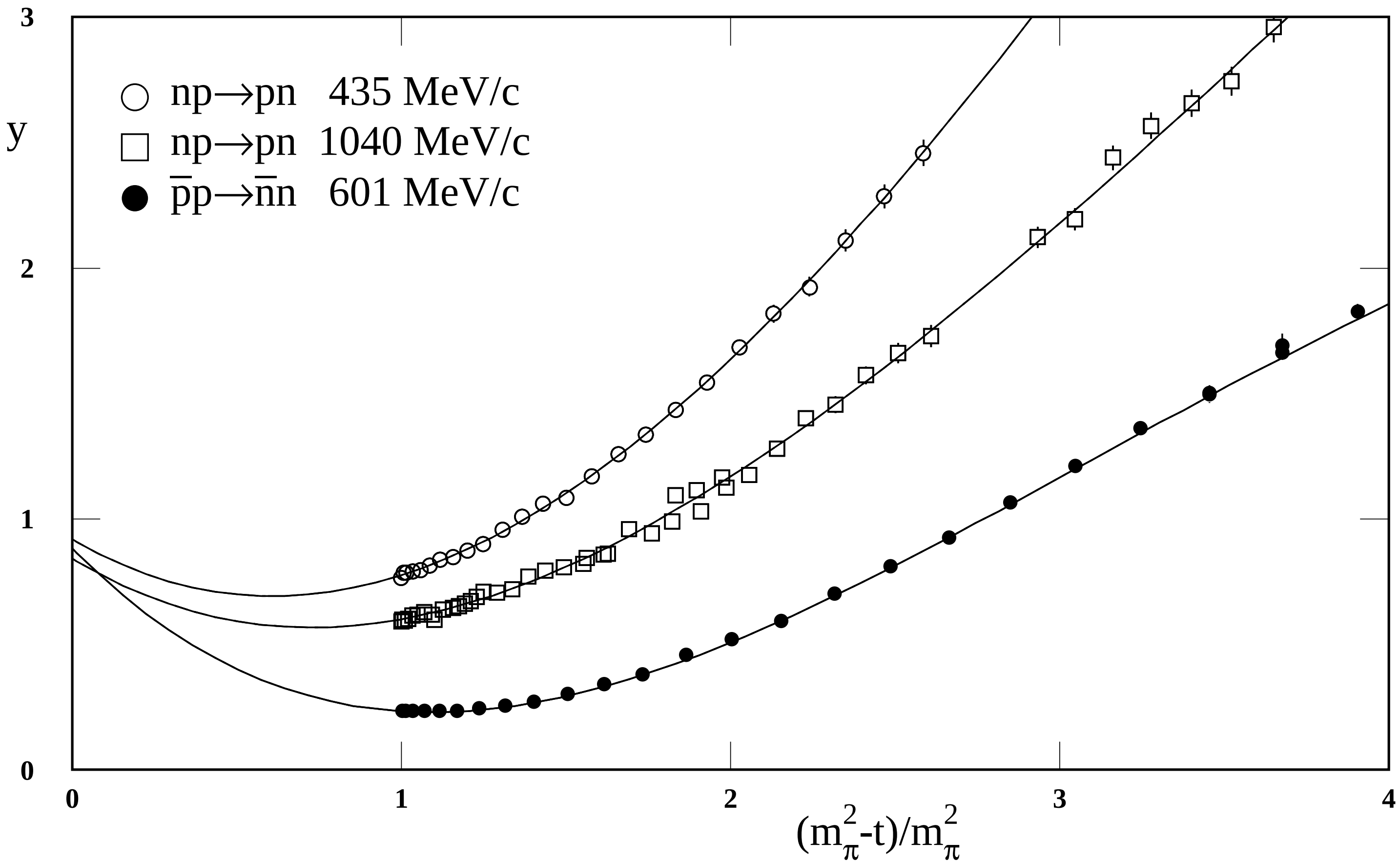

Figure 2: Plots of $y \propto (m_\pi^2 - t)^2 d\sigma/d\Omega$ vs $(m_\pi^2 - t)/m_\pi^2$. Also shown are some polynomial fits to the data. The normalization constants have been so chosen that a value of one for the extrapolation at zero corresponds to $g_c^2 = 13.6$. Both $\bar{p}p \to \bar{n}n$ and the $np \to pn$ data show a similar behaviour, and extrapolate to the same value at the pion pole.