

## The “Proton Spin Crisis” — a Quantum Query

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The “proton spin crisis” was introduced in the late 1980s, when the EMC-experiment revealed that little or nothing of a proton’s spin seemed to be carried by its quarks. The main objective of this paper is to point out that it is wrong to assume that the proton spin, as measured by completely different experimental setups, should be the same in all circumstances, an assumption explicitly made in all present theoretical treatments of the “crisis”. As spin is a genuine quantum property, without any objective existence outside its measuring apparatus context, proper account of quantum mechanical measurement theory must be taken.

The “proton spin crisis” [1] essentially refers to the experimental finding that very little of the spin of a proton seems to be carried by the quarks from which it is supposedly built. This was a very curious and unexpected experimental result of the European Muon Collaboration, EMC [2] (later consolidated by other experiments), as the whole idea of the original quark model of Gell-Mann [3] and Zweig [4] was to account for 100 percent of the hadronic spins, solely in terms of quarks. Although “improved” parton models can just about accommodate the experimental results, the purpose of this paper is to point out that the “proton spin crisis” may be due to a misinterpretation of the underlying, quantum mechanical theory. As spin is a fundamentally quantum mechanical entity, without any classical analog, special care must be taken to treat it in a correct quantum mechanical manner.

According to Niels Bohr, *the whole experimental setup* must be considered when we observe quantum mechanical systems. It means that a quantal object does not “really exist” independently of how it is observed. This notion was later quantified by Bell [5], and verified experimentally by Clauser and Freedman [6], Aspect, Dalibard and Roger [7] and others. These experimentally observed violations of Bell’s theorem [5] are in accordance with quantum mechanics, but incompatible with a locally realistic world view, proving that quantum objects do not have objective properties unless and until they are actually measured\*. The quantum states are not merely unknown, but completely undecided until measured. It is important to stress that *this is not merely a philosophical question, but an experimentally verified prediction based upon the very foundations of quantum theory itself*. To quote John Wheeler: “No elementary quantum phenomenon is a phenomenon until it is a registered (observed) phenomenon” [8]. Unless a specific observable is actually measured, it really does not exist. This means that we should not *a priori* assume that different ways of probing the system will give the same results, as the *system itself* will change when we change the method of observation.

\*To be exact, also the possibility exists of non-local “hidden variable” theories, where objects *do* exist at all times. However, such theories manifestly break Lorentz-covariance.

To exemplify this for the spin of the proton, let us compare two different experimental setups designed to measure it:

- i) The Stern-Gerlach (SG) experiment, which uses an inhomogeneous magnetic field to measure the proton spin state;
- ii) Deep inelastic scattering (DIS), which uses an elementary probe (electron or neutrino) that inelastically scatters off the “proton” (actually elastically off partons).

We should at once recognize i) and ii) as different, or — in the words of Bohr — “complementary”, physical setups. If one measures the first, the other cannot be measured simultaneously, and vice versa. DIS disintegrates the proton and produces “jets” of, often heavier, hadrons as the collision energy is much larger than the binding energy, so there is no proton left to measure. Also, the very fact that the hard reaction in DIS is describable in perturbation theory means that we are dealing with a different quantum mechanical object than an undisturbed proton.

In the case of using a SG apparatus to measure the spin, the proton is intact both before and after the measurement, potential scattering being by definition elastic. SG thus measures the total spin state of the proton, but does not resolve any partons. It therefore seems natural to identify the spin of an undisturbed proton with the result from a Stern-Gerlach type of experiment.

As we have seen, i) and ii) simply do not refer to the same physical system, but the “fundamental spin sum-rule”, always assumed to hold in treatments of the spin crisis, explicitly equates the spin of the proton, i), with the sum-total of the measured partonic spins and orbital angular momenta, ii). Instead, it should generally read

$$\frac{\Sigma}{2} + L_q + L_G + \Delta G \neq \frac{1}{2}, \quad (1)$$

as the left hand side describes the measured spin of the partons, while the right hand side describes the spin of the proton. (Remember that the left and right hand sides correspond to different physical systems, as defined by the respective *complementary* experimental setups used to measure them.) The quantities above stand for:  $\Sigma$  = fraction of proton’s spin

carried by the spin of quarks and anti-quarks,  $L_q$  = quark orbital angular momentum contribution,  $L_G$  = gluon orbital angular momentum contribution,  $\Delta G$  = gluon spin contribution.

An additional complication is the following: While in quantum electrodynamics (QED) an atomic wave function can approximately be separated into independent parts due to the weak interaction, and the spins of the constituents (nuclei and electrons) can be measured separately as they can be studied in isolation\*, in quantum chromodynamics (QCD) it fails as the interactions between fields in an undisturbed proton are much stronger than in the QED case, making even an approximate separation impossible. Still worse, in QCD at low momentum transfers†, like in an undisturbed proton, the particles “quarks” and “gluons” cannot even be defined [9] and thus do not “exist” within the proton, even when disregarding the quantum mechanical measurement process described above. The simple parton model (with or without orbital angular momenta) is simply not tenable in strong QCD.

However, even if we would assume, as is conventional, that (“clothed”) partons within the proton *are* defined, the proton wave function,  $\Psi$ , could not be factorized into separate valence quark spin wave functions ( $|\chi_1\rangle, |\chi_2\rangle, |\chi_3\rangle$ ) as this would not result in an eigenstate of the strongly spin-dependent Hamiltonian, entering the energy eigenvalue equation

$$H\psi_n = E_n\psi_n. \quad (2)$$

The proton wave function could as usual be written as a superposition of energy eigenstates

$$\Psi = \sum_n c_n \psi_n, \quad (3)$$

but

$$\Psi^{SG}(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, s_1, s_2, s_3) \neq u(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) |\chi_1\rangle |\chi_2\rangle |\chi_3\rangle, \quad (4)$$

where  $s_1, s_2, s_3$  encodes the spin-dependence, and  $u(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$  would be the space-part of a spin-independent system. In reality the quarks would always be correlated and the wave function could never be separated into product states, except as an approximation if the interaction would be sufficiently small, as in DIS

$$\Psi^{DIS}(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3, s_1, s_2, s_3) \simeq u(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) |\chi_1\rangle |\chi_2\rangle |\chi_3\rangle. \quad (5)$$

Note that  $\Psi^{SG} \neq \Psi^{DIS}$  as they describe *different* physical systems, defined by their different modes of observation. In SG there would be an intrinsic, unavoidable *interference effect* for the spin (much like in the famous double-slit experiment for position) which is lost when DIS experiments measure spin structure functions of the “proton”. The DIS structure functions are proportional to cross sections, which by

\*Wigner’s classification of particles according to their mass and spin is given by irreducible representations of the Poincaré group, *i.e.* noninteracting fields.

†More precisely, the elementary quanta of QCD are defined only as the momentum transfer goes to infinity.

necessity are classical quantities incapable of encoding quantum interference. As each individual experimental data point is a classical (non-quantum) result, structure functions are by construction related to incoherent sums of individual probability distributions. Thus, even if we (wrongly) would assume the parton model to be applicable in both cases i) and ii), SG would result from adding spin *amplitudes* (taking full account of quantum interference terms), while DIS would result from adding spin *probabilities* (absolute squares of amplitudes). However, we emphasize again that in the case of SG the parton spins are not merely unknown, but actually *undefined*. An experiment like SG probes the spin state of the *proton*, while an experiment like DIS probes the spin state of the *partons* and the final (= observed) system is not a proton at all but “jets” of hadrons. These two experiments are disjoint, or complementary in the words of Bohr, and do *not* describe the same physical object.

In conclusion, we have explained why the “proton” tested by different experimental setups in general *cannot* be considered as the same physical object. Rather, the whole experimental situation must be taken into account, as quantum mechanical objects and observables do not have an objective existence unless measured. We should thus not enforce, by the “spin sum-rule”, the same spin (1/2) for the “proton” when measured by DIS as when it is directly measured on the proton as a whole, *e.g.* by SG. The “proton” as measured by deep inelastic scattering is a *different* physical system than a (virtually) undisturbed proton. There is no reason why spin measurements on one should apply to the other. Especially, there is no need for parton spins, as measured by DIS, to add up to the polarized spin of an otherwise undisturbed proton, just like the EMC-experiment [2] and its successors show. On a more pessimistic note, DIS spin data can never directly unravel the spin of the proton because the two are mutually incompatible. At best, DIS can only serve as an indirect test of QCD by supplying asymptotic boundary conditions to be used in future non-perturbative QCD calculations of the proton spin. If the result of those calculations does not come out spin-1/2, QCD is not the correct theory of strong interactions.

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