# Precise determination of the spin structure function $g_1$ of the proton, deuteron and neutron

(The HERMES Collaboration)

A striking feature of the universe as seen through the eyes of science is its structural hierarchy ranging over vast scales. Galaxies have a dense core surrounded by orbiting solar systems, each of which has in turn a star as a central nucleus surrounded by planets and debris. Most of this visible material is made of atoms also having a central nucleus with most of the mass, but in this case surrounded by electrons we call elementary, as we have yet to discern in them any physical size or internal structure. However, the atomic nucleus still offers two more stages in this descent in microscopy, as it consists of protons and neutrons (generically called nucleons). The next and last stage lies at the limit of our present knowledge, and is a subject of intense investigation – the internal structure of the nucleon itself. Here we are working at a scale about a million times smaller than the typical size of an atom, which in turn is almost a million times smaller than the thickness of a human hair.

One reason for the fevered activity is the tantalizing nature of this problem—so much is elegantly clear, yet much remains shrouded in mystery. We have known for decades that each nucleon contains three apparently elementary almost massless particles that we call quarks, each of "flavour" either *up* ($u$) or *down* ($d$) with respective electric charge $-\frac{2}{3}$ or $-\frac{1}{3}$ of the negative elementary electron charge. The proton contains a $uud$ combination with total charge $+1$, while the neutron contains the neutral $udd$ combination. These three quarks are bound together by the strongest force yet discovered, through the exchange of electrically neutral elementary particles we call gluons. (It is only the "residual leakage" of this force just outside of the nucleon that provides the still-strong binding together of the nucleons in the atomic nucleus, accounting for the energy produced in the core of the sun and other stars.) The strong force is beautifully described by the laws of Quantum Chromo Dynamics (QCD), one of the intellectual triumphs of the twentieth century. Yet here the mystery begins. QCD apparently does not allow quarks to be isolated from each other, even though they may be "seen" inside the nucleon using light consisting of photons powerful enough to resolve them. It requires accelerators kilometers in diameter to generate beams of electrons that can radiate such powerful photons. In fact these photons must be "virtual"— their existence is fleeting as they are exchanged between the electrons in the probing beam and the quarks that absorb them, thereby being scattered out of their parent nucleon. Our conceptual picture of this "Deeply Inelastic Scattering" process is illustrated in Fig. 1. The state of motion of the quarks before they were struck is revealed by the energy and momentum of those virtual photons that they are able to absorb. Quarks are bound so tightly that they move inside the nucleon at speeds approaching that of light. Even though the QCD force appears to be completely understood in principle, it has certain features that overburden armies of the fastest modern computers in efforts to calculate predictions of the quark internal motion to compare with the results of experiments.

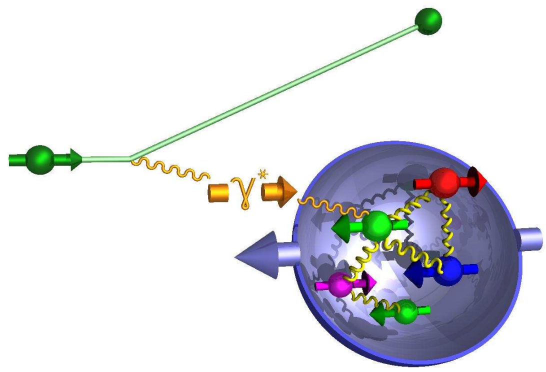


FIG. 1: A "Feynman" diagram illustrating our conceptual understanding of the process of deeply inelastic scattering of polarized electrons on a polarized nucleon target. The incoming high-energy electron emits a virtual photon, which inherits with high probability the spin direction of the electron, as indicated by the arrows. The photon is aborbed (only) by a quark with spin direction opposite to that of the photon.

This basic picture of nucleon structure was known three decades ago. However, both nucleons and their constituent quarks have another property called spin, in an amount that is its smallest possible quantum. (Physicists theorizing about such problems like to warn each other: "If you think you understand something, try adding spin.") In each such type of particle, its spin is intimately related to its magnetic strength or "moment"—each such particle acts like a tiny magnet that tends to align itself with external magnetic fields. The magnetic moments of supposedly elementary particles such as electrons and quarks can be predicted from their electric charge and mass, whereas those of composite systems such as the nucleon are a function of their internal structures. Furthermore, the degree of alignment of the spin orientations of the quarks with that of their parent nucleon is a delicate consequence of the QCD force, which depends strongly on the relative orientations of the quark spins. About two decades ago, this alignment of the quark spins came under experimental investigation using virtual photons

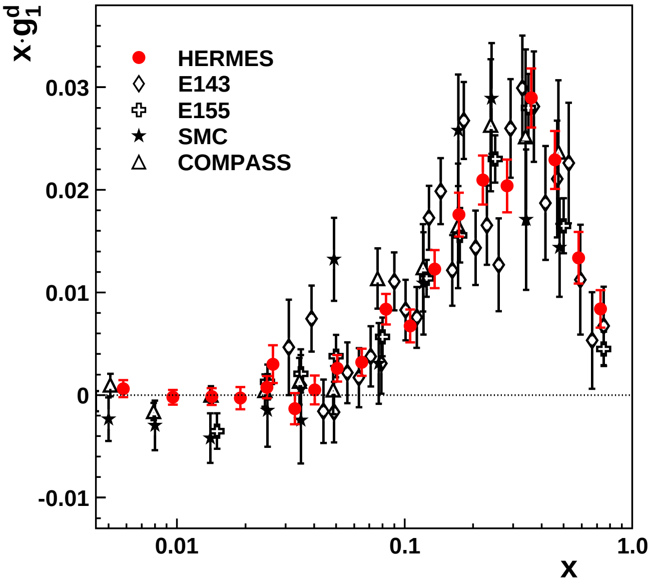


FIG. 2: The spin structure function of the deuteron, which is a measure of the sensitivity of the photoabsorption probability to the relative orientation of the spins of the virtual photon and target deuteron. The horizontal logarithmic axis is the so-called "Bjorken-$x$ variable, which can be interpreted as the fraction of the momentum of a very fast-moving nucleon that was carried by the struck quark. HERMES data from the present work are compared to those from previous publications. The error bars represent the experimental uncertainties.

of polarized light incident on polarized target nucleons, with the spins of both beam and target particles prepared with known orientation with respect to each other. A quark can absorb a virtual photon only if their spins point in opposite direction (see Fig. 1). Hence the relevant observable here is the difference in the scattering yield caused by reversing the relative orientation of the beam and target spin polarizations between parallel and anti-parallel. The result can be related to the probability that a quark will be found with its spin parallel or antiparallel to that of its parent nucleon. It came as a shock to find that the spins of the three quarks inside each nucleon don't combine to form the nucleon spin as expected from simple models. (Again QCD could presumably tell us the correct answer if we knew how to do the very complicated calculations in a relevant time scale.) A series of major experiments at several laboratories in the U.S. and Europe, of ever increasing precision, has confirmed that the net contribution of the quarks' intrinsic spins can account for only a fraction of the nucleon's spin. There must be other substantial contributions, possibly from the gluons being exchanged, each of which has an intrinsic spin twice that of a quark, or from the orbital motion of the quarks and gluons about each other.

The present paper from the HERMES Collaboration working at the DESY Laboratory in Hamburg reports the most precise high energy measurement using a polarized electron beam incident on a polarized target of deuterons, which are heavy-hydrogen nuclei containing both a proton and a neutron with their spins aligned in parallel. The beam is accelerated and then circulates in the DESY HERA electron ring, in a vast tunnel under the city of Hamburg. The target is a gas of deuterium atoms, with their nuclear spins aligned via delicate manipulation by strong magnetic fields and radio-frequency electric fields. The electrons scattered by the collisions are tracked through another more extensive magnetic field created by a big steel magnet, which deflects the electrons to a degree inversely related to their momenta, thereby revealing the momentum transferred to the struck quark by the exchanged virtual photon. The resulting new data are shown in Fig. 2, in comparison with previously published such data. The improvement in the precision is apparent, as indicated by the vertical bars on the data points representing the experimental uncertainties. It turns out that data for this target nucleus combining a proton and a neutron lend themselves to the extraction of a precise value for the net contribution of quark spins to that of the nucleon. This value is found to be $55 \pm 7\%$ of what could be expected from models of the internal motion of quarks. Furthermore, quarks of the so-called "strange" flavour, which exist in the nucleon only virtually when a gluon happens to "decay" into a strange quark and a matching anti-quark, are confirmed to have their spins aligned with opposite orientation from that of the parent nucleon, to a significant degree. This latter finding provides an example of how apparently unrelated issues in physics can connect in unexpected ways. One of the most important measurements that can shed light at the frontier of our understanding of the structure of matter is the search with ever increasing sensitivity for a nonzero value of the electric dipole moment of the neutron. This quantity can be imagined as the miniscule degree to which the internal charges of the electrically neutral neutron spontaneously separate themselves into positive and negative at opposite poles. It turns out that the quantitative interpretation of these measurements in terms of new theories to explain the observed properties of matter depends sensitively on the relative orientation of quarks and their parent nucleon, even the rare strange quarks because of their greater mass. Thus, results from measurements of the spin structure function such as the one reported here are being used in the search for a new more profound theory of matter.

The results from this and previous such measurements have inspired new efforts at HERMES and elsewhere to measure directly the contributions to the nucleon spin from both gluons and orbital angular momentum. This requires the investigation of more complicated processes involving more than one hard interaction with quarks. Results of these measurements are continuing to appear in other publications by HERMES.