The Q^2 Dependence of the Generalised Gerasimov-Drell-Hearn Integral

HERMES Collaboration

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The proton is a composite object possessing an electric charge equal to the smallest quantum known to exist on free particles, as well an intrinsic spin of $\frac{1}{2}\hbar$, the smallest quantum of angular momentum. It is believed to consist of a dynamic collection of pointlike charged quarks, each also with spin $\frac{1}{2}$, and electrically neutral gluons with spin 1. A question that is fascinating researchers today is how the spins and 'orbital angular momenta' of these 'partons' (arising from their motion inside the proton) conspire together to make the immutable spin of the composite object.

As a *static* reflection of the proton's internal structure, the strength of its intrinsic magnetism as a tiny magnetic dipole aligned with its spin axis is much larger than expected for a point-like, unit-charged, spin-1/2 particle. This excess is quantified as the degree to which the "anomalous magnetic moment" κ exceeds unity. On the other hand, as a *dynamic* reflection of its internal structure, the ability of the proton to absorb a high energy photon or "gamma ray" (quantum of electromagnetic energy) depends in a complex way on the photon's energy, indicating the existence of many very short-lived excited states of the proton, known as proton resonances. In the mid sixties, three theoreticians working independently discovered an astonishing and profound connection between these static and dynamic properties. This connection arises from only very general principles that are obeyed by all known physical systems (aside from one technical mathematical step that some workers worry about), and depends on no assumptions about the details of the proton structure. This connection is named after its discoverers the Gerasimov–Drell–Hearn (GDH) Sum Rule. It relates the anomalous magnetic moment of the proton to the degree to which the probability of inelastic absorption of a photon by the proton is affected by their spin alignment — *i.e.* whether the photon's spin 1 is aligned or anti-aligned with the spin half of the proton. To make the quantitative comparison, this difference in probabilities must be 'summed' or integrated over all possible photon energies including the proton resonances. A number of experiments at various facilities worldwide are now testing this relation.

In the meantime, other theoreticians have considered how this GDH Sum might change or 'generalize' when the 'real' photons discussed up to now are replaced by 'virtual' photons that have only a very fleeting existence determined by the Heisenberg Uncertainty Principle as they mediate electromagnetic interactions between charged particles. These virtual photons have an additional and very useful property not shared by real photons. They can be readily absorbed by the pointlike quarks. Hence they can be used to peer inside a tiny complex composite object such as the proton and 'see' the individual partons (by colliding with and ejecting only one at a time), in spite of the fact that the partons are very strongly bound to one another and are moving at velocities comparable to the speed of light. In other words, virtual photons have superior resolving power that can be 'tuned' to a desired level of spatial resolution independently of the energy of the photon. This tuning is done by controlling the 'kinematic' parameters (directions and energies of the interacting particles) of the interaction between the proton and an energetic probing electron that emits the virtual photon. The spatial resolution is essentially the distance that can be travelled by the virtual photon during its brief lifetime, between the point-like electron and a charged parton. Most of what we know about proton structure has been learned through the use of virtual photons with high resolving power.

The intriguing thing about the generalized GDH sum rule is that, even based on the limited information that existed two years ago, the value of the 'Sum' (integral of differences in absorption probabilities) for virtual photons with resolving power sufficient to 'see' individual partons seemed to have an arithmetic sign that is opposite to that expected for real photons! Now as the photon resolving power is tuned down so that one is probing ever more collective properties of the partons (the photons becoming closer to 'real'), the Sum must finally approach the value expected for real photons that is calculated from the anomalous magnetic moment. It is believed that studying this mysteriously sudden 'collectivity transition' will teach us more about the structure of the proton.

The HERMES experiment located in the East Hall of the HERA accelerator ring at the DESY Laboratory in Hamburg uses the HERA high energy polarized electron beam to probe the spin structure of the proton with a wide range in energy and resolving power of the virtual photons. The HERMES researchers first measured with various resolutions the portion of the generalised GDH Sum that must be measured with photons with high energies — above those that can excite the proton resonances. This was shown for the first time to constitute a substantial part of the Sum. Then they combined this information with the results of a new analysis of data using lower energy photons to determine the complete generalized GDH Sum covering the resonance region as well as the high energy region, over the same range of spatial resolution. For the first time, it was possibile to look for a tendency of the Sum for virtual photons to show signs of collective behavior of the partons (correlated motion) at the lowest available resolving powers. If correlations are small, a very simple dependence on the resolving power is expected that is a continuation of the behaviour observed at high resolving power where the spin distributions of individual partons are seen. Now finally, the collaboration has repeated all of these measurements for the deuteron target, which can be treated as a loosely bound proton plus neutron, the electrically neutral partner of the proton, with small corrections. Hence the studies described above can now be reconsidered for the neutron, by effectively subtracting the result for the proton GDH Sum from that for the deuteron.

These results for all three "targets" are shown in the first 3 panels of Fig. 1, as identified in the caption. The contributions from the resonance regions vanish quickly with increasing resolving power, designated here as Q^2 — which is in some sense the square of the 'mass' of the virtual photon. (Real photons are massless.) In contrast to expectations from some models of nucleon resonances, their contribution to the integral is found to not become dominant in the range of Q^2 covered by this measurement. The total Sums shown include a theoretical extrapolation up to infinite energy. (This extrapolation rests on solid ground and is seen to be a small correction for the whole measured resolution range.) The theoretical curves to be compared to the total Sums represent predictions for the simplest dependence of I_{GDH} on Q^2. The good agreement between these predictions and the data shows that the effects of the parton correlations are still small at the lowest resolving power employed here. Hence the change in sign of the Sums for the proton and deuteron as Q^2 is decreased further must be sudden and dramatic to meet the expected values for real photons at $Q^2 = 0$.

The difference of the Sums between those for the proton and neutron target, shown in the fourth panel, apears in an even more fundamental Sum Rule — that associated with its discoverer Bjørken. If this Sum Rule were found to be violated, it would shake the foundations of the entire science of elementary particles. Fortunately, the magnitude of the difference obtained by the fit to the data indicated by the dashed curve agrees with the theoretical expectation within the experimental uncertainties of these measurements.

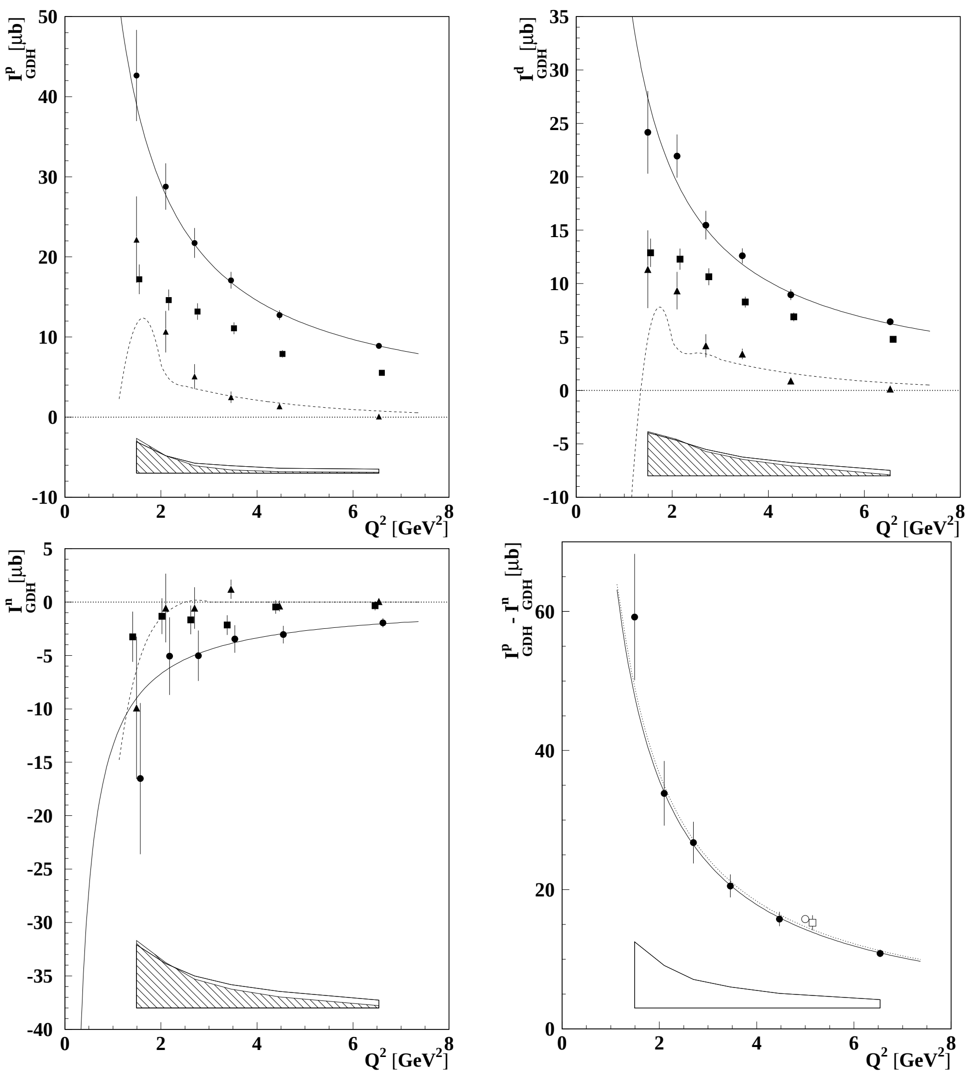

Figure 1: The first 3 panels show respectively the quantities measured by HERMES for the proton, deuteron and inferred for the "neutron' target. The symbols represent the measured values: the circles (•) show the complete generalised Gerasimov–Drell–Hearn Sum I_{GDH}, including the extrapolation to "infinite energy", the black triangles (▲) show the contribution from the nucleon-resonance region at low photon energies, and the squares (■) represent the part from the absorption of higher energy virtual photons on individual quarks. The error bars represent the statistical uncertainties, while the bars at the bottom show the systematic uncertainties. The curves are theoretical predictions to be compared to the circles and triangles. The fourth panel shows the difference between the GDH Sums for the proton and neutron. In this case only the dotted curve represents a theoretical prediction; The dashed curve is a simple fit to the data with a function of the form $1/Q^2$. The empty symbols represent previous measurements by other collaborations.