PROTON SPIN-SPIN ASYMMETRIES FOR LARGE ANGLE ELECTRON-PROTON ELASTIC SCATTERING

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PROTON SPIN-SPIN ASYMMETRIES FOR LARGE ANGLE ELECTRON-PROTON ELASTIC SCATTERING

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Résumé : Nous considérons un modèle que nous avons développé précédemment pour décrire les asymétries spin-spin dans la diffusion p-p à grands angles et nous l'appliquons pour prédire les asymétries spin-spin du proton dans la diffusion e-p. Nos résultats diffèrent de ceux attendus dans le schéma de la QCD perturbative. La mesure des asymétries de spin fournirait une mesure directe des deux facteurs de forme élastiques du proton et un test clair des différents mécanismes. Nous commentons d'autres effets de spin.

Abstract - We consider a model previously developed to describe spin-spin asymmetries in proton-proton large angle elastic scattering and apply it to predict proton spin-spin asymmetries in electron-proton elastic scattering. Our results differ from those commonly expected in a perturbative QCD scheme. The measurement of the spin asymmetries would provide a direct measurement of the two proton elastic form factors and a clean further test of different mechanisms. We comment on some other spin effects

I am going to report on the results of some work recently done in collaboration with E. Predazzi.(1)

A few years ago many theoretical models(2)-(9) tried to explain some striking experimental data(10) on the spin-spin asymmetry A_{NN}, in large angle elastic proton-proton scattering, in terms of quark-quark hard scattering.

In particular, application of perturbative QCD to large P_T exclusive reactions was widely discussed. The most general, QCD inspired, scheme is that of Ref. (11).

It gives qualitatively correct predictions for the Q^2 dependence of the hadronic form factors and the fixed angle elastic cross-sections. It also leads to the helicity sum rule according to which in any large Q^2 exclusive reaction $AB \to CD$ which can be described in its scheme, the sum of the initial helicities must equal (in the limit in which we neglect the masses of the quarks compared to their energies) the sum of the final ones:

$$(1) \qquad \lambda_A+\lambda_B = \lambda_C+\lambda_D.$$

The helicity sum rule has immediate consequences for many spin observables. In particular it requires the proton-proton double helicity flip amplitude $\Phi_2 = \langle ++|\Phi|--\rangle$ and the single helicity flip one $\Phi_5 = \langle ++|\Phi|+-\rangle$ to be zero. This implies that the longitudinal spin-spin asymmetry A_{LL} must be related to the transverse one A_{NN}, at $\theta = \frac{\pi}{2}$, by

$$(2) \qquad 2A_{NN}(\tfrac{\pi}{2})-A_{LL}(\tfrac{\pi}{2}) = 1.$$

It also implies(12) that the large angle proton polarization must be zero.

Recent measurements of both A_{LL}(13) at $\theta = \frac{\pi}{2}$ and the proton polarization at large P_T(14), contradict the previous conclusions . Moreover, also the preliminary re-

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sults on the measurement of the helicity density matrix element ρ_{1-1} of the ρ vector meson produced at large P_T in the process $\pi^+p \to \rho^+p$ [15], seem to contradict the scheme of Ref. (11): in fact the indication of a large value of ρ_{1-1} again violates the helicity sum rules which forces ρ_{1-1} to be zero.

These experimental results seem to be an indication that, at least when large P_T values are involved, the simple way of computing the hadron helicities by summing the helicities of the quarks, which, through the helicity conserving elementary hard scattering, are always parallel to the hadron direction, may not be satisfactory. The recombination of the scattered quarks or, in other words, the role of the hadronic wave function, may be important in giving spin effects other than those given by the QCD elementary quark interactions.

In the model of Ref. (9) I described the spin-spin asymmetries in p-p large angle elastic scattering essentially taking into account, when computing the proton helicities in terms of the quark ones, the fact that in such reactions we always have some partonic configurations with one of the quarks at a large angle to the other quarks. This implies that we cannot simply sum the quark helicities in order to get the proton ones, but we have to properly compute the quark and proton spin projections in different directions.

This model seems to be the only one which describes well the experimental results on A_{NN} and A_{LL} [13]; though I have not computed its prediction for the helicity density matrix ρ_{1-1} (ρ^+) in the process $\pi^+p\to\rho^+p$ [15], there is no need in its scheme for ρ_{1-1} to be zero; the value of the proton polarization at large P_T, instead, is predicted to be zero, and I will make some comments on that at the end of my talk.

Since the main effects of the model of Ref. (9) come from the different spin recombination mechanism rather than the quark elementary interactions, it seems important to further test its validity by applying it to another reaction.

In Ref. (1) we used the model of Ref. (9) to describe the proton spin-spin asymmetries in large angle electron-proton elastic interactions. Again, we found some qualitative results which differ from the common expectations, thus offering a clear possibility of further testing the main idea of the model.

The helicity amplitudes for the $pe^- \to pe^-$ elastic scattering in the Center of Mass system (C.M., see Fig. 1 for the definition of the kinematics) are given by

$$(3) \qquad M_{\lambda'\nu';\lambda\nu}(\theta) = \frac{-1}{q^2}\,\bar{u}_{\lambda'}(p')\,\Gamma_\mu u_\lambda(p)\,\bar{u}_{\nu'}(k')\,\gamma^\mu u_\nu(k)$$

where $\lambda,\nu(\lambda',\nu')$ denote respectively the initial (final) helicities of the proton and the electron. As usual, Γ_μ is the most general form of the proton vertex allowed by parity conservation and time reversal invariance

$$(4) \qquad \Gamma_\mu = F_1(q^2)\gamma_\mu + \frac{\kappa}{2m}F_2(q^2)\,i\sigma_{\mu\nu}q^\nu,$$

where κ is the anomalous magnetic moment of the proton measured in Bohr magnetons, $\kappa = 1.79$, and m is the proton mass.

From eqs. (3) and (4) we have, neglecting the electron and proton masses compared to their C.M. energies, the 3 independent amplitudes:

$$(5) \quad \begin{cases} M_{++;++} = M_{--;--} = \dfrac{-4E^2}{q^2}\,2F_1 \\ M_{+-;+-} = M_{-+;-+} = \dfrac{-4E^2}{q^2}(1+\cos\theta)\,F_1 \\ M_{-+;++} = M_{--;+-} = -M_{+-;--} = -M_{++;-+} = \dfrac{-4E^2}{q^2}\,2E\sin\theta\,\dfrac{\kappa}{2m}F_2 \end{cases}$$

The spin-spin asymmetries corresponding to different polarization states of the initial and final protons can be written in terms of the amplitudes (5). For longitudinally polarized protons (helicity states) we have, with obvious notations

$$(6)\qquad D_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)} = \frac{|M_{++;++}|^2+|M_{+-;+-}|^2 - 2|M_{++;-+}|^2}{|M_{++;++}|^2+|M_{+-;+-}|^2 + 2|M_{++;-+}|^2} .$$

For protons with spin projection $\pm\frac{1}{2}$ along the y direction (that is perpendicular to the scattering plane) we have:

$$(7)\qquad D_{NN} = \frac{\sigma(N_+N_+) - \sigma(N_+N_-)}{\sigma(N_+N_+) + \sigma(N_+N_-)} = \frac{2M_{++;++}M_{+-;+-}+2|M_{++;-+}|^2}{|M_{++;++}|^2+|M_{+-;+-}|^2+2|M_{++;-+}|^2}$$

and for protons polarized in the scattering plane perpendicularly to their direction of motion:

$$(8)\qquad D_{SS} = \frac{\sigma(S_+S_+) - \sigma(S_+S_-)}{\sigma(S_+S_+) + \sigma(S_+S_-)} = \frac{2M_{++;++}M_{+-;+-}-2|M_{++;-+}|^2}{|M_{++;++}|^2+|M_{+-;+-}|^2+2|M_{++;-+}|^2} .$$

The denominator of eqs. (6)-(8) is proportional to the unpolarized cross-section, $d\sigma/dq^2 = \frac{1}{4}\frac{\pi\alpha^2}{s^2}\sum_{\lambda\nu;\lambda'\nu'}|M_{\lambda'\nu';\lambda\nu}|^2$. Notice also that, by proper combination of the spin-spin asymmetries, we have a possible way of measuring separately the proton form factors F_1 and F_2.

In the scheme of Ref. (11) the proton helicity flip amplitude $M_{++;-+}$ is forced to be zero by the helicity sum rule (1) (in the limit in which we neglect the quark masses compared to their energies). In such a case we have, from eqs. (5)-(8), the simple large Q^2 predictions:

$$(9)\qquad \begin{cases} D_{LL} = 1 \\ D_{NN} = D_{SS} = \dfrac{4(1+\cos\theta)}{4+(1+\cos\theta)} \end{cases} .$$

The measurement of the spin-spin asymmetries (6)-(8) would then constitute a further crucial test of the Brodsky-Lepage mechanism.

The main points of the model of Ref. (9) can be seen from Figure 2. During the high energy Center of Mass interaction between the proton and the electron, one quark of the proton is freely scattered by the electron via one photon exchange; the final proton configuration is one in which the scattered quark is at a very large angle α and has a high transverse momentum with respect to the other spectator quarks.

The p-e scattering amplitude corresponding to the configuration of Figure 2 can be written, in terms of the elementary amplitude $\hat{M}$ and the proton wave function ψ, as (dropping for the moment all the spin indices)

$$(10)\qquad M(\theta)\sim \sum\!\!\!\!\!\!\int dx\,\psi\,(x)\,\hat{M}\,(\alpha(\theta,x))\,\psi^*\,(x'(\theta,x);\,\vec{k}'_T(\theta,x)),$$

where the sum and integration are over all the allowed quark and kinematical configurations and where(9)

$$(11)\qquad \cos\alpha = \frac{\cos\theta + (1-x)}{\sqrt{1+(1-x)^2 - 2(1-x)\cos\theta}} .$$

x is the fraction of longitudinal momentum carried by q_1; the fraction of longi tudinal momentum and the transverse momentum, with respect to the final proton p', carried by q_1' are given by

$$(12)\qquad \begin{cases} x' = 1 - (1-x)\cos\theta \\ |k_T'| = (1-x)\,|\vec{p}|\,\sin\theta. \end{cases}$$

One has to stress at this point that, for all models like ours, the validity of using the parton model picture to describe exclusive reactions in terms of the elementary scattering of two free quarks (or one quark and one electron), taken to be on their mass-shell, is far from being clear; the non perturbative confinement into the final hadron obviously prevents the scattered quark (q_1') from being free and on its mass shell (unless we consider the limit $x \to 1$[16]).

We do not know how much this approximation could affect our results: that would require a complete knowledge of the relativistic proton wave function in terms of quark masses, spins and relative motion. However, we think that, despite the inevitable approximations, our model is correct in assuming, in all these large angle exclusive reactions, the contribution from parton configurations containing quarks with a large intrinsic transverse momentum; this is essentially what makes the difference with the other models.

As we did in Ref. (9) we consider here only the spin analysis of the p-e process; the full computation of the energy and P_T dependence of the elastic cross-section would require the complete knowledge of the proton wave function. Though we could try to give some estimates by using phenomenological k_T and x dependence in $\psi(x, k_T)$, we prefer to discuss here only the spin-spin asymmetries; when computing the ratios giving such asymmetries, in fact, we can expect the energy dependence to cancel out.

Referring again to the case of Fig. 2, it is convenient to compute the scattering amplitudes in two different steps. First we describe the final proton spin state by quantizing it along the z direction (canonical spin state). We assume the spin state of the proton in terms of the quarks to be described by SU(6) wave functions, with the proton and the quark spins quantized along the z direction. The spectator quark spin states thus coincide with helicity states whereas for the scattered quark q_1' its canonical spin state is a mixture of $|+\rangle$ and $|-\rangle$ helicity states:

$$(13)\quad \begin{cases} |q_1', s_z = \frac{1}{2}\rangle = \cos\frac{\alpha}{2}\,|+\rangle - \sin\frac{\alpha}{2}\,|-\rangle \\ |q_1', s_z = -\frac{1}{2}\rangle = \sin\frac{\alpha}{2}\,|+\rangle + \cos\frac{\alpha}{2}\,|-\rangle . \end{cases}$$

The second step is that of rotating the amplitudes obtained after the first step to helicity amplitudes; taking into account not only the configuration of Fig. 2, but also its "timed reversed" one, in which the initial proton has quarks with large intrinsic transverse momentum, while the final one contains only parallel quarks, we get:

$$(14)\quad \begin{cases} M_{++;++}(\theta) = M_{--;--}(\theta) \sim 2\cos\frac{\alpha-\theta}{2}\,\hat{M}_{++;++}(\alpha) \\ M_{+-;+-}(\theta) = M_{-+;-+}(\theta) \sim 2\cos\frac{\alpha-\theta}{2}\,\hat{M}_{+-;+-}(\alpha) \\ M_{-+;++}(\theta) = -M_{+-;--}(\theta) = -M_{++;-+}(\theta) = M_{--;+-}(\theta) = \\ \qquad \sim \sin\frac{\alpha-\theta}{2}(\hat{M}_{++;++}(\alpha) + \hat{M}_{+-;+-}(\alpha)) , \end{cases}$$

where all amplitudes are helicity ones.

In eqs. (14) we dropped the integration over x and the proton wave functions (see eq. (10)); this simple form corresponds to a δ-like choice of $\psi(x)$, $\psi(x) = \delta(x-x_0)$, which is what we shall use in order to give some numerical estimates for the spin-spin asymmetries. The common factor $\psi(x'(\theta,x_0), k'_T(\theta,x_0))$, which we did not write in eqs. (14), cancels out in the ratios giving the spin asymmetries, but would contribute to the cross-section and its energy dependence.

Notice that in our scheme, due to our spin recombination mechanism, the proton single helicity flip amplitudes are not zero (except in the limit $x \to 1$, $\alpha \to \theta$), but they are of the same order as the non helicity flip ones; this leads to predictions for the spin-spin asymmetries different from those obtained in the Brodsky-Lepage scheme, eqs. (9). It also leads to a different behaviour of $F_2(q^2)$ (see eqs. (5)),

$$(15) \qquad F_2(q^2) \sim \frac{m}{\sqrt{-q^2}} F_1(q^2),$$

rather than

$$(16) \qquad F_2(q^2) \sim \frac{mm_q}{(-q^2)} F_1(q^2) ,$$

as in Ref. (11).

As we already said, though we could try to fit the large Q^2 experimental behaviour of the form factors and the cross-sections by using phenomenological dependences in $\psi(x,\vec{k}_T)$, we prefer, at this stage, to give predictions for the spin-spin asymmetries.

In order to do so we need to know the elementary q-e scattering amplitudes. In the q-e center of mass system (c.m.) they are given by

$$(17) \qquad \begin{cases} \hat{M}_{++;++} \sim \dfrac{2}{1 - \cos\alpha'} \\ \hat{M}_{+-;+-} \sim \dfrac{1+\cos\alpha'}{1-\cos\alpha'} \end{cases} .$$

The elementary c.m. scattering angle α' is related to the scattering angle α in the p-e C.M. system by

$$(18) \qquad \cos\alpha' = \frac{\cos\alpha - \beta}{1 - \beta\cos\alpha'} \quad , \ \beta = \frac{x-1}{x+1}$$

so that we have

$$(19) \qquad \begin{cases} \hat{M}_{++;++}(\alpha) \sim \dfrac{(x+1) - (x-1)\cos\alpha}{x(1-\cos\alpha)} \\ \hat{M}_{+-;+-}(\alpha) \sim \dfrac{1+\cos\alpha}{x(1-\cos\alpha)} \end{cases}$$

where $\cos\alpha$ is given in terms of θ and x by eq. (11).

We are now in the position to give some qualitative predictions for the spin-spin asymmetries; we assume for simplicity a δ-shaped dependence for $\psi(x)$, $\psi(x) = \delta(x-x_o)$, with $x_o = \frac{1}{3}$. From eqs. (14), (19) and (11) (evaluated at $x = \frac{1}{3}$) we can then get numerical values for the spin-spin asymmetries (6)-(8).

In Figs. 3-5 we plot respectively D_{LL}, D_{SS} and the difference $D_{NN}-D_{SS}$ as functions of θ (solid lines); we also plot for comparison (dashed lines) the corresponding predictions of the Brodsky-Lepage scheme, eq. (9).

There is a large difference between the two sets of predictions; in particular in our model we have some clear qualitative consequences such as $D_{LL} \neq 1$ and $D_{NN} \neq D_{SS}$. The measurement of such quantities would therefore constitute a further crucial test of our mechanism and, in general, a way of better understanding the role of the proton wave function and of non perturbative effects in large angle exclusive reactions.

Existing experimental data[17] on the proton electromagnetic elastic form factors do not allow yet a clean separation between F_1 and F_2 (or G_E and G_M); as we said before, the measurement of the proton spin-spin asymmetries would give a possible way of measuring separately F_1 and F_2.

Let me conclude with some comments on the recent measurement of a large value of the polarization in the high P_T elastic scattering of protons, with $E_{Lab.}$ = 28 GeV/c, at Brookhaven.[14]

None of the existing models which try to describe p-p elastic scattering in pure terms of q-q scattering[(2)-(9), (11)], can explain such a large value; in all of them the polarization should be zero.

One has to notice, however, that for protons with a laboratory momentum of 28 GeV/c the C.M. ratio $\frac{m}{E}$ is still rather large, $\frac{m}{E} \simeq 0.26$. This might mean that the large polarization is a mass effect[(18)], which should go away at higher energy.

Again, mass effects are hidden in the unknown proton wave function and they are normally neglected in the quark models; in my model[(9)] I have taken into account some wave function effect, in the way of computing the proton helicity in terms of the quark ones, but I do not take into account any mass effect.

If mass effects are important in giving a large polarization, they might be also important when computing double spin effects, like A_{NN} and A_{LL}, measured at an even lower energy[(10), (13)].

Even if one can hope that mass effects do not affect much double spin effects (in QCD or QED we have large double spin effects but no single spin effect, even with massless quarks) such large value of the polarization might mean instead that we are not in an energy region large enough as to safely apply the parton model picture when dealing with spin effects; the wave function effects, in other words, could still be so strong as to overwhelmingly influence, independently of the underlying elementary process, the final hadronic properties.

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