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Review

COMPASS and HERMES contributions to our understanding of the nucleon spin

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Abstract

An update is given on the ongoing experimental investigation of the spin structure of the nucleon, with particular emphasis on the results from the COMPASS and HERMES experiments. Both longitudinal and transverse spin phenomena are covered. In the first case, the hot topic is the direct measurement of the gluon polarization. Evidence is presented for $\Delta G/G$ being small around $x_g \simeq 0.1$, and the first moment of ΔG should not be larger than 0.2–0.3. About transverse spin effects, evidence is given for new phenomena, associated with transverse-momentum-dependent distribution and fragmentation functions, which might explain the transverse spin phenomena observed for a long time in pp scattering.

Keywords: Deep inelasti scattering; Nucleon spin structure

1. Introduction

Deep Inelastic Scattering (DIS) is the standard technique to investigate the structure of the nucleon. Using polarized lepton beams and polarized targets the spin structure of the nucleon can be measured. If both the beam and the target spins are aligned along the direction of the incident lepton, one structure function, g_1, can be measured from the cross-section asymmetry of the inclusive scattering. In the quark–parton model this structure function can be written as

$$g_1(x) = \frac{1}{2}\Sigma_q e_q^2 \cdot \Delta q(x)$$

where $\Delta q(x) = \{(q(x)^{\downarrow\uparrow} + \bar{q}(x)^{\downarrow\uparrow}) - (q(x)^{\uparrow\uparrow} + \bar{q}(x)^{\uparrow\uparrow})\}$ are the differences of the quark densities for quark spin antiparallel or parallel to the target nucleon spin. Adding up over the quark flavours the first moments $\Delta q = \int_0^1 \Delta q(x)\mathrm{d}x$, one obtains $\Delta\Sigma = \Delta u + \Delta d + \Delta s$, i.e. the contribution of the quarks to the spin of the nucleon, which in general terms can be written as

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle. \quad (1)$$

In this expression, ΔG is the contribution of the gluons, and $\langle L_z \rangle$ is a possible contribution from the gluons and quarks angular momenta.

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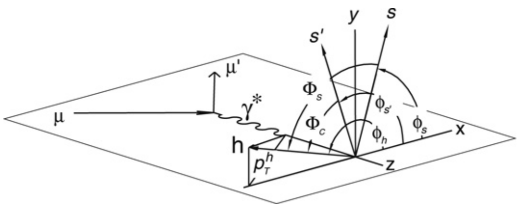

Fig. 1. Definition of the Collins ($\Phi_C = \phi_h + \phi_S - \pi$) and Sivers ($\Phi_C = \phi_h - \phi_S$) angles.

After the original discovery of the European Muon Collaboration [1] that $\Delta\Sigma$ is small, several other polarized DIS experiments on the proton, the deuteron, and ^{3}He, have confirmed the EMC result, establishing $\Delta\Sigma$ to be between 20% and 30% [2,3].

Given the smallness of $\Delta\Sigma$, understanding the nucleon spin requires the investigation of ΔG and $\langle L_z \rangle$. While measurements of $\langle L_z \rangle$ are for the moment out of reach, direct measurements of ΔG have become a priority issue.

In inclusive DIS, ΔG can only be determined from the Q^2 dependence of the spin structure function g_1. The precision of these fits is however strongly limited by the small Q^2 range covered by the data. In semi-inclusive DIS or in proton–proton scattering, the final state can be used to select hard processes involving gluons from the nucleon. In polarized semi-inclusive DIS, the polarization $\Delta G/G$ of gluons carrying a fraction x_g of the nucleon momentum can be obtained from the cross-section helicity asymmetry of the photon–gluon fusion (PGF), $\gamma^* g \to q\bar{q}$.

The knowledge of the helicity distributions $\Delta q(x)$ and $\Delta G(x)$ does not exhaust the spin structure of the nucleon. It has been realised that to fully specify the quark structure of the nucleon at the twist-two level, the transverse spin distributions $\Delta_T q(x)$ must be added to the momentum distributions $q(x)$ and the helicity distributions $\Delta q(x)$ [4]. The definition of $\Delta_T q(x)$ is analogous to that of $\Delta q(x)$, but it refers to transversely polarized quarks in a transversely polarized nucleon. If the quarks are collinear with the parent nucleon (no intrinsic quark transverse momentum k_T), or after integration over k_T, these three distributions exhaust the information on the internal dynamics of the nucleon. More distributions are allowed admitting a finite k_T, or at higher twist [5].

These studies were originally motivated by the attempt to understand the spectacular transverse spin effects which had been observed in pp reactions [6]. These effects persist even at very large energy, and have been observed again at RHIC, at $\sqrt{s} = 200$ GeV [7]. An ambitious project is ongoing to understand these effects in terms of transverse-momentum-dependent (TMD) distribution functions and fragmentation functions. Along this line, transverse spin effects have been predicted in SIDIS.

The transversity distributions $\Delta_T q$ are difficult to measure, since they are chirally odd and therefore absent in inclusive DIS. They may instead be extracted from measurements of the single-spin asymmetries in cross-sections for semi-inclusive DIS (SIDIS) of leptons on transversely polarized nucleons, in which a hadron is also detected in the final state. In these processes the measurable asymmetry, the "Collins asymmetry" A_{Coll}, is due to the combined effect of $\Delta_T q$ and another chirally-odd function, $\Delta_T^0 D_q^h$, which describes the spin-dependent part of the hadronization of a transversely polarized quark q into a hadron h [8]. At leading order A_{Coll} can be written as

$$A_{\text{Coll}} = \frac{\sum\limits_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum\limits_q e_q^2 \cdot q \cdot D_q^h} \tag{2}$$

where e_q is the quark charge. The quantities $\Delta_T^0 D_q^h$ can also be obtained by investigating the fragmentation of a polarized quark q into a hadron h, f.i. in $e^+e^- \to$ hadrons. This asymmetry is expected to show up as a $\sin \Phi_C$ modulation of the $\vec{p}_T^{\,h}$-dependent quark fragmentation function, where Φ_C is the azimuthal angle of the hadron with respect to the spin direction of the struck quark $\phi_{s'}$ (see Fig. 1).

A different mechanism has also been suggested in the past [9] as a possible cause of a spin asymmetry in the cross-section of SIDIS of leptons on transversely polarized nucleons. Allowing for an intrinsic $\vec{k}_T$ dependence of the quark distribution in a nucleon, a left–right asymmetry could be induced in such a distribution by the transverse nucleon polarization. Neglecting the hadron transverse momentum with respect to the fragmenting quark, this $\vec{k}_T$ dependence could cause the "Sivers asymmetry"