Flavor Decomposition of the Sea Quark Helicity Distributions in the Nucleon from Semi-inclusive Deep-inelastic Scattering

(The Hermes Collaboration)

As particle beams of ever higher energy have become available over the last 70 or more years, the spatial resolution with which we can probe the structure of matter has steadily improved. During the decade of the 1930's, it was discovered that the atomic nucleus is made up of protons and neutrons. By the 1960's, the technology of electron accelerators had reached the stage that the sub-structure of the proton itself could be investigated. In some classic measurements at the SLAC laboratory near Stanford, it was revealed that the proton contains "partons" that each carry a fraction of the proton's electric charge, but possess the same *intrinsic* angular momentum or "spin" as the proton, which is one-half in elementary units. At the spatial resolution then available, these partons appeared to be point-like. (Even with the 10,000-times better resolution of the highest-energy electron-proton collisions now available, at the DESY Laboratory in Hamburg, this is still found to be the case today!) These fractionally charged partons came to be identified with the *up* and *down* "quarks" with respective charges 2/3 and 1/3, which had been previously hypothesized theoretically. More detailed studies soon showed that the total inertial mass carried by the quarks amounted to only about one-half of that of the proton, leaving the rest to be eventually attributed to the neutral gluons being exchanged by the quarks to bind them together in the proton.

One of the next questions to naturally emerge was how the spins of the quarks combined together to make the same value of total spin of the proton. There seemed to be a natural answer that also explained the magnitude of the magnetic moment (magnetic strength) of the proton in terms of those of the quarks, which can be calculated from elementary principles for point charges. In this simple picture, the spins of two of the quarks are parallel and add together, while the third is anti-parallel and tends to cancel. However, in the 1980's electron scattering experiments became feasible with both the beam and target particles polarized — i.e. with their spins aligned in a controlled way. Such a measurement at the CERN Laboratory near Geneva demolished this simple spin picture. The quark spins were shown to make only a small net contribution to the proton spin, creating what came to be known as the "spin puzzle" that spawned thousands of theoretical papers offering possible explanations. This interpretation of the data was based on a possibly questionable assumption called "SU(3) flavour symmetry" — that all flavours of quark, including *up*, *down* and the virtual *strange* quarks, behave dynamically the same inside the proton in spite of the substantially greater mass of the strange quark. The analysis led to the conclusion that the strange quarks play a significant (cancelling) role in the proton spin, even though their existence there is fleeting.

The reason that an unambiguous picture could not be derived from that "inclusive" electron scattering data where only the scattered electron was detected is that this probe is sensitive to only the *magnitude* of the electric charges of the partons. Down and strange quarks have the same charge magnitude, and this is also true of all quarks q and their corresponding anti-particles $\bar{q}$. The "sea" of virtual quarks in the proton is believed to contain $\bar{u}$ and $\bar{d}$ as well as s and $\bar{s}$ quarks. An experimental solution to the problem of decoding the spin contributions of the various quark and anti-quark flavours can be found in observations of other products of this deep-inelastic scattering (DIS) process besides the scattered electron. In this process, the beam electron emits an energetic virtual photon, which is absorbed by a single quark. The force between individual quarks grows without limit as they are separated, forcing the energetic struck quark to combine with other virtual (anti-)quarks from the vacuum to make a jet or spray of hadrons. The types of the most energetic hadrons in this jet offer clues as to the flavour of the struck quark. For example, an up quark tends to produce a π^+ meson, which itself contains an up quark, while down quarks similarly tend to generate π^- mesons.

The Hermes experiment was inspired by the spin puzzle, and represented a new approach to study the spin structure of the nucleon. It has been running at the HERA electron accelerator at the DESY laboratory in Hamburg Germany since 1995, measuring spin asymmetries in DIS. Its combination of a polarized high energy electron beam in a storage ring with undiluted polarized atomic gas targets is unique in this field, and has important experimental advantages. Furthermore, the spectrometer detecting the scattered electrons has substantial acceptance and the capability to identify all types of hadrons produced in coincidence.

The main goal of the collaboration was to precisely determine the helicity distributions $\Delta q(x) \equiv q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$ of the quarks and antiquarks of all light flavours $q = \{up, down, strange\}$. Here the superscripts on the probability densities indicate whether the quark's helicity (spin alignment with the beam direction) is equal or opposite to that of the nucleon, and x is the Bjorken scaling variable representing the momentum fraction of the target carried by the parton in the frame where the target has "infinite" momentum. The determination of these dis-

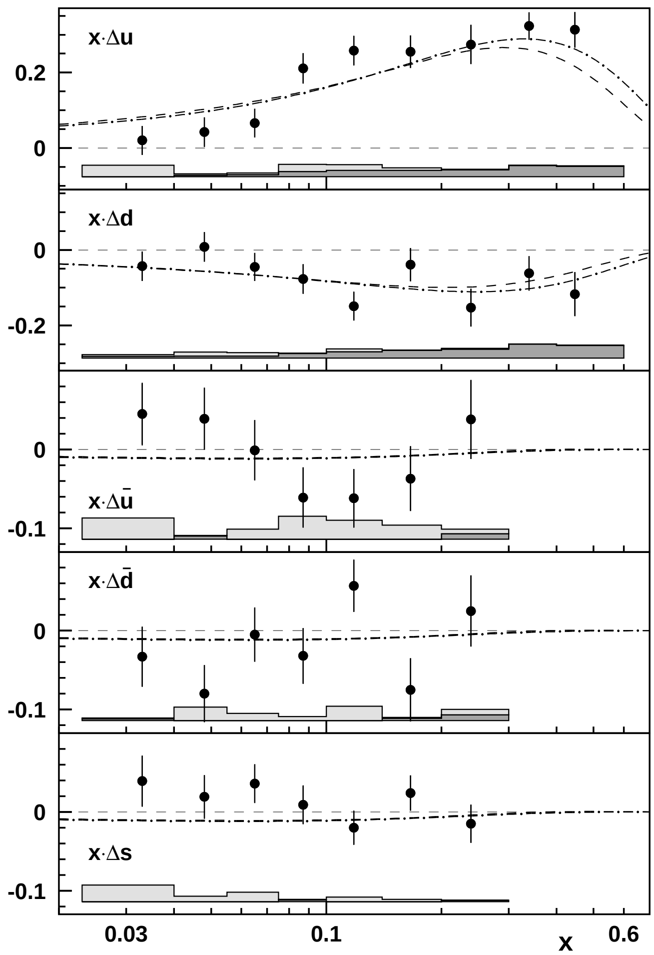

FIG. 1: Fig. 1. Quark helicity distributions as a function of Bjorken-x. The curves are LO QCD parameterizations of previous world inclusive data assuming SU(3) flavour symmetry.

tributions requires the combination of longitudinal spin asymmetries on both hydrogen and deuterium polarized targets. To distinguish the contributions of the quark flavours and in particular of the virtual sea quarks, a leading hadron is detected in coincidence with the deep-inelastic scattering of a lepton. As mentioned above, this method exploits the correlation between the quark flavour and the type of leading hadron produced from the struck quark.

The HERMES collaboration has presented results from an analysis of their complete data set recorded in the period 1996–2000. These results, shown in Fig. 1, constitute the most precise information on quark helicity distributions, and for the first time provide separate determinations of the polarizations of the up, down and strange sea quarks. They reveal that the sea quark polarisations are all small — there is little evidence of the "cancellation" between the contributions of valence and sea quarks that had been hypothesized to explain the small net contribution inferred from inclusive data under the assumption of SU(3) flavour symmetry. In particular, there is no evidence that Δs is negative as was indicated by that model-dependent analysis.

The proton spin puzzle continues to evolve. The contributions of both the spins and the orbital angular momentum of motion of both quarks and gluons are now expected to be important. The gluon polarisation will soon be measured in the collision of polarised protons at the RHIC accelerator in the Brookhaven National Laboratory. Recent theoretical insights have led to the recognition that orbital angular momentum can in principle be probed by hard exclusive processes that involve two almost-balancing hard interactions leaving the target nucleon intact. HERMES has recently demonstrated that it can make pioneering asymmetry measurements for deeply virtual Compton scattering (DVCS), a cleanly interpretable hard exclusive process that results in the production of only one energetic real photon. HERMES will continue to record data until at least the end of 2006.