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PHYSICS WITH POLARIZED PHOTONS

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PHYSICS WITH POLARIZED PHOTONS

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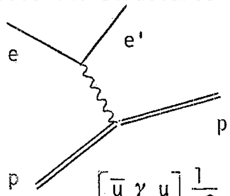
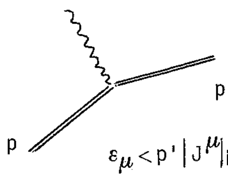
1. PHOTON POLARIZATION

The availability of fully polarized and monochromatic photon beams obtained with Compton scattering at Frascati[1] and Brookhaven[2] has stimulated over the past few years considerable interest in the role that polarization can have in the interaction of real and virtual photons with nuclear matter[3]. In these two cases the structures of the interaction are very similar



$\left[\bar{u}\,\gamma_\mu u\right]\frac{1}{q^2}\;\langle p'|J^\mu|p\rangle$



$\varepsilon_\mu\langle p'|J^\mu|p\rangle$

and both lead to a factorized form for the differential cross section

$$d\sigma \sim L_{\mu\nu}T^{\mu\nu} \qquad (1)$$

where

$$T^{\mu\nu} \sim \langle p'|J^\mu|p\rangle\langle p'|J^\nu|p\rangle^*$$

$$L_{\mu\nu} \sim (\bar{u}\,\gamma_\mu u)(\bar{u}\,\gamma_\nu u)^* \qquad \text{for virtual photons} \qquad (2)$$

$$L_{\mu\nu} \sim \Sigma_{\lambda\lambda'}\varepsilon^\lambda_\mu\,\varrho_{\lambda\lambda'}\varepsilon^{*\lambda'}_\gamma \qquad \text{for real photons} \qquad (3)$$

and ε^λ_μ is the photon polarization vector.

The polarization density matrix $\varrho_{\lambda\lambda'}$ is usually defined for real photons, but moving in the Breit frame defined as the frame in which the electron scatters backward with no loss in energy, the analogous quantity can be defined also for virtual photons[4]. In a very elegant way this allows for a complete analogy be tween the two cases and furnishes a powerful method to define the polarization

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state also for virtual photons.

The photon polarization $\bar{e}$ intervenes in the definition of the vector potential of the radiation

$$\bar{A} = \bar{e}\, e^{i(\bar{k}\cdot\bar{r}-kt)} \tag{4}$$

and is in general a complex vector $\bar{e}\cdot\bar{e}^{*}=1$ that for real photons is perpendicular to the photon momentum $\bar{k}$, $\bar{\varepsilon}\cdot\bar{k}=0$.In an arbitrary coordinate system with unit vectors $\bar{\varepsilon}_x$ and $\bar{\varepsilon}_y$ such that $\bar{\varepsilon}_x$, $\bar{\varepsilon}_y$ and $\bar{k}$ form a right-handed orthogonal coordinate system, any pure state of polarization $\bar{e}_i$ can be expressed by

$$\bar{e}_i = \Sigma_\lambda c_{i\lambda}\, \bar{\varepsilon}_\lambda \qquad (\lambda = x,y). \tag{5}$$

Any photon beam is a mixed state or an incoherent sum of pure states $\bar{e}_i$ each occurring with statistical weights p_i. If we define the unitary density matrix

$$\varrho_{\lambda\lambda'} = \Sigma_i\, p_i\, c^{*}_{i\lambda}\, c_{i\lambda'} \tag{6}$$

the cross section (1) for the photon absorption by an hadronic system can be written as

$$d\sigma \sim \Sigma_{\lambda\lambda'} f^{\lambda} \varrho_{\lambda\lambda'} f^{*\lambda'} = \mathrm{Tr}\{f\varrho f^{*}] \tag{7}$$

where the amplitudes

$$f^{\lambda} = \varepsilon^{\lambda}_{\mu} < p'\, |J^{\mu}|p > = \varepsilon^{\lambda}_{\mu} T^{\mu} \tag{8}$$

describe the photon interaction with the electromagnetic current J^{μ}. The form of the cross section (7) holds whether the process is completely differential or when some of the particle momenta or polarization are not observed. We can now specialize eqs.(5),(6),(7) to the following different cases.

Linear Polarization.- Two orthogonal states of linear polarization can be written as:

$$\bar{e} = \cos\varphi\, \bar{\varepsilon}_x + \sin\varphi\, \bar{\varepsilon}_y \quad , \qquad \bar{e}' = - \sin\varphi\, \bar{\varepsilon}_x + \cos\varphi\, \bar{\varepsilon}_y \tag{9}$$

where φ is an arbitrary angle between $\bar{e}$ and $\bar{\varepsilon}_x$. If we define the beam polarization P as such that

$$p_1 = \frac{1}{2}\,(1+P) \ , \qquad p_2 = \frac{1}{2}\,(1-P) \ , \qquad p_1+p_2 = 1 \tag{10}$$

where $p_{1,2}$ are the probabilities to find a photon in the states $\bar{e}$, $\bar{e}'$, then the density matrix (6) becomes

$$\varrho_{\lambda\lambda'} = \begin{Vmatrix} \frac{1}{2}(1 + P\cos 2\varphi) & \frac{1}{2}P\sin 2\varphi \\ \frac{1}{2}P\sin 2\varphi & \frac{1}{2}(1 - P\cos 2\varphi) \end{Vmatrix} \qquad (11)$$

and the cross section (7) for the detection of one particle is:

$$d\sigma \sim \frac{|T_x|^2 + |T_y|^2}{2} + P\,\frac{|T_x|^2 - |T_y|^2}{2}\cos 2\varphi + P\,\mathrm{Re}\left[T_x T_y^*\right]\sin 2\varphi\,. \qquad (12)$$

The (2φ) dependence of eq.(12) reflects the symmetry of the problem under the transformation $\varphi \rightarrow \varphi + \pi$.

In the case of no-polarization (P=0), eq.(12) reproduces the usual result

$$d\sigma \sim \frac{|T_x|^2 + |T_y|^2}{2} \qquad (13)$$

for unpolarized photons.

Circular Polarization.- For the case of circular polarization the electric and magnetic field strengths of the radiation, rotate with constant amplitudes and the two states of right-handed and left-handed circular polarization are given by

$$\bar{e}_{R,L} = \frac{1}{\sqrt{2}}(\bar{\varepsilon}_x \pm i\,\bar{\varepsilon}_y)\,. \qquad (14)$$

The density matrix and the cross section become respectively:

$$\varrho_{\lambda\lambda'} = \begin{Vmatrix} 1/2 & -i\,P/2 \\ i\,P/2 & 1/2 \end{Vmatrix} \qquad (15)$$

and

$$d\sigma \sim \frac{|T_x|^2 + |T_y|^2}{2} + P\,\mathrm{Im}\left[T_x T_y^*\right] \qquad (16)$$

where P is the degree of circular polarization of the beam defined as in (10).

Elliptic Polarization.- Analogous to the case of linear polarization the vectors may, for the case of elliptic polarization, be written as[5] :

$$\bar{e} = (a\cos\varphi - i\xi b\sin\varphi)\bar{\varepsilon}_x + (a\sin\varphi + i\xi b\cos\varphi)\bar{\varepsilon}_y$$
$$\bar{e}' = (b\cos\varphi + i\xi a\sin\varphi)\bar{\varepsilon}_x + (b\sin\varphi - i\xi a\cos\varphi)\bar{\varepsilon}_y \qquad (17)$$

where the real, positive numbers a and b satisfy

$$a^2 + b^2 = 1 \tag{18}$$

and ξ is ± 1 for right-handed and left-handed elliptic polarization respectively.

The ratio a/b is the ratio of the axes of the polarization ellipse, so that a/b=1 for circular polarizations and a/b is infinite or zero for linear polarization. Analogous to the previous cases the cross section becomes:

$$d\sigma \sim \frac{|T_x|^2+|T_y|^2}{2} + P\left\{\left[\frac{|T_x|^2-|T_y|^2}{2}\cos 2\varphi + \mathrm{Re}\left[T_x T_y^*\right]\sin 2\varphi\right](a^2-b^2) + 2\xi ab\ \mathrm{Im}\left[T_x T_y^*\right]\right\} \tag{19}$$

where P is the degree of elliptical polarization.

Virtual Photons.- With the same formalism one can show that the state of polarization for virtual photons produced by an unpolarized electron beam correspond to an equal incoherent mixture of two pure polarization states[6]:

$$\begin{aligned} \bar{e} &= \sqrt{1+\varepsilon}\,(\cos\Phi\,\bar{\varepsilon}_x + \sin\Phi\,\bar{\varepsilon}_y) + \sqrt{2\varepsilon}\,\bar{\varepsilon}_z \\ \bar{e}' &= \sqrt{1-\varepsilon}\,(-\sin\Phi\,\bar{\varepsilon}_x + \cos\Phi\,\bar{\varepsilon}_y) \end{aligned} \tag{20}$$

where

$$\varepsilon = \frac{1}{1 - 2\,\dfrac{\nu^2-q^2}{q^2}\,tg^2\,\dfrac{\theta}{2}}\ , \qquad \nu = E - E', \quad q^2 = -4EE'\sin^2\frac{\theta}{2}\ . \tag{21}$$

By constructing the density matrix and accounting for gauge invariance one can deduce the very well known unpolarized lepton, unpolarized target and one particle exclusive electroproduction cross section

$$d\sigma \sim \frac{|T_x|^2+|T_y|^2}{2} + \frac{|T_x|^2-|T_y|^2}{2}\cos 2\Phi + \frac{-q^2}{\nu^2}|T_z|^2 + \sqrt{\frac{-2q^2\varepsilon(1+\varepsilon)}{\nu^2}}\ \mathrm{Re}\left[T_x^* T_z\right]\cos\Phi \tag{22}$$

where the azimuthal angle Φ is now referred to the electron reaction plane instead of the photon polarization direction as it was for real photons. The terms in $\sin\Phi$ and $\sin 2\Phi$ vanish in (22) for exclusive reactions and the process is described by only four structure functions. Generalization to exclusive n particle reactions with polarized electrons would lead to a total of 9 structure functions corresponding to the 3x3 independent terms of the bilinear products of the electromagnetic current[7].

We note that in (22) the terms containing the longitudinal current (z subscripts) vanish in the limit $q^2 \rightarrow 0$ and reproduce the cross section for real and linearly polarized photon with polarization

$$\varepsilon = \frac{2\,EE'}{E^2 + E'^2} \tag{23}$$

which is kinematics dependent. Owing to parity invariance the terms arising from $\mathrm{Re}\left[T_x T_y^*\right]$ and $\mathrm{Im}\left[T_x T_y^*\right]$ vanish in eqs.(12),(16) and (19) when no target polarization is involved and summation over the unseen observables is carried out. On the other hand if particular final state configurations are selected these terms can be used either as polarization analysers or indicators of parity violating effects. As indicated by eqs.(12),(13),(16) and (19), real photons can only probe the transverse part of the hadronic current whereas virtual photons enlarge the domain of investigation also to the longitudinal part. A longitudinal photon couples to a nuclear system in a different way than a transverse photon does. For instance, the pion exchange currents do not contribute to the first order to the longitudinal cross section which is more sensitive than the transverse cross section to the short range part of the nuclear wave function. In a rather simplified description which however may contain the essential physics involved one can say that the nucleus looks different for electrons and photons. Electrons see the net electric charge e, whereas photons see the individual charges of the nucleus constituents[8]. Consequently exchange effects hardly influence the longitudinal component of the current but considerably affect the transverse components. This effect has been clearly demonstrated in the electrodisintegration of the deuteron at threshold performed at Mainz[9].

2. DEUTERON PHOTODISINTEGRATION WITH LINEARLY POLARIZED PHOTONS

Following eq.(12), the Partovi's approximation for the deuterium disintegration in the CM is given by

$$\frac{d\sigma}{d\Omega} = I_0(\theta) + P\, I_1(\theta) \cos 2\varphi \tag{24}$$

where:

$$I_0 = a + b \sin^2\theta + c \cos\theta + d \sin^2\theta \cos\theta + e \sin^4\theta$$
$$I_1 = f \sin^2\theta + g \cos\theta \sin^2\theta + h \sin^4\theta \, . \qquad (25)$$

A measurement of the asymmetry

$$\Sigma(\theta) = \frac{I_1(\theta)}{I_0(\theta)} = \frac{|T_x|^2 - |T_y|^2}{|T_x|^2 + |T_y|^2} \qquad (26)$$

at $\theta = \pi/2$ in CM and for $(10 < E_\gamma < 70)$ MeV has been performed at Frascati few years ago with the Ladon monochromatic and polarized photon beam ($I_\gamma \sim 2\text{x}10^5\ s^{-1}$; $P \sim 1$).

The results shown in Fig. 1, clearly indicated the need for an explicit inclusion of MEC beyond the contribution given by the Siegert theorem in the energy region $E_\gamma < 100$ MeV where the unpolarized cross section $(|T_x|^2 + |T_y|^2)$ resulted almost unaffected.

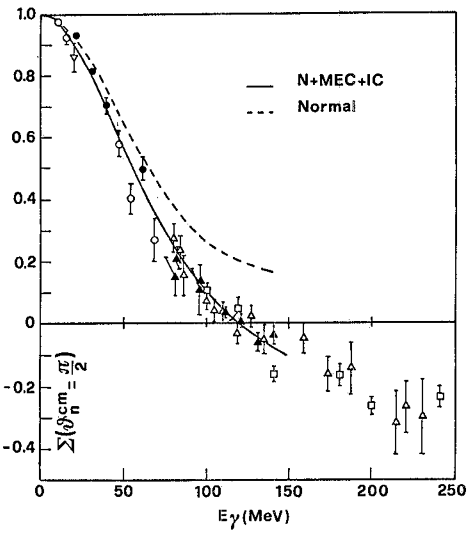

FIG. 1 - Plot of the asymmetry factor $\Sigma(\theta_n = \pi/2)$ vs. laboratory gamma-ray energy (MeV). Our present data (solid circles) are compared with the results of earlier experiments of Liu (solid and open triangles, Ref.19), Del Bianco et al. (inverted open triangle), Ref. 20), our previous data (open circles, Ref. 21), Gorbenko et al. (open squares, Ref. 22). The theoretical curves have been obtained in Ref. 23 with the RSC potential. The dashed line corresponds to the standard Partovi approximation (Ref. 24); the solid line reflects the inclusion of MEC and IC corrections.

In a subsequent, more detailed study of this reaction $I_0(\theta)$ and $I_1(\theta)$ have been separately measured as function of energy and the results normalized to the total cross section (σ_T) are reported in Fig. 2.

By assuming the values of σ_T given by the fit of all the worldwide available data[10] one can deduce the values for the forward differential cross section

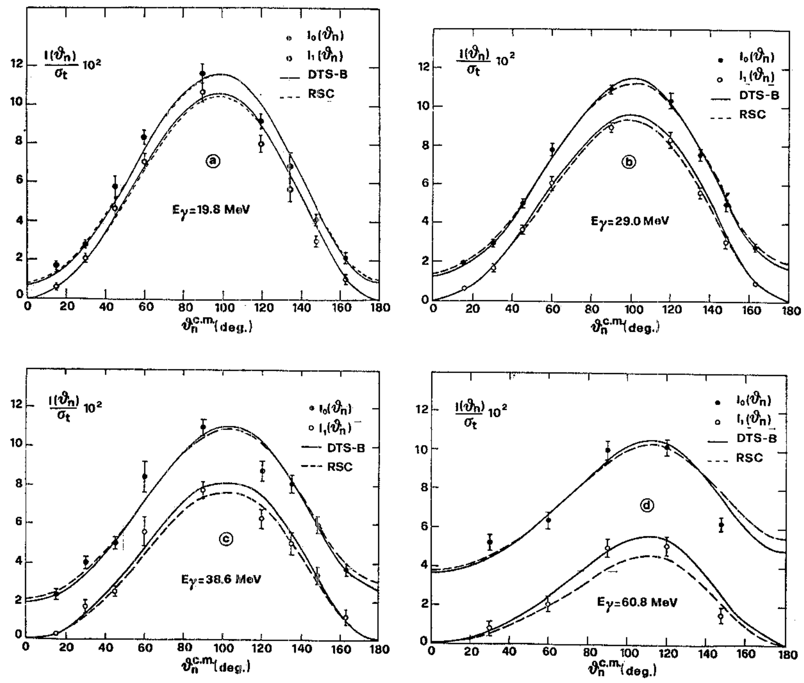

FIG. 2: Plots of $[I_0(\theta_n)/\sigma_t]10^2$ and of $[I_1(\theta)/\sigma_t]10^2$ as a function of the CM neutron angles $\theta_n=(\pi-\theta)$ at: (a) E =19.8 MeV; (b) 29.0 MeV; (c) 38.6 MeV; (d) 60.8 MeV. Dashed and solid lines represent theoretical calculations of Reference 25 with the Reid soft-core (RSC) and the De Tourreil-Sprung (DTS-B) potentials, respectively.

$I_0=(a+c)$ shown in Fig. 3 together with the Mainz, Louvain and Indiana results. The substantial agreement among all these experiments is remarkable.

Besides being extremely sensitive to the dynamics of the interaction, the term $(|T_x|^2-|T_y|^2)/2$ in eq.(12) has the typical $\cos2\varphi$-dependence that makes it of invaluable help to observe small amplitudes by interferences with the leading term. Typical example is the electric and magnetic multipoles separation in the (γ,γ')-reactions on nuclei, as it has been pointed out on many occasions. In particular the possibility to measure the E2/M1 interference term in the Δ-excitation appears very straightforward with linearly polarized photons.

The differential cross sections for meson photoproduction in a $P_{3/2}$ state by a magnetic dipole or electric quadrupole absorption of a plane polarized photon are given by

$$I^{M1}(\theta, \varphi) \sim \frac{1}{2}\sin^2\theta(5 - 3\cos2\varphi) - \cos^2\theta , \qquad (27)$$

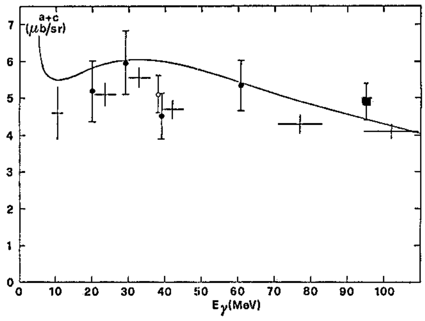

FIG. 3 - Experimental results for the forward differential section in the deuteron photodisintegration. Full circles (●): present experiment; crosses (+): Mainz (Ref. 26 and contribution C 17 at this Conference); open circle (o): Louvain (Ref. 27); full square (■): Indiana (Ref. 28); The theoretical calculation (full line) is due to Cambi et al. (Ref. 29).

$$I^{E2}(\theta, \varphi) \sim \frac{1}{2}\sin^2\theta(1 - \cos 2\varphi) + \cos^2\theta \qquad (28)$$

respectively.

In the plane $\varphi=0$, $I(MI) \sim$ const, but $I(E2) \sim \cos^2\theta$ and consequently a possible E2/M1 interference term can be evidenced with good accuracy. Since it is very difficult to extract unambiguously a value for the E2 amplitude at resonance, the present experimental value for the E2/M1 ratio is -0.012 ± 0.013[(11)]. On the other hand the presence of an admixture of quadrupole strength in the Δ-excitation would drive immediately to consider quark d-state components in the baryons wave function as a direct consequence of the hyperfine splitting due to the residual forces of QCD[12] This has been discussed by several authors also in connection with corrections to the static properties of the hadron,even if there are serious difficulties in the proper treatment of the center-of-mass motion of the nucleon bag[13,14].

In a similar way, electric (α) and magnetic (β) polarizability can be separated in the Compton scattering of plane polarized photons on nucleons where eq. (12) specializes into

$$d\sigma = \frac{d\sigma^{\parallel}+d\sigma^{\perp}}{2} + \frac{d\sigma^{\parallel}-d\sigma^{\perp}}{2}\cos 2\varphi \qquad (29)$$

where

$$d\sigma^{\perp} = d\sigma_0^{\perp} - 2\left(\frac{e^2}{M}\right)^2\left(\frac{E_\gamma}{M}\right)^2(\alpha + \beta\cos\theta) \qquad (30)$$

$$d\sigma^{\parallel} = d\sigma_0^{\parallel} - 2\left(\frac{e^2}{M}\right)\left(\frac{E_\gamma}{M}\right)^2(\beta + \alpha\cos\theta) \qquad (31)$$

and $d\sigma_0$ is the no-structure nucleon cross section.

As it has been discussed extensively elsewhere[15], these two quantities can be related to the usual expression for the electric and magnetic dipole moments of a composite system

$$\alpha \sim \langle p|\bar{d}^2|p\rangle \qquad \beta \sim \langle p|\bar{m}^2|p\rangle$$
$$\bar{d} = e\,\Sigma_i\,\hat{e}_i\bar{r}_i \qquad \bar{m} = \mu_p\,\Sigma_i\hat{\alpha}_i\bar{\sigma}_i \tag{32}$$

where $\hat{e}_i$ and $\hat{\alpha}_i$ characterize the nature of the constituent quarks. From eqs.(32) it is evident how α, β are essentially related to the dimension of the nucleon bag and its internal structure respectively. Therefore they may also depend on whether the nucleon is free or embedded inside the nuclear matter and from this point of view a comparison hydrogen-deuterium could be highly illuminating. Linearly polarized photons are the best tool to definitely measure these two very basic and largely unknown properties of the nucleons.

3. CIRCULARLY POLARIZED PHOTONS

Circularly polarized photons appear to be very appealing when used together with polarized target.

The differential Compton cross section of circularly polarized γ-rays on polarized electrons at rest is given by[16] :

$$\frac{d\sigma^{\pm}}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\omega_2}{\omega_1}\right)^2 \left\{ \left[\frac{\omega_1}{\omega_2} + \frac{\omega_2}{\omega_1} - \sin^2\theta\right] \pm \left[\left(\frac{\omega_2}{\omega_1} - \frac{\omega_1}{\omega_2}\right)\cos\theta\cos\psi + \left(\frac{\omega_2}{\omega_1} - 1\right)\sin\theta\,\sin\varphi\sin\psi\right]\right\} = A(\theta) \pm B(\theta)\,\sin\varphi \tag{33}$$

where $r_0 = \frac{e^2}{mc^2}$ and ψ is the polar angle of the electron spin direction with respect to the incoming photon momentum. The energies of the incident and scattered photons $\omega_{1,2}$ are related by

$$\omega_2 = \frac{\omega_1}{1 + \frac{\omega_1}{M}(1 - \cos\theta)} \tag{34}$$

and the upper-lower signs refer to the two possible orientations of the electron spin. The first term in the equation gives the ordinary Compton scattering cross section and the second gives the spin dependent one. This equation can be easily generalized for many electrons and it has been used for studying spin densities in ferro-magnetic materials ($\psi=0$) In a similar way the Compton scattering on transverse ($\psi=\pi/2$) polarized electrons is currently used to monitor the transverse beam polarization in storage rings. In both cases the relevant parameter is always the asymmetry

$$\Sigma = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{B}{A}\,\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \tag{35}$$

that measures the spin distributions $N^{\uparrow}$, $N^{\downarrow}$ inside the ensemble of electrons explored.

There is no reason, in principle, why this argument could not be applicable to other systems of fermions like nucleons in the nucleus or quarks or partons in a nucleon. In the case of an oriented nucleus this is just the extension of the Compton scattering on bound nucleons where, besides isolating the spin dependent part of eq. (33), the emphasis is concentrated on the nucleon spin distribution. This, of course, requires the assumption that, during the scattering, one can neglect the interactions between the nucleons and the momentum transfer to be high enough to resolve details on a length scale much less than the nucleus size, typically

$$q^2 \simeq 4\,\omega_1\omega_2 \sin^2\frac{\theta}{2} \geqslant 0.1 \text{ GeV}^2 \,. \tag{36}$$

Besides when $q^2 \gtrsim 0.7$ GeV^2 the nucleon structure starts entering the game and from the nucleon spin physics we pass to quark/parton spin physics. In this case the cross section should be exactly the electron-point like cross section (33) and eq.(35) becomes

$$\Sigma = \frac{B}{A}\,\frac{\Sigma_i\, e_i^2(q_i^{\uparrow} - q_i^{\downarrow})}{\Sigma_i\, e_i^2(q_i^{\uparrow} + q_i^{\downarrow})} \tag{37}$$

where e_i are the charges of the u, d quarks and $q^{\uparrow}$, $q^{\downarrow}$ the probabilities to find them with spins parallel (antiparallel) to the proton. If there is negligible L in the system then two quarks will have $S_z=1/2$ and one $S_z=-1/2$.

Hence the quark spins will be dominantly alligned along the direction of the proton spin and so we expect $\Sigma > 0$. If we take the SU(6) wave functions for the proton, then the probabilities are[18]

$$u^{\uparrow} = \frac{5}{9}\ , \qquad u^{\downarrow} = \frac{1}{9}\ , \qquad d^{\uparrow} = \frac{1}{9}\ , \qquad d^{\downarrow} = \frac{2}{9} \tag{38}$$

and we can quantity Σ as follows:

$$\Sigma^{\gamma p} = \frac{B}{A}\ \frac{\frac{4}{9}\left(\frac{5}{9} - \frac{1}{9}\right) + \frac{1}{9}\left(\frac{1}{9} - \frac{2}{9}\right)}{\frac{4}{9}\left(\frac{5}{9} + \frac{1}{9}\right) + \frac{1}{9}\left(\frac{1}{9} + \frac{2}{9}\right)} = \frac{5}{9}\frac{B}{A}\ . \tag{39}$$

Similarly for the neutron one finds $\Sigma^{\gamma n}$=0. These conclusions appear to be remarkable even if they have been obtained under very simplifying conditions. Moreover, if they are really significant as they appear, their q^2-dependence could give important indications of the spin-distribution at the different levels of complexity of the hadronic matter: nuclei, nucleons, quarks.

From this point of view, circular photons together with polarized targets could open new perspectives in the experimental nuclear physics studies.

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