Quark correlations in the ground and excited - nucleon states via the photo-absorption sum rules

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Preliminaries

Prologue: Non-relativistic dipole sum rules for atomic and nuclear photoeffect.

$$\sigma_n(E1) = \int_{thr}^{\infty} d\omega \; \omega^n \; \sigma_{E1}(\omega)$$

Examples: $n = -2 \;\; \rightarrow$ Kramers-Heisenberg sum rule (SR) for static electric-dipole polarizability of a given quantum system;
$n = -1 \;\; \rightarrow$ the bremsstrahlung-weighted SR, dependent of charged-"parton" correlation in a given system;
$n = 0 \;\; \rightarrow$ the famous Thomas-Reiche-Kuhn SR, known as a precusor of not less as Quantum Mechanics itself.

Digressing to spin-dependent sum rules

The a.m.m. sum rules express a model-independent correspondence between static properties of a particle (or bound system of particles) and integrals over the photo-absorption spectrum. For particles with the spin $S = 1/2$ the sum rule for the anomalous magnetic moment κ reads

$$\frac{2\pi^2\alpha\kappa^2}{m^2} = \int_{thr}^{\infty} \frac{d\nu}{\nu}(\sigma_p(\nu) - \sigma_a(\nu))$$

Digressing to spin-dependent sum rules

The validity of the SR was checked in the lowest order of QED (SG, somewhere in the interval 1960-1963,unpubl.), S.G. and J.Moulin, Tests of Sum Rules for Photon Total Cross Sections in Quantum Electrodynamics and Mesodynamics // Nucl.Phys.B.1975.V.98.P.349. taking the Schwinger's $\kappa = \frac{\alpha}{2\pi}$ successful analytic and partially computer check of SR was done by Dicus and Vega (2000). Later on, for the physical reasons, we shall replace κ^2 entering different sum rules just by its integral expression in the GDH sum rule.

QED and Atoms

In what follows we will consider relativistic dipole moment fluctuation sum rules in the "valence-parton" approximation, that is neglecting virtual particle-antiparticle configurations in the ground state of the considered systems or diffractively produced in the final states of photo-absorption reactions.

QED and Atoms

$$4\pi^2\alpha[\frac{1}{3} < D^2 > -\frac{\kappa^2}{4m^2}] = \int_{thr}^{\infty}\frac{d\nu}{\nu}\sigma_{tot}(\nu)$$

or, using

$$\frac{2\pi^2\alpha\kappa^2}{m^2} = \int_{thr}^{\infty}\frac{d\nu}{\nu}(\sigma_p(\nu) - \sigma_a(\nu))$$

we get another form to be used later

$$4\pi^2\alpha[\frac{1}{3} < D^2 >] = \int_{thr}^{\infty}\frac{d\nu}{\nu}(\sigma_p(\nu)$$

QED and Atoms

We apply derived sum rule to the system of the highly ionized atom Pb^{81+}, thoroughly considered about half-century ago by J.S Levinger and co-workers:Phys.Rev.(1956-1957). Using the form of the sum rule with our included term $\kappa_{atom} \simeq \mu_{el.}$, we reduced deviation between left- and right-hand sides of the sum rule to one-half percent. Numerically:

$$4\pi^2\alpha\frac{1}{3} < D^2 > [937.2b] - 4\pi^2\alpha(\frac{\kappa}{2M})^2[67.9b] = \int_{thr}^{\infty}\frac{d\nu}{\nu}\sigma_{tot}(\nu)[874b]$$

QED and Atoms

The sum rule for the free electron in the α^2-approximation was checked analytically in the work by E.A. Kuraev, L.N.Lipatov and N.P.Merenkov (1973).

CQM and Nucleons

Following formally to the $p_z \to \infty$ techniques derivation of the Cabibbo-Radicati or GDH sum rule we can obtain the relation

$$4\pi^2\alpha(\frac{1}{3} < \vec{D}^2 > -(\frac{\kappa_N}{2m_N})^2) = \int \frac{d\nu}{\nu}\sigma_{tot}^{res}(\nu),$$

We use the definitions

$$\hat{D} = \int \vec{x}\hat{\rho}(\vec{x})d^3x = \sum_{j=1}^{3} Q_q(j)\vec{d}_j,$$

$$\hat{r_1^2} = \int \vec{x}^2\hat{\rho}(\vec{x})d^3x = \sum_{j=1}^{3} Q_q(j)\vec{d}_j^{\,2}$$

CQM and Nucleons

The defined operators $Q_q(j)$ and $\vec{d}_j$ are the electric charges and configuration variables of point-like interacting quarks in the infinite-momentum frame of the bound system.

Finally, we relate the electric dipole moment operator correlators, sucessively for the proton, the neutron and the pure "isovector-nucleon" part equal for both nucleons and the isovector part of the mean-squared radii operators, which all are sandwiched by the nucleon state vectors in the "infinite - momentum frame", with experimentally measurable data on the resonance parts of the photoabsorption cross sections on the proton and neutron presently known below ~ 2 GeV.

CQM and Nucleons

The listed operator mean values are parametrized as follows

$$R_V = \frac{1}{2}(< r_1^2 >_P - < r_1^2 >_N) = \alpha - \frac{1}{2}\beta$$

$$J_P = \frac{1}{3} < \hat{D}^2 >_P = \frac{8}{27}\alpha + \frac{1}{27}\beta + \frac{8}{27}\gamma - \frac{8}{27}\delta$$

$$J_N = \frac{1}{3} < \hat{D}^2 >_N = \frac{2}{27}\alpha + \frac{4}{27}\beta + \frac{2}{27}\gamma - \frac{8}{27}\delta$$

$$J_V = \frac{1}{3} < \hat{D}^2 >_V = \frac{2}{3}\alpha + \frac{1}{3}\beta + \frac{2}{3}\gamma - \frac{4}{3}\delta$$

CQM and Nucleons

where $< \vec{d_1}^2 >=< \vec{d_2}^2 >= \alpha, < \vec{d_3}^2 >= \beta, < \vec{d_1} \cdot \vec{d_2} >= \gamma,$
$< \vec{d_1} \cdot \vec{d_3} >=< \vec{d_2} \cdot \vec{d_3} >= \delta$ indices "1" and "2" refer to the like quarks (i.e. to the $u(d)$- and "3" to the odd quark.

CQM and Nucleons

Evaluation of the relativistic electric dipole moment fluctuation and the isovector charge radius sum rules for the nucleon was carried out with the available compilation of the resonance pion-photoproduction data on the proton and neutron $A_{1/2}^{P(N)}$ and $A_{3/2}^{P(N)}$ and all integrals over photoexcited nucleon resonances were taken in the narrow resonance approximation, when

$$J_{p(a)}^{res} \simeq \frac{4\pi m_n |A_{3/2(1/2)}^{res}|^2}{m_{res}^2 - m_n^2},$$

where $m_{n(res)}$ is the nucleon (or resonance)mass.

CQM and Nucleons

Solving the system of the linear equations and evaluating the $R_V, J_{P,N,V}$ with the help of experimentally known partial amplitudes of main photo-excited resonances, we find our final results for the numerical values α, β and the opening angle θ_{12} and θ_{13} between vectors $\vec{d_1}$ and $\vec{d_2}$ and vectors $\vec{d_1}$ and $\vec{d_3}$:

$$\alpha^{1/2} = 0.75 \pm 0.06 fm$$
$$\beta^{1/2} = 0.77 \pm 0.12 fm$$
$$\theta_{12} \simeq 120^0$$
$$\theta_{13} \simeq \theta_{23} \sim 120^0$$
$$< {r_1}^2 >_V = 0.25 \pm 0.02 fm^2 (exp : .29 fm^2)$$

CQM and Nucleons

In this section we illustrate explication of the qualitative isospin-depending features of the (mainly, electric-dipole) 2-nd and (the electric-quadrupole) 3-rd resonance photo-excitation regions. The value of effective dipole moments, determining the excitation cross section of the electric-dipole-type nucleon resonances, includes apparently the pionic degrees of freedom of the constituent quarks. This is supported by the fundamental principle of the charge symmetry of strong interaction dynamics. The participation of the pion degrees of freedom plays the role in the dynamical formation of the quark-diquark spatially looking nucleon structure. We suggest to illustrate it numerically choosing the experimental data on the resonance photo-absorption data on the $J^P = 3/2^-$ and $J^P = 1/2^-$ -resonances,composing the region of the second resonance.

CQM and Nucleons

Performing the evaluations analogous the earlier presented we obtain the different results from earlier cited
$\alpha^{1/2} = 0.82(0.75) fm, \beta^{1/2} = 0.53(0.77) fm$
$\theta_{12} \simeq 130^0(120^0), \theta_{13} \simeq 70^0(120^0), \theta_{23}$ 160^0 A pronounced asymmetry of the sides of the triangles Oud and Ouu
$C_u^{min} d$ / C_{uu} $\simeq$0.8 fm/1.5 fm
can testify to the validity of the quark-diquark model of considered resonances though diquarks are not apparently strongly bound.