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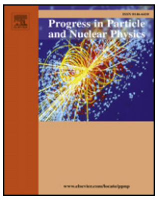

Review

Spin structure of the nucleon—status and recent results

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ABSTRACT

After the initial discovery of the so-called "spin crisis in the parton model" in the 1980s, a large set of polarization data in deep inelastic lepton–nucleon scattering was collected at labs like SLAC, DESY and CERN. More recently, new high precision data at large x and in the resonance region have come from experiments at Jefferson Lab. These data, in combination with the earlier ones, allow us to study in detail the polarized parton densities, the Q^2 dependence of various moments of spin structure functions, the duality between deep inelastic and resonance data, and the nucleon structure in the valence quark region. Together with complementary data from HERMES, RHIC and COMPASS, we can put new limits on the flavor decomposition and the gluon contribution to the nucleon spin. In this report, we provide an overview of our present knowledge of the nucleon spin structure and give an outlook on future experiments. We focus in particular on the spin structure functions g_1 and g_2 of the nucleon and their moments.

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1. Introduction

The measurement of a spin dependent observable is generally a daunting task, but with rich rewards, because spin seems to have a scalpel-like ability to expose weaknesses and failures of theories. Witness the switch from S, T to $V - A$, which led to the Weinberg–Salam electroweak theory, or the demise of Regge poles, which had successfully described hadronic cross-sections and shrinking diffraction peaks, or the spin crisis in the parton model of deep inelastic scattering, supposedly resolved by an anomalous gluon effect, now shown to be untenable, and, most recently, the realization that some of the information, gathered for 40 years on the fundamental electromagnetic form factors of the nucleon, is unreliable.

In this review we attempt to survey the tremendous experimental and theoretical effort, mainly involving studies of polarized lepton–hadron scattering and polarized proton–proton reactions, that has led to our present knowledge of the internal spin structure of the nucleon,

Deep inelastic lepton–hadron scattering (DIS) has played a seminal role in the development of our present understanding of the sub-structure of elementary particles. The discovery of Bjorken scaling in the late 1960s [1] provided the critical impetus for the idea that elementary particles contain point-like constituents and for the subsequent invention of the Parton Model. DIS continued to play an essential role in the long period of consolidation that followed, in the gradual linking of partons and quarks, in the discovery of the existence of missing constituents, later identified as gluons, and in the wonderful confluence of all the different parts of the picture into a coherent dynamical theory of quarks and gluons—Quantum Chromodynamics (QCD). Polarized DIS, involving the collision of a longitudinally polarized lepton beam with a longitudinally or transversely polarized target, provides a complementary and equally important insight into the structure of the nucleon.

At first sight the theoretical treatment of the polarized case seems to mimic the unpolarized case, with the structure functions $F_{1,2}(x)$ replaced by the polarized structure functions $g_{1,2}(x)$, and with parton densities $q(x)$ replaced by polarized densities $\Delta q(x)$. But it turns out that the polarized case is much more subtle: there is an anomalous gluon contribution to $g_1(x)$, and $g_2(x)$ has no interpretation at all in purely partonic language.

The latter insights were mainly inspired by the unexpected results of the European Muon Collaboration (EMC) measurement of $g_1(x)$ in 1988 [2]. The first excitement caused by this experiment was its indication of the failure of a sum rule due to Ellis and Jaffe based on the assumption that the contribution from strange quarks to g_1 is negligible [3]. It was soon realized, however, that there were more profound ramifications, which led to an intense scrutiny of the theory, since they implied a “spin crisis in the parton model” [4]— the spins of the quarks seemed to provide only a tiny fraction of the spin of the nucleon, in contrast to the situation in simple-minded constituent quark models of hadrons, where the quark spins account for a very large fraction of the proton spin. The crisis was believed to be resolved via a large polarized gluon contribution.

Of course the parton model predates QCD. In the more general field-theoretic framework we know that Bjorken Scaling [5], i.e. the fact that structure functions and parton densities depend only on x, cannot hold exactly, and these functions have a Q^2 dependence which can be calculated perturbatively in QCD, resulting in some of the most stringent tests of the validity of the theory. Moreover, because of the unfortunate need to renormalize the theory, the parton densities lose their simple physical meaning, and their actual functional form depends upon the renormalization scheme employed.

At present the situation, as will be discussed, is full of interest.

- Measurements of the polarized gluon density suggest that it is much too small to resolve the spin crisis [6,7]. This almost certainly implies that the partons possess orbital angular momentum, and it appears possible to estimate this, at least for the quarks, via a study of deeply virtual Compton scattering on protons [8].
- More precise data expected from the COMPASS experiment at CERN and the pp program at RHIC will allow further scrutiny of the validity of the above conclusion.
- There are now significant measurements of $g_2(x)$ which can be used to test the Wandzura–Wilczek approximation [9], the Burkhardt–Cottingham sum rule [10], and the Efremov–Leader–Teryaev sum rule [11].
- Measurements at Jefferson Laboratory are probing the hitherto inaccessible region of large x, where there are intriguing predictions about the behavior of the ratios $\Delta q(x)/q(x)$, as well as the region of low Q^2, where higher twist effects are important and where the issue of “duality” between the resonance and deep inelastic regions can be studied.
- By combining DIS data with the growing reservoir of data on semi-inclusive DIS (SIDIS) it should become possible to learn about the polarized sea densities $\Delta\bar{u}$ and $\Delta\bar{d}$ and to resolve the present disagreement between DIS and SIDIS about the sign of the strange quark density $\Delta s(x) + \Delta\bar{s}(x)$.

The aim of this review is phenomenological, i.e., it tries to strike a reasonable balance between theory and experiment. The theoretical treatment is thus conventional QCD and does not address interesting, and sometimes profound, matters like the Chern–Simons current and non-perturbative effects such as instantons, axial ghosts, and the U(1) problem. These are discussed in detail in the review of Anselmino, Efremov and Leader [12], and in the review of Bass [13], who also examines the consequences of a fixed pole in the virtual-photon Compton amplitude.