Measurement of the high energy contribution to Gerasimov-Drell-Hearn sum rule

The Gerasimov-Drell-Hearn (GDH) sum rule [1] is a fundamental relation of quantum field theory whose validity depends on the internal dynamical properties of the particle to which the sum rule is applied. It relates the anomalous magnetic moment κ of a particle to its helicity-dependent photoproduction cross sections:

$$I = \int_{\nu_0}^{\infty} \frac{\Delta\sigma(\nu)}{\nu} d\nu = \frac{4\pi^2 S \alpha \kappa^2}{M^2}, \tag{1}$$

where ν is the probing photon energy, ν_0 is the pion production threshold energy, S is the spin of the particle, M is its mass, and α the QED coupling. $\Delta\sigma \equiv \sigma_P - \sigma_A$, where σ_P and σ_A are the photoproduction cross sections for which the photon spin is parallel and antiparallel to the target particle spin, respectively. Eq. (1) reveals that the excitation spectrum of composite particles is related to their non-zero κ. A saturation of the sum rule beyond a given ν indicates the scale at which the object structure or mass scales become irrelevant. Thus, while resonances contribute most to the nucleon GDH sum, the high-energy part is equally important since it may reveal possible substructure or unknown structural process. Possible causes for a GDH sum rule violation are reviewed in [2]. The ones most considered are the existence of non-zero quark anomalous moments, the existence of a $J = 1$ pole of the nucleon Compton amplitude, and the chiral anomaly. All proposed mechanisms would manifest themselves at high-ν.

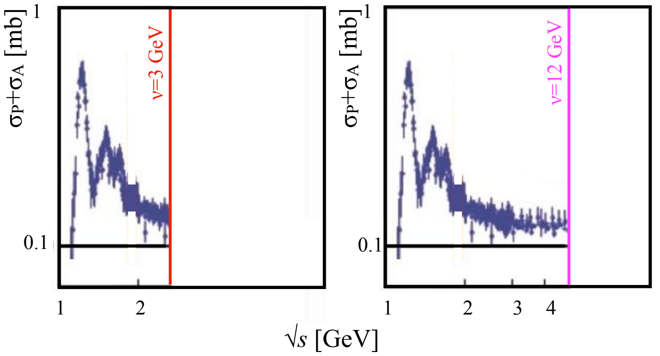

Figure 1: Unpolarized total photoabsorption cross-section $\sigma_P + \sigma_A$ for the proton, vs Mandelstam $\sqrt{s}$ (log scale), after Ref. [3].

We summarize here a proposal to measure for the first time the high-ν behavior of the GDH integrand $\Delta\sigma/\nu$. The experiment would run in Hall D, using a FROST-type target and a polarized beam on an Aluminum radiator. The measurement would be on both protons and neutrons, to allow for an isospin analysis of their high-ν behavior. The high-ν domain is where the sum rule may fail. In fact, the unpolarized equivalent of the GDH integral converges neither for the proton nor for the neutron, a fact clear only from high-ν data ($\nu > 3$ GeV) greater than the present upper reach of 2.9 GeV for measurement of the GDH integrand; see Fig. 1. On its left panel, the red line marks the current highest $\sqrt{s}$ at which the GDH integrand $\Delta\sigma/\nu$ has been measured. There would be no sign of potential divergence for the unpolarized equivalent of the GDH sum rule, $\int(\sigma_P + \sigma_A)d\nu$, if its measurement had stopped at this limit. On the right panel, the magenta line indicates the highest $\sqrt{s}$ reachable in Hall D. It is clear that the persistent flat dependence of $\sigma_P + \sigma_A$ represents a convergence problem for the unpolarized sum.

The proposed measurement, up to $\nu = 12$ GeV, would allow to study the convergence property of the GDH sum rule. This depends on two conditions: A) the spin-dependent forward Compton amplitude $f_2(\nu)$ must vanish at large ν; and B) the imaginary part of $f_2(\nu)$ must decrease with ν faster than $\approx 1/\ln(\nu)$. With a possible violation of the sum rule interpreted in terms of quark compositeness (among other causes proposed for a putative violation), the proposed experiment would constrain quark compositeness at the TeV-level.

Regardless of the convergence and sum rule validity, the data will constrain our knowledge of diffractive QCD, whose phenomenology is unverified in the spin sector. To quote the review [4]: *"above the resonance region, one usually invokes Regge phenomenology to argue that the integral converges [...] However, these ideas have still to be tested experimentally. [...] the real photon is essentially absorbed by coherent processes, which require interactions among the constituents such as gluon exchange between two quarks. This behavior differs from DIS, which refers to incoherent scattering off the constituents."* As pointed out in [2], not even a model prediction is available for the magnitude of the $J = 1$ pole effect, due to our absence of knowledge of polarized diffractive QCD. In fact, results from fits of photoproduction data and of DIS data independently disagree with the Regge theory expectation for the sign of the Regge intercept driving the isovector part of $\Delta\sigma$. The proposed experiment would clarify this problem. Given the success of Regge theory to describe unpolarized diffractive scattering data, this problem may well illustrate Bjorken's oft-quoted statement that *"Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might well ban such measurements altogether out of self-protection."* [5]

Analyzing $\Delta\sigma(\nu)$ using dispersion relation techniques will provide $f_2(\nu)$. This will further clarify the convergence property of the GDH sum rule, which depends on both the real and imaginary parts of f_2, and will test Chiral Effective Field Theory (χEFT). The latter is especially important since tests of χEFT with polarized observables by the JLab experimental program on low-Q^2 spin sum rule revealed that currently, χEFT has difficulties to consistently describes spin observables [6].

Furthermore, the experiment will provide a $Q^2 = 0$ baseline for Electron Ion Collider

(EIC) studies [7]. This will be helpful in particular for the study of the transition between the DIS regime characterized by partonic degrees of freedom to the diffractive regime characterized by effective degrees of freedom such as the pomeron and the reggeon.

Finally the data will constraint the polarizability contribution to the muonic hydrogen hyperfine splitting.

We propose to focus primarily on measuring the yield difference $\Delta y(\nu) = N^+ - N^-$ (where $N^{+(-)}$ is the number of events in a bin ν for positive (negative) beam helicity), rather than the absolute $\Delta\sigma$. This eliminates uncertainties coming from normalization factors, such as polarimetry and acceptance, which are typically dominant in experiments measuring cross-sections. Furthermore, uncertainties from unpolarized contributions (target dilution) cancel in the Δy. Measuring $\Delta y(\nu)$ is sufficient to establish the convergence of the integral. As an example, supposing that $\Delta\sigma = a\nu^b$, the primary goal of the present experiment is to measure b, without need of an accurate measurement of a. The three main ingredients needed for measuring $\Delta y(\nu)$ are: A) a circularly polarized photon beam; B) a longitudinally polarized target; and C) a large solid-angle detector.

Highly circularly polarized photons can be generated using CEBAF's polarized electrons with an amorphous radiator. No beam polarimetry is needed since we are concerned about measuring a yield. It can nevertheless be measured at 5% level using the injector Mott polarimeter or the polarimeters in Hall A, B or C.

Two polarized target systems suited for the experiment exist at JLab: the HDice and the FROST systems. The proposed experiment is short and thus investing in the demanding HDice system is not needed. The FROST butanol target is best suited. Target group indicated its preference to build a dedicated Hall D FROST target rather than using that of Hall B. Their estimated building cost is $0.5M. Two months will be necessary to install the target in the hall and test it. No commissioning beam time is needed. To switch from the deuteron to proton data taking takes about 0.5 day in all.

Hall D is the best suited hall at JLab to measure the total photoproduction cross-section thanks to its large solid angle and high luminosity. The standard Hall D detector package plus the Compton Calorimeter is assumed. It provides detection of neutral and charged particles over polar angles from 0.2° to 145° with a nearly complete azimuthal coverage. It can be compared to the 7° to 145° coverage of the LEGS detector at BNL and to the 1.6° to 174° coverage of the GDH-detector at ELSA.

The expected rates from butanol are 36 kHz or 40 kHz for proton and deuteron respectively,. This yields a useful proton rate of 5 kHz and a deuteron rates 10 kHz. The butanol rates are well below the current 60 kHz DAQ limit of Hall D. Hence, there

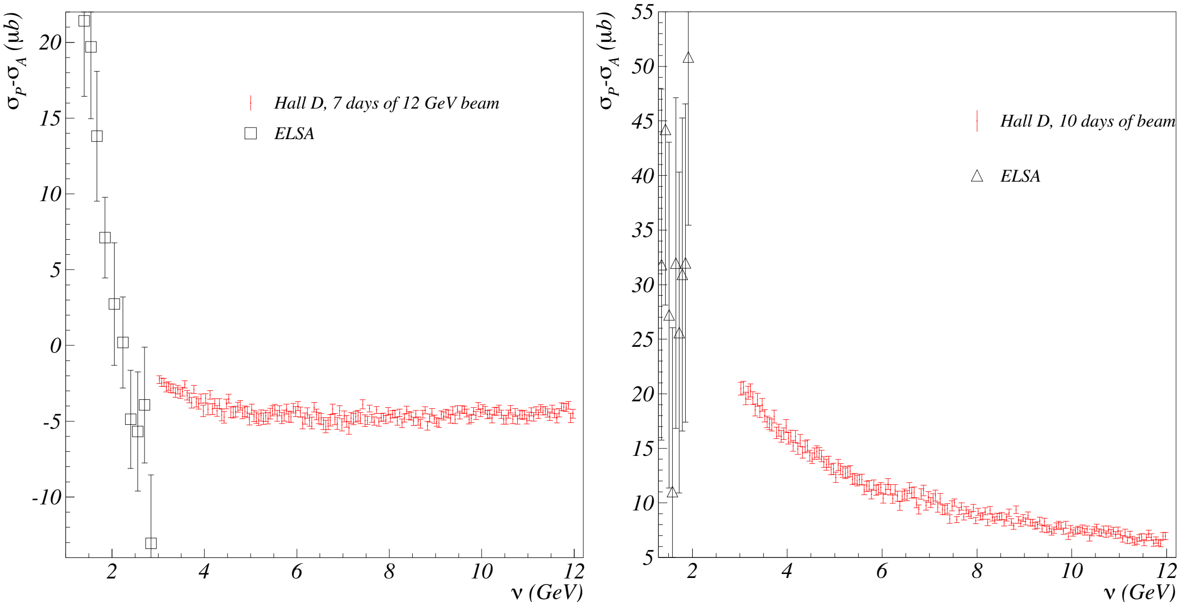

Figure 2: Left: $\Delta\sigma$ on the proton from ELSA high-ν data and expected results from Hall D. Right: Same as left, but for the neutron extracted from deuteron data.

will be no deadtime or other DAQ limitation.

One week of running on the proton and two weeks on the deuteron would yield the data shown in Fig. 2. If $\Delta\sigma$ obeys the presumed Regge behavior, the experiment would determine the relevant Regge intercepts at the level of 1 to 2%, to be compared to the 30 to 50% level at which they are presently known. This will be enough to assess the convergence of the GDH sum rule. It will also clarify the problem that results from fits of photoproduction and DIS data disagree with the Regge theory expectation. In Regge theory, the high-energy behavior of the isovector and isoscalar cross-section differences are driven by the $a_1(1260)$ and $f_1(1285)$ Regge trajectories such that

$$\Delta\sigma^{(p-n)} \sim s^{\alpha_{a_1}-1}\,, \qquad \Delta\sigma^{(p+n)} \sim s^{\alpha_{f_1}-1}\,.$$

Photoproduction and DIS data fits both yield $\alpha_{a_1} \approx +0.45$, while the Regge expectation is $\alpha_{a_1} = 1 - \alpha' m_{a_1}^2 \approx -0.34$, where $\alpha' = 1/(2\pi\sigma) \approx 0.88\,\mathrm{GeV}^{-2}$ and σ is the string tension, which is known to be approximately $0.18\,\mathrm{GeV}^2$. If α_{a_1} were indeed ≈ 0.45, this would imply a string tension more than twice as high as the commonly accepted value. The problem at the root of the discrepancy is partly that $a_1(1260)$ is the only $I^G(J^{PC}) = 1^-(1^{++})$ meson to form a "trajectory", while the second candidate, the $a_1(1640)$, has been omitted from the PDG Summary Tables as it still needs confirmation.

A precise measurement of $\Delta\sigma$ at high ν for both proton and neutron targets would help to remove this uncertainty.

In all, three weeks of beam time are needed to reach these goals. Once a polarized target is available in Hall D, a rich experimental program will open [8]. It is sensible to initiate it with the simplest experiment and a robust observable.

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