Proton-helium elastic scattering: a possible high-energy polarimeter at RHIC-BNL

C. Bourrely and J. Soffer

Centre de Physique Théorique - CNRS - Luminy,
Case 907 F-13288 Marseille Cedex 9 - France

Abstract

We examine a suggestion to use p-\(^4\)He elastic scattering, as an absolute polarimeter for high-energy polarized proton beams, by means of a Coulomb-Nuclear Interference effect for the single-spin asymmetry \(A_N(t)\), around the diffractive minimum of the differential cross section |\(t| \sim 0.21\text{GeV}^2\). Although this reaction has a fairly simple dynamical structure, our theoretical uncertainties and the present experimental inaccuracy of the differential cross section in this \(t\) region, allows one to generate dramatic effects for \(A_N(t)\), which will be discussed.

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High-energy polarized proton beams are under construction at RHIC – BNL and thanks to the so-called Siberian snake technique, the beam polarization is expected to reach the value $P = 70\%$ and to be maintained at this impressive high level. This is one of the key elements supporting the vast spin phenomena programme for $pp$ collisions, which will be undertaken in the near future [1]. It has also motivated some detailed studies at DESY in order to decide whether or not HERA could operate as a $ep$ collider with both electron and proton beams polarized [2]. However, one should have a reliable method for measuring $P$ and the primary goal would be to achieve an accuracy of 5\% or better, i.e. $\Delta P/P \leq 0.05$. This important calibration problem has given rise recently to some activity, several methods have been proposed and their limitations have been discussed [3]. In particular, one interesting candidate is the so-called Coulomb-Nuclear Interference (CNI) polarimeter relying on an idea, first suggested by Schwinger [4]. If we consider $pp$ elastic scattering near the forward direction, say for $|t| \sim 10^{-3}\text{GeV}^2$, the single-spin asymmetry $A_N(t)$ arises primarily from the interference between the real electromagnetic helicity-flip amplitude and the imaginary hadronic helicity-nonflip amplitude. It can be calculated exactly [5, 6] and one finds that it has a maximum value of about 4\% for $|t| \sim 3.10^{-3}\text{GeV}^2$, which is almost energy independent. This effect has been investigated by the E-704 experiment at FNAL at $p_{lab} = 200\text{GeV}/c$ [7] and the results are consistent with the theoretical prediction. However, the situation is not as simple as that, because the hadronic interaction need not conserve helicity in the small $t$ region and the existence of a non-zero single-flip hadronic amplitude introduces a substantial uncertainty on the predicted asymmetry [8, 9, 10]. Unfortunately, the lack of accuracy in the E-704 experiment leaves too much freedom on the size of the single-flip hadronic amplitude and as a result, given the present data, the CNI polarimeter is not a method which can achieve the desired 5\% beam polarization error goal.

Another polarimetry method which involves $p-^{4}\text{He}$ elastic scattering has been first briefly suggested in Ref. [3] and we think it deserves a careful phenomenological analysis, which is presented in this paper. Since $^{4}\text{He}$ is a spinless object, $p-^{4}\text{He}$ elastic scattering is a simple reaction which is described in terms of two helicity amplitudes, the nonflip $\phi_{+}(t)$ and the flip $\phi_{-}(t)$. The differential cross section reads

$$\frac{d\sigma(t)}{dt} = |\phi_{+}(t)|^2 + |\phi_{-}(t)|^2$$

and the single-spin asymmetry is

$$A_N(t) = \frac{2Im[\phi_{+}(t)\phi_{-}(t)^{*}]}{[\phi_{+}(t)]^2 + [\phi_{-}(t)]^2}.$$  \hfill (2)

$\phi_{+}$ and $\phi_{-}$ are written in terms of hadronic and electromagnetic amplitudes in the form

$$\phi_{\pm}(t) = \phi_{\pm}^{h}(t) + e^{i\delta}\phi_{\pm}^{e}(t),$$

where $\delta$ is the Coulomb phase shift. We have

$$\phi_{+}^{e}(t) = -\frac{4\alpha\sqrt{\pi}}{|t|}G_{p}(t)G_{He}(t),$$

where $\alpha$ is the fine-structure constant, $G_{p}(t)$ is the proton electromagnetic form factor $G_{p}(t) = 1/(1 + |t|/0.71)^2$ and $G_{He}(t) = [1 - (2.56t)^6]e^{11.70t}$ is the $^{4}\text{He}$ electromagnetic form factor [11]. Similarly we have

$$\phi_{-}^{e}(t) = \sqrt{|t|} \frac{\mu_{p} - 1}{2m_{p}}\phi_{+}^{e}(t),$$

\hfill (4)
where $\mu_p$ is the magnetic moment of the proton and $m_p$ its mass.

Our theoretical knowledge of $\phi^h_\pm(t)$ is less straightforward, but before going into this discussion, let us briefly review the experimental situation. At low energies, say, $1.1 \leq p_{lab} \leq 2.5 GeV/c$, the differential cross section and the single-spin asymmetry have been accurately measured at the ZGS-Argonne [12], using polarized proton beams. The cross section has a diffractive minimum around $|t| = 0.21 GeV^2$ and $A_N(t)$, which is large (40-50%), exhibits also an interesting behavior in the dip region. At higher energies, say, $45 \leq p_{lab} \leq 400 GeV/c$, only $d\sigma/dt$ has been measured [13], and the diffractive minimum remains essentially at the same $t$ value (see Fig. 1).

Since we are concerned by the proton beams at RHIC – BNL, whose momentum lie between 50$GeV/c$ and 250$GeV/c$, we will concentrate on the high-energy data. Several analysis of these data have been made in the past based on, for example, a Chou-Yang type model [14] or a Glauber model [13], but here we will present a rather simple phenomenological model. A Regge exchange approach is greatly simplified by the fact that, since $^4$He is an isoscalar, the isovector "$\rho$ exchange", which has a large flip coupling, is forbidden. Moreover only isoscalar trajectories can be exchanged. They contribute mainly to the non-flip amplitude $\phi_+(t)$ and the Pomeron prevails at very high-energy. Consequently, one can assume the dominance of a purely diffractive Pomeron of the form $Ae^{Bt}$, at fixed high-energy [1]. Therefore, as a first approximation, we take the simple parametrization

$$Im\phi^h_+(t) = Ae^{Bt} - Ce^{Dt},$$

(5)

where the second term stands for rescattering effects, so we expect $C \ll A$ and $D \ll B$. For the moment we neglect $Re\phi^h_+(t)$ and $\phi^h_-(t)$, but we will come back to them later. The fit of the cross section data at $E_{lab} = 393 GeV$, shown in Figs. 1-2 is excellent and leads to the following values of the parameters

$$A = 31.84\sqrt{mb/GeV}, \quad B = 15.51 GeV^{-2}, \quad C = 3.69\sqrt{mb/GeV}, \quad D = 5.68 GeV^{-2}.$$ 

(6)

We have also well fitted the total cross section $p-^4$He value, namely $\sigma_{tot} = (125.9 \pm 0.6)mb$. Note that in this case, $Im\phi^h_+(t)$ changes sign at $|t| = 0.219 GeV^2$, so we find a very deep diffractive minimum, namely $d\sigma/dt = 5.10^{-5}mb/GeV^2$ at this $|t|$ value, which is due to the contributions of $\phi^h_\pm(t)$. Although the data are not very accurate in this region, it would be surprising to get such a small cross section, but one cannot rule out such a possibility [2]. If we now calculate $A_N(t)$, it is driven by the product $Im\phi^h_+(t) \cdot \phi^e_-(t)$ and the result is depicted by the solid line in Fig. 3. In the very small $|t|$ region we check that we have the usual CNI effect at the level of 4% or so, and in the vicinity of the dip, we find a strong oscillation between $+35\%$ and $-35\%$, which is better displayed in Fig. 4.

As already mentioned above, there is no fundamental theoretical reason to believe that $\phi^h_-(t) = 0$, even in a dynamical framework where the Pomeron dominates. This

1The energy dependence and the phase of the Pomeron, which have been obtained in a very successful analysis of $pp$ and $\bar{p}p$ elastic scattering [13], could be also used here, but it goes beyond the scope of this paper.

2Assuming a conservative $^4$He jet density and a realistic proton beam intensity, the luminosity is expected to be high enough, to allow such a measurement with a reasonable accuracy (W.Guryn, private communication).
important issue of the size of the Pomeron flip coupling has been studied in details \[16, 17\] and if we take, in analogy with Eq. (4),

\[ Im\phi^h_-(t) = r \frac{\sqrt{|t|}}{m_p} Im\phi^h_+(t) , \] (7)

one finds from different arguments a value of \( r \) of 10% or below. We have also included such a contribution in our fit of \( d\sigma/dt \) and the best fit leads to \( r = 0.25 \), with almost no changes in A, B, C and D. This new contribution fills up the dip in the cross section, as show in Fig. 2 (dotted line) and we see in Figs. 3-4 that the strong oscillation of \( A_N(t) \) is now replaced by a smooth curve with a maximum value of 13% or so, in the dip region.

This situation is somehow oversimplified because, so far, we have neglected the fact that from the data \[13\], one can extract \( \rho \), the ratio of the real to the imaginary part of the forward scattering amplitude and they find \( \rho = +0.102 \pm 0.035 \). Therefore it is clear that we should take \( Re\phi^h_+(0) \neq 0 \). We don’t know the \( t \)-dependence of \( Re\phi^h_+(t) \) but for simplicity we will assume it has the slope \( B \) of the leading term of \( Im\phi^h_+(t) \). So if we now take

\[ Re\phi^h_+(t) = E e^{Bt} , \] (8)

the best fit leads to \( E = 3.09 \sqrt{mb}/GeV \). The net effect of this real part is also to fill up the dip, as show in Fig. 3. We have first considered the case where \( r = 0 \) (small dashed curve) and a second case with \( r \neq 0 \), which was fitted and led to \( r = 0.15 \) (dotted-dashed curve). This value is much smaller than that found above, in the absence of \( Re\phi^h_+(t) \). These two cases correspond to very different predictions for \( A_N(t) \) as shown in Figs. 3-4. In the first case \( A_N(t) \) is a smooth curve (small dashed line) which changes sign at the dip position and in the second case it is very large and reaches almost -100%. This effect is entirely due to the product of \( Re\phi^h_+(t) \) and \( Im\phi^h_+(t) \), which dominate and become almost equal in magnitude at the dip position. Since the sign of \( Im\phi^h_+(t) \) is unknown, by changing this sign one can have the mirror effect. In this case, it is no longer a CNI effect.

Finally, one can envisage another realistic situation, where \( Re\phi^h_+(t) \) has not the same \( t \)-dependence as \( Im\phi^h_+(t) \). This is the case in various models and in particular in Ref. \[15\], where the real part decreases faster than the imaginary part. So we have used again eq.(8) with a larger value of the slope, that is \( B = 20 GeV^{-2} \), and \( r = 0.15 \). The results are shown in Figs. 3-4-5 by the large dashed lines. As expected, the filling of the dip is less pronounced than with the previous value \( B = 15.51 GeV^{-2} \). The shape of \( A_N(t) \) is not affected, but its magnitude is reduced accordingly.

To summarize, this phenomenological study of \( p-d \) elastic scattering, shows that this simple reaction cannot be easily used as an absolute polarimeter. An accurate measurement of \( d\sigma/dt \) in the dip region, might help us to pin down the value of \( Re\phi^h_+(t) \), but in order to clearly disentangle its effect, on the filling of the dip, from that of \( Im\phi^h_+(t) \), one certainly needs a direct measurement of \( A_N(t) \), which hopefully, will have large values in the dip region.

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References

[1] Proceedings of the Workshop *RHIC Spin Physics*, Riken BNL Research Center, April 27-29 (1998) (vol.7, Ed. T.D. Lee) report BNL-65615 and references therein.

[2] Proceedings of the Workshop *Deep Inelastic Scattering off Polarized Targets:Theory meets Experiment*, DESY-Zeuthen, September 1-5 (1997) (Eds. J. Blümlein, A. De Roeck, T. Gehrmann and W.-D. Nowak) report DESY 97-200 and references therein.

[3] B.Z. Kopeliovich, High-Energy Polarimetry at RHIC, [hep-ph/9801414](https://arxiv.org/abs/hep-ph/9801414).

[4] J. Schwinger, Phys. Rev. **73**, 407 (1948).

[5] B.Z. Kopeliovich and I.I. Lapidus, Sov.J.Nucl. Phys. **19**, 114 (1974).

[6] N.H. Buttimore, E. Gotsman and E. Leader, Phys. Rev. **D18**, 694 (1978).

[7] N. Akchurin *et al.*, Phys. Lett. **229B**, 299 (1989); Phys. Rev. **D48**, 3026 (1993).

[8] B.Z. Kopeliovich and B.G. Zakharov, Phys. Lett. **226**, 156 (1989).

[9] L.T. Trueman, preprint BNL-63700, [hep-ph/9610429](https://arxiv.org/abs/hep-ph/9610429).

[10] C. Bourrely and J. Soffer, Proceedings of the ”12th Int. Symp. on High-energy Spin Physics”, Amsterdam Sept.10-14 (1996), World Scientific (1997) p.825 (Eds. C.W. de Jager *et al.*).

[11] J.S. McCarthy *et al.*, Phys. Rev. **C15**, 1396 (1977).

[12] R. Klem *et al.*, Phys. Rev. Lett. **22**,1272 (1977); Phys. Lett. **70B**, 155 (1977).

[13] A. Bujak *et al.*, Phys. Rev. **D23**, 1895 (1981).

[14] R.J. Lombard and A. Tellez-Arenas, Phys. Lett. **165B**, 205 (1985).

[15] C. Bourrely, J. Soffer and T.T. Wu, Proceedings of the VIth Blois Workshop, Blois, 20-24 June 1995, Editions Frontières 1996, p.15 and references therein.

[16] Proceedings of the Workshop *Hadron Spin-Flip at RHIC Energies*, Riken BNL Research Center, July 21-August 22 (1997) (vol.3, Ed. T.D. Lee) report BNL-64724 and references therein.

[17] N.H. Buttimore, B.Z. Kopeliovich, E. Leader, J. Soffer and L.T. Trueman, preprint CPT-98/P.3693 (in preparation).
Figure 1: Differential cross section for p-^{4}He at $E_{\text{lab}} = 393\text{ GeV}$ as a function of $|t|$. Data are from Ref. [13]. The solid line is the result of our fit using eqs. (5) and (6).
Figure 2: Enlarged dip region of Fig. 1, showing different possibilities described in the text.

$E_{\text{lab}} = 393$ GeV
Figure 3: Single-spin asymmetry $A_N(t)$ for p-$^4$He at $E_{lab} = 393$ GeV as a function of $|t|$, showing different predictions explained in the text.
Figure 4: Enlarged dip region of Fig. 3.