SPIN EFFECTS IN LEPTON-NUCLEON REACTIONS
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Abstract

We summarize some theoretical issues, which have been considered of special importance in the discussions of the above working group session.

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1 Introduction

In this summary talk we would like to cover the following topics. First we will comment on the interpretation of new results from SLAC and SMC on measurements of the spin-dependent structure functions $g_1(x)$ with different targets. Testing the validity of sum rules is an important issue for perturbative QCD which is also related, in particular, to the determination of the value of the proton spin carried by the strange quarks $\Delta s$. There are some arguments, based on $SU(3)$ breaking effects, which introduce uncertainties, such that $\Delta s$ might turn out to be close to zero. The same conclusion can be obtained by using positivity arguments and the fact that there are very few strange quarks in the proton. Of course this is also related to the total light quark contribution to the proton spin $\Delta \Sigma$, whose value is now, more accurately known, larger than before and getting closer to the naive expectation. However one should keep in mind that all these experiments measure indeed $g_1(x)$, not its first moment, and one should, in the first place, try to understand properly the useful information contained in these $x$-distributions.

Next we will recall the importance of the other polarized structure function, so-called $g_2(x)$, its origin, its properties and what we expect to learn from its measurement which is now under way, at the very early stage. Finally, we will review briefly the spin programme which will be undertaken in a few years time at BNL, by using RHIC as a polarized proton-proton collider. We will recall the main motivations of the project and, because the center-of-mass energy will be reaching up to 500 GeV, it will be possible, for the first time, to test the spin sector of perturbative QCD. We will also indicate that it will allow to pin down, in a unique way, some polarized parton distributions which are not directly accessible in polarized deep inelastic scattering experiments.

2 Spin content of the nucleon and the $g_1(x)$ structure function

Seven years ago, the first results of the EMC at CERN\[1\] on the $g_1^p(x)$ structure function on a proton target were rather surprising, because they uncovered a very serious defect in the Ellis-Jaffe sum rule \[2\]. This defect was confirmed by recent experiments from SMC and SLAC \[3\] and has been inter-
interpreted as due to a large negative value for $\Delta s$, the contribution of the proton spin carried by the strange quarks and a small value of $\Delta \Sigma = \Delta u + \Delta d + \Delta s$, total contribution of the quark spins. Such a large negative $\Delta s$ was not found by the E142 at SLAC \[3\] in the measurement of the neutron structure function $g_1^p(x)$ directly with a polarized $He^3$ target, which gives a result consistent with $\Delta s = 0$. Of course the mean value of $Q^2$ is smaller than for the earlier EMC and the more recent SMC proton experiments, and one can be tempted to blame non-perturbative effects for the difference between the proton and the neutron cases. One more piece of data coming from SMC and SLAC on deuteron targets \[3\], leads also to a negative value for $\Delta s$. At this stage it is important to recall that the experimental determination of $\Delta s$ and $\Delta \Sigma$ relies on exact $SU(3)$ flavor symmetry which is a questionable assumption. If one ignores $SU(3)$ flavor breaking, it was shown \[1\] that there is strong correlation between $\Delta \Sigma$ and $\Delta s$, e.g. $\Delta \Sigma = 0.337 + 0.57 \Delta s$ for the proton case, which disappears when one takes into account $SU(3)$ breaking effects. In a recent work \[5\], one postulates that $F$ and $D$ parameters are related only to the valence quarks and the $SU(3)$ symmetry breaking for the decay $\Sigma^- \rightarrow n$ is realized by a suppression of the strange pair production in both $n$ and $\Sigma^-$ seas and described by one parameter $\varepsilon$. In this case one can show \[4\], by studying the dependence of $\Delta \Sigma$ and $\Delta s$ on $\varepsilon$, both for proton and deuteron, that $\Delta \Sigma$ remains around 0.3 and is almost insensitive to the value of $\varepsilon$, whereas $\Delta s$ varies strongly between $-0.1$ and $-0.02$. In a different approach \[6\] where one reanalyzes hyperon beta decay to extract the $F/D$ ratio, one is assuming that the $SU(3)$ breaking can be evaluated just in terms of mass difference of the baryons. Instead of the value $F/D = 0.575 \pm 0.016$ generally used, one finds a smaller value with a large uncertainty $F/D = 0.49 \pm 0.08$. In this case there is no violation of the proton Ellis-Jaffe sum rule and again $\Delta s$ is consistent with zero. Finally there is another independent argument for $\Delta s$ small based on positivity \[7\], namely one should have $|\Delta s(x)| \leq s(x)$ for all $x$. Using the data on $s(x)$ extracted from charm production in neutrino deep inelastic scattering, one finds that the strange quark distribution is essentially dominated by the Pomeron which goes like $1/x$ and is spin independent. As a result it follows that $\Delta s$ is consistent with zero, but perhaps this analysis should be reconsidered by using more recent CCFR data \[8\].

To conclude this discussion we think it would be extremely useful to have a
direct measurement of $\Delta s$ and any suggestion is very welcome\footnote{\textsuperscript{*}}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{Experimental test of eq.(2) (see text) taken from ref.[13]}
\end{figure}

\textsuperscript{*}$\Delta s$ can also be measured in elastic $\nu p$ scattering by separating the axial form factor contribution $G_A(Q^2)$ extrapolated to $Q^2 = 0$. The existing data \cite{2} yields a large negative $\Delta s$ with large errors which are due to several uncertainties in getting $G_A(0)$\cite{3}.
As indicated before, we believe that the $x$-dependence of the $g_1(x)$ structure functions contains relevant information which is somehow washed out when one considers only first moment sum rules[11]. Moreover testing sum rules involves necessarily some uncertain extrapolations of the data due to the limited kinematic range accessible in any experiment. We will now briefly illustrate this point as follows. The $g_1(x)$ structure functions for proton, neutron and deuteron are expressed in terms of three distributions $\Delta u(x)$, $\Delta d(x)$, $\Delta s(x)$ (here $u$ means $u + \bar{u}$ etc...). It is well known that $g_1^p(x) - g_1^n(x)$ is independent of $\Delta s(x)$ and similarly one can eliminate $\Delta d(x)$ by considering $4g_1^p(x) - g_1^n(x)$. Let us now assume $\Delta s(x) \equiv 0$ and, as explained in Ref.[12], let us postulate the following simple relation between unpolarized and polarized distributions

$$\Delta u(x) = u(x) - d(x) .$$

(1)

It implies

$$5xg_1^p(x) - 4/(2 - 3\omega_D)xg_1^d(x) = 5(F_2^p(x) - F_2^d(x))$$

(2)

a simple relationship between two $g_1$ and two unpolarized structure functions $F_2(x)$ directly measured by experiment. We have used the standard relations between deuteron, proton and neutron and for the polarized case and $\omega_D$ is the $D$-state probability in the deuteron. We show in Fig.1 an experimental test of eq.(2). We have tested eq.(2) by using for the l.h.s., the SLAC data on the $g_1$'s at $Q^2 = 3\text{GeV}^2$ (full circles) and for the r.h.s., the NMC parametrization for $F_2^p$ and $F_2^d$ (full line and dash lines for the estimated errors)[14]. In the small $x$ region we have also included the preliminary SMC data[13] (full squares). The test is indeed very well satisfied and gives, within the present experimental errors, a fairly good support to eq.(1) and $\Delta s(x) \equiv 0$. Moreover if one takes the first moment of both sides of eq.(2) using also ref.[13], one finds for the l.h.s. $0.588 \pm 0.054$ and for the r.h.s. $0.587 \pm 0.065$ which are in remarkable agreement.

Let us end by making a few remarks on the prospects of the $g_1$ structure functions. First in testing the sum rules, one is relying on the crucial assumption that the measured asymmetry $A_1(x, Q^2)$ is independent of $Q^2$, which allows to rescale the $g_1(x, Q^2)$ obtained at different $Q^2$, to a single $Q^2$ value. This has to be more firmly established. Second, the Bjorken sum rule is now satisfied up to 13%[14] and this important test must be confirmed at
a higher level of accuracy. Of course this is connected to the behaviour of $g_1(x)$ in the very small $x$ region which seems to be different for proton and neutron according to the recent SMC data\cite{3}. This puzzling situation must be resolved urgently.

3 The $g_2$ structure function

In deep inelastic $\mu(e)$ scattering with the lepton beam longitudinally polarized and the target with the spin transverse with respect to the beam direction, one can measure a spin asymmetry which is related to a ”transverse” spin-dependent structure function $g_T(x, Q^2)$. It turns out that $g_T$ has a simple expression in terms of $g_1$ and another structure function, so called $g_2(x, Q^2)$, since we have $g_T = g_1 + g_2$. The basic properties of $g_2$ have been nicely summarized in the contribution of X. Ji\cite{16}. In the simple parton model, as a consequence of helicity conservation, one finds that $g_T$ must vanish and therefore, in the scaling limit, one has $g_2(x) = -g_1(x)$. However from an analysis in terms of operator product expansion (OPE) on the light cone, one finds that the situation is not so simple and $g_2$ can be decomposed into two sets of operators. The first set is twist-2 operators, which are the same as those of the decomposition of $g_1$. The second set is twist-3 operators, which involve quark-gluon correlation functions. Therefore one can write

$$ g_2(x, Q^2) = g^{WW}_2(x, Q^2) + \tilde{g}_2(x, Q^2), \quad (3) $$

where $g^{WW}_2$ and $\tilde{g}_2$ correspond to twist-2 and twist-3 respectively. It was shown that $g^{WW}_2$ is fully determined by $g_1$ because one has\cite{17}

$$ g^{WW}_2(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(x, Q^2), \quad (4) $$

but since there is a priori no theoretical reason to expect $\tilde{g}_2 \ll g^{WW}_2$, it is important to measure $g_2$.

Very preliminary results were obtained recently both on proton and deuteron targets at SLAC\cite{3} and, although the errors are large, they seem to indicate that for proton, $\tilde{g}_2$ is small except in a region around $x = 0.01$. There is also the Burkhardt-Cottingham (BC) sum rule\cite{18} which says that

$$ \int_0^1 dx g_2(x, Q^2) = 0 \quad (5) $$

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and this important result has to be checked experimentally. The $Q^2$ dependence of the BC sum rule and its possible violation in the very low $Q^2$ region is an interesting problem which has new implications\cite{19}. In perturbative QCD, the validity of the BC sum rule was checked\cite{20} at order $\alpha_s$ on a quark target of mass $m$ to all orders in $m^2/Q^2$, a result which might help to clarify the nucleon target case. Finally, it is worth recalling the relevance of the second moment of $g_2$ and, in particular, the twist-3 coefficient $d^{(2)}$ for which there are different theoretical predictions\cite{16} which will have to be confronted to future accurate data.

4 Spin physics at RHIC

Before one can come up with a realistic picture of the nucleon, many fundamental questions remain to be answered and, in particular as we have seen above, in the area of the polarized parton distributions. Polarized deep inelastic scattering provides some valuable insight in this direction, but polarized hadron-hadron collisions at high energy give access to new spin-dependent observables which contain also, in some cases, a far more unique information. A Relativistic Heavy Ion Collider (RHIC) is now under construction at Brookhaven National Laboratory and more than four years ago, it was already realized that one should propose a very exciting physics programme, provided this machine could be ever used as a polarized $pp$ collider. Of course all these considerations rely on the foreseen keys parameters of this new facility, i.e. a luminosity up to $2.10^{32} cm^{-2}sec^{-1}$ and an energy of 50 – 250 GeV per beam with a polarization, either longitudinal or transverse, of 70%. Since then, the RHIC Spin Collaboration (RSC) has produced a letter of intent\cite{21} and has undertaken several serious studies in various areas, leading to a proposal\cite{22} which is now fully approved. Both detectors STAR and PHENIX of the heavy ion programme will be involved and the first data taking is expected by 1999. Some of the physics topics which will be explored at RHIC have been reviewed in the working group by A. Schäfer\cite{23} who also presented many interesting results from a dedicated Monte Carlo code. The magnitude and the sign of the polarized gluon distribution $\Delta G(x, Q^2)$ has to be determined because it is believed to affect the quark helicity distributions $\Delta q(x, Q^2)$, via the axial anomaly\cite{24}, and it is also needed to perform their $Q^2$ evolution. So far nothing is known about $\Delta G(x, Q^2)$ experimentally,
but it can be measured by the double helicity asymmetry $A_{LL}$, for example, in direct $\gamma$ production and in jet production. Direct photon production in $pp$ collisions is largely dominated, at leading order, by the Compton diagram $qg \rightarrow q\gamma$ and therefore $A_{LL}$ provides an almost direct measurement of $\Delta G(x, Q^2)/G(x, Q^2)$. The number of subprocess contributing to jet production is larger, because we have $gg$, $gq$ and $qq$ as initial states. However for one-jet production, gluon-gluon scattering dominates the $p_T$ spectrum in the low $p_T$ region, i.e. for $10 < p_T < 20$ GeV/c at the RHIC energy, and this also allows to extract $\Delta G$. In the large $p_T$ region (i.e. $p_T > 50$ GeV/c), the cross section is dominated by quark-quark scattering, so $A_{LL}$ will be driven by $(\Delta u/u)^2$. Another very efficient way to isolate $\Delta q/q$ or $\Delta \bar{q}/\bar{q}$ for both $u$ and $d$ quarks, is by measuring the single (or double) helicity parity-violating asymmetry in weak boson production\[25]. This is due to the anticipated high luminosity (i.e. $800 pb^{-1}$ in three months running time) which will allow to collect a very copious number of $W^\pm$ and $Z$ bosons. In addition the polarized antiquark distribution can be very well measured through $A_{LL}$ in lepton pair production, described by the standard Drell-Yan mechanism and, for example, if $\Delta \bar{q} = 0$ one will observe $A_{LL} = 0$.

Finally, it is worth mentioning that with the option of transversely polarized protons at RHIC, we will be able to measure directly, for the first time, the leading twist-2 quark transversity distribution, so called $h_1^q(x)$\[26]. Clearly there is one such distribution for each flavor ($u, d$, etc...) and for both quark and antiquark, but nothing is known experimentally about them. At the level of the parton model, there is a useful bound\[27], implied by positivity, which reads

$$q(x) + \Delta q(x) \geq 2|h_1^q(x)|.$$  \hfill (6)

Once more, lepton pair production and $Z$ production are the best hadronic probes for these new transversity distributions which are simply related to the double transverse spin asymmetry $A_{TT}$\[12].

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