Axial and Tensor Charges in the Relativistic Mean Field Approximation

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April 8, 2008

Outline

Nucleon Picture at Leading Twist

3 parton distributions:

Unpolarized $f_1(x) = q_+(x) + q_-(x) = q_\uparrow(x) + q_\downarrow(x)$

Helicity $g_1(x) = q_+(x) - q_-(x)$

Transversity $h_1(x) = q_\uparrow(x) - q_\downarrow(x)$

$q_\pm$ density of quarks with helicity $\pm$

$q_{\uparrow\downarrow}$ density of quarks with transverse polarisation $\uparrow\downarrow$

Transversity basis

$$|\uparrow\downarrow\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle \pm |-\rangle\right)$$

Nucleon Picture at Leading Twist

Soffer's inequality

$f_1^a + g_1^a \geq 2|h_1^a|$ where a is *valence* flavor (Q and $\bar{Q}$)

Nucleon charges

$$\text{Vector} \quad q = \int_0^1 \mathrm{d}x \left[f_1^q(x) - f_1^{\bar{q}}(x) \right]$$

$$\text{Axial} \quad \Delta q = \int_0^1 \mathrm{d}x \left[g_1^q(x) + g_1^{\bar{q}}(x) \right]$$

$$\text{Tensor} \quad \delta q = \int_0^1 \mathrm{d}x \left[h_1^q(x) - h_1^{\bar{q}}(x) \right]$$

$q = u, d, s$

Light-Cone Approach

3 "good" currents $\gamma^+, \gamma^+\gamma^5, \gamma^+\gamma^\perp$:

$$\text{Vector} \quad q = \frac{1}{2P^+} \langle P\uparrow | \bar{\psi}_{LC}\gamma^+\psi_{LC} | P\uparrow\rangle$$

$$\text{Axial} \quad \Delta q = \frac{1}{2P^+} \langle P\uparrow | \bar{\psi}_{LC}\gamma^+\gamma^5\psi_{LC} | P\uparrow\rangle$$

$$\text{Tensor} \quad \delta q = \frac{1}{2P^+} \langle P\uparrow | \bar{\psi}_{LC}\gamma^+\gamma^R\psi_{LC} | P\downarrow\rangle$$

$$\gamma^R = (\gamma^1 + i\gamma^2)/2$$

Melosh rotated states

$$\psi_{LC} = \mathcal{R}_M\psi = \frac{(m+z\mathcal{M})\mathbb{1} + i\mathbf{n}\cdot(\boldsymbol{\sigma}\times\mathbf{p}_\perp)}{\sqrt{(m+z\mathcal{M})^2+\mathbf{p}_\perp^2}}\,\psi$$

z fraction of longitudinal momentum, m quark mass and $\mathcal{M}$ nucleon mass.

Light-Cone Approach

Nucleon light-cone wave function $|PS\rangle$?

Standard approach

$|PS\rangle = |3q\rangle$ with $SU(6)$ symmetry spin-flavor structure

$$\begin{aligned} \text{Vector} \quad q_{LC} &= \langle M_V \rangle q_{NR} \\ \text{Axial} \quad \Delta q_{LC} &= \langle M_A \rangle \Delta q_{NR} \\ \text{Tensor} \quad \delta q_{LC} &= \langle M_T \rangle \delta q_{NR} \end{aligned}$$

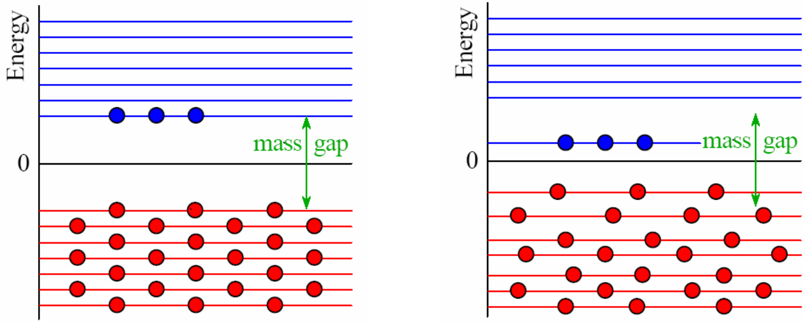
with

$$M_V = \frac{(m+z_i\mathcal{M})^2 + \mathbf{p}_\perp^2}{(m+z_i\mathcal{M})^2+\mathbf{p}_\perp^2}, \; M_A = \frac{(m+z_i\mathcal{M})^2 - \mathbf{p}_\perp^2}{(m+z_i\mathcal{M})^2+\mathbf{p}_\perp^2}, \; M_T = \frac{(m+z_i\mathcal{M})^2}{(m+z_i\mathcal{M})^2+\mathbf{p}_\perp^2}$$

Chiral Quark-Soliton Model

χQSM Lagrangian

$$\mathcal{L}_{\chi QSM} = \bar{\psi}(i\gamma^\mu\partial_\mu - MU^{\gamma_5})\psi$$



$\pi = 0 \Rightarrow U^{\gamma_5} = \mathbb{1}$ $\pi \neq 0 \Rightarrow U^{\gamma_5} \neq \mathbb{1}$

Light-Cone Baryon Wave Function

$SU(3)$ baryon wave function

$$|\Psi_B\rangle = \prod_1^{N_C} \int (\mathrm{d}\mathbf{p}) F(\mathbf{p}) a^\dagger(\mathbf{p}) \qquad \text{Discrete level part}$$
$$\times \exp\left(\int (\mathrm{d}\mathbf{p})(\mathrm{d}\mathbf{p}')\, a^\dagger(\mathbf{p}) W(\mathbf{p},\mathbf{p}') b^\dagger(\mathbf{p}')\right) |\Omega_0\rangle \qquad \text{Sea part}$$

with

- valence level wave function $F \Rightarrow h$ (s-wave) and j (p-wave)
- quark-antiquark pair wave function W
- $R, R^\dagger$ $SU(3)$ rotation matrices
- $B^*(R)$ baryon rotational wave function

[Diakonov & Petrov, Phys.Rev. D72 (2005) 074009]

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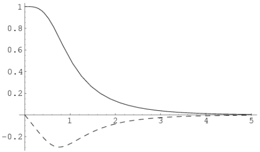
LCWF: Valence Part

One-particle Dirac Hamiltonian in mean field

$$\begin{cases} h' + h\,M \sin P - j(M\cos P + E_{lev}) = 0 \\ j' + 2j/r - j\,M\sin P - h(M\cos P - E_{lev}) = 0 \end{cases}$$



$E_{lev} \approx 200$ MeV for $M = 345$ MeV

Light-cone valence wave function

$$F^{j\sigma}(z,\mathbf{p}_\perp) = \sqrt{\frac{\mathcal{M}}{2\pi}}\left[\epsilon^{j\sigma} h(p) + (p_z\mathbf{1} + i\mathbf{p}_\perp \times \tau_\perp)^{\sigma}_{\sigma'}\,\epsilon^{j\sigma'}\frac{j(p)}{|\mathbf{p}|}\right]$$

with j isospin and σ spin indices, $p_z = z\mathcal{M} - E_{lev}$

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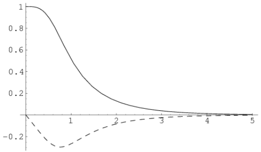

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LCWF: Sea Part

$W \Rightarrow$ approximate quark propagator in mean field $\sim \frac{1}{i\gamma^\mu\partial_\mu - MU^{\gamma_5}}$

Light-cone pair wave function

$$W^{j\sigma}_{j'\sigma'}(z,\mathbf{p}_\perp;z',\mathbf{p}'_\perp)=\frac{M\mathcal{M}}{2\pi Z}\Big\{\Sigma^j_{j'}(\mathbf{q})[M(z'-z)\tau_3+\mathbf{Q}_\perp\cdot\tau_\perp]^\sigma_{\sigma'} +i\Pi^j_{j'}(\mathbf{q})[-M(z'+z)\mathbf{1}+i\mathbf{Q}_\perp\times\tau_\perp]^\sigma_{\sigma'}\Big\}$$

where $\mathbf{Q}_\perp=z\mathbf{p}'_\perp-z'\mathbf{p}_\perp$,
$Z=\mathcal{M}^2zz'(z+z')+z(\mathbf{p}'^2_\perp+M^2)+z'(\mathbf{p}^2_\perp+M^2)$

LCWF: Rotational Part

$$T(B)^{f_1 f_2 f_3 f_4 j_5 \dots}_{j_1 j_2 j_3 j_4 f_5 \dots, k} = \int \mathrm{d}R\, B^*_k(R) R^{f_1}_{j_1} R^{f_2}_{j_2} R^{f_3}_{j_3} (R^{f_4}_{j_4} R^{\dagger j_5}_{f_5}) \dots$$

Proton: $p^*_k(R) \propto \epsilon_{kl} R^{\dagger l}_1 R^3_3$

Proton 3Q rotational wave function

$$T(p)^{f_1 f_2 f_3}_{j_1 j_2 j_3 \dots, k} \propto \epsilon_{kl} \int \mathrm{d}R\, R^{\dagger l}_1 R^3_3 R^{f_1}_{j_1} R^{f_2}_{j_2} R^{f_3}_{j_3}$$
$$\propto \epsilon^{f_1 f_2} \epsilon_{j_1 j_2} \delta^{f_3}_1 \epsilon_{k j_3} + \text{cycl. perm. of } (1,2,3)$$

Non-relativistic wave function: $F^{j\sigma}(p) \approx \epsilon^{j\sigma} h(p)$

Proton non-relativistic 3Q wave function

$$\Psi_{p,k} \propto \epsilon^{f_1 f_2} \epsilon^{\sigma_1 \sigma_2} \delta^{f_3}_1 \delta^{\sigma_3}_k h(p_1) h(p_2) h(p_3) + \text{cycl. perm. of } (1,2,3)$$

$\equiv SU(6)$ wave functions!

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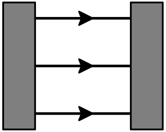
Matrix Elements

$3Q$



- three $F^{j\sigma}$ (left rectangle)
- three $F^{\dagger}_{l\tau}$ (right rectangle)
- contractions α, f, σ, p (arrows)

$5Q$ *direct* $5Q$ *exchange*

- one $W^{j\sigma}_{j'\sigma'}$ (left light rectangle)
- one $W^{l'\tau'}_{c,l\tau}$ (right light rectangle)

[Lorcé, Phys.Rev. D74 (2006) 054019]

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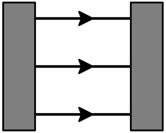

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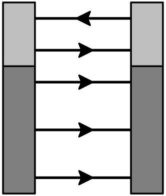

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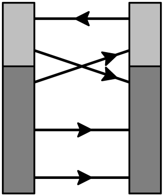

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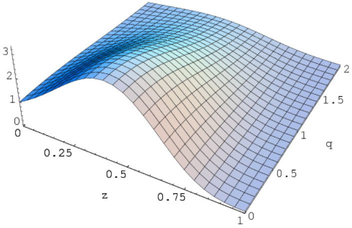
Relativistic Effects: Angular Momentum

Vector valence distribution $\propto \int[\prod_{i=1}^{3} \mathrm{d}^3 p_i F_i F_i^\dagger]\delta(\mathbf{P}-\mathbf{p}_1-\mathbf{p}_2-\mathbf{p}_3)$

Non-relativistic



$FF^\dagger \propto h^2$

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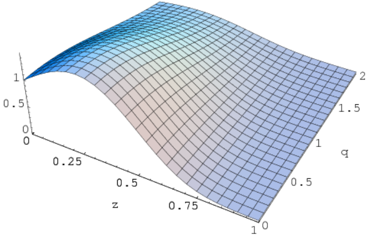
Relativistic



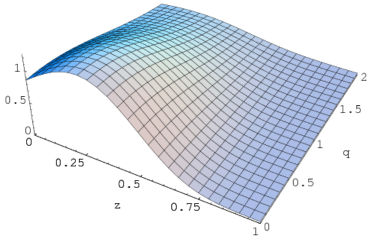
$FF^\dagger \propto h^2 + 2\frac{p_z}{|\mathbf{p}|}hj + \frac{p_z^2+\mathbf{p}_\perp^2}{\mathbf{p}^2}j^2$

[Lorcé, Phys.Rev. D74 (2006) 054019]

Relativistic Effects: Polarization

Different currents see different valence distributions

Axial



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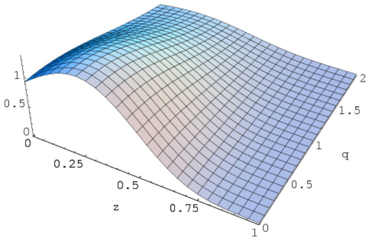
Tensor



$$F(\tau_3)F^\dagger \propto h^2 + 2\frac{p_z}{|\mathbf{p}|}hj + \frac{p_z^2}{\mathbf{p}^2}j^2$$

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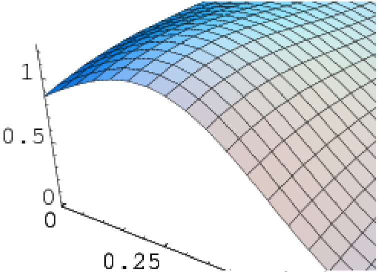

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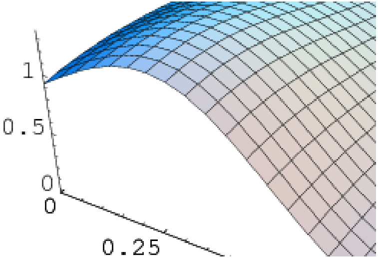

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Baryon Components

Question:

Which part of baryons is actually made of $3Q$?

	$3Q$	$5Q$	$7Q$
B_8 & B_{10}	$\approx 72\%$	$\approx 21\%$	$\approx 7\%$
$B_{\overline{10}}$	0%	$\approx 61\%$	$\approx 39\%$

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Proton Axial Charges

isovector $g_A^{(3)} = \Delta u - \Delta d$

octet $g_A^{(8)} = \frac{1}{\sqrt{3}} (\Delta u + \Delta d - 2\Delta s)$

flavor singlet $g_A^{(0)} = \Delta u + \Delta d + \Delta s$

	$g_A^{(3)}$	$g_A^{(8)}$	$g_A^{(0)}$
$NR\,3Q$	$\frac{5}{3} = 1.667$	$\frac{1}{\sqrt{3}} = 0.577$	1
$3Q$	$\frac{5}{3}\,\Phi^A = 1.435$	$\frac{1}{\sqrt{3}}\,\Phi^A = 0.497$	$\Phi^A = 0.861$
$3Q + 5Q$	1.241	0.444	0.787
$Exp.$	1.257 ± 0.003	0.34 ± 0.02	0.31 ± 0.07

Axial gluon anomaly $\Rightarrow$ $\Delta q(Q^2) = \Delta q - \alpha_s(Q^2)\Delta g(Q^2)$

Model scale $Q_0^2 \simeq 0.36$ GeV^2

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Proton Tensor Charges

Tensor charges: only quarks on the discrete level contribute

$$\begin{array}{lcl} \text{Axial} & & \text{Tensor} \\ \Delta u = 1.01 & v.s. & \delta u = 1.17 \\ \Delta d = -0.23 & v.s. & \delta d = -0.31 \\ \Delta s = 0.01 & v.s. & \delta s = -0.01 \end{array}$$

Perturbative picture: gluon splitting $\Rightarrow \quad \delta s = 0$

Non-perturbative picture: kaon cloud $\Rightarrow \quad \delta s \neq 0$

Summary of Results for Tensor Charges (u, d)

[Barone, Drago & Ratcliffe, Phys.Rept. 359 (2002) 1]

Model (Q_0^2 GeV^2)	$\delta u(Q_0^2)$	$\delta d(Q_0^2)$	$\delta u(Q^2)$	$\delta d(Q^2)$
NRQM (0.08)	1.33	-0.33	0.97	-0.24
MIT Bag (0.76)	1.09	-0.27	0.99	-0.25
CDM (0.16)	1.22	-0.31	0.99	-0.25
CQM (0.64)	0.80	-0.15	0.72	-0.13
LC (0.08)	1.17	-0.29	0.85	-0.21
Spect. (0.06)	1.22	-0.25	0.83	-0.17
Latt. (1.96)	0.84	-0.23	0.80	-0.22
χQSM1 (0.36)	1.12	-0.42	0.97	-0.37
χQSM2 (0.36)	0.89	-0.33	0.77	-0.29
χQSM3 (0.36)	1.17	-0.31	1.01	-0.28

$Q^2 = 10$ GeV^2

Summary of Results for Tensor Charges (u, d)

Models predictions @ $Q^2 = 10$ GeV^2

$\delta u = 0.7\text{-}1.0$ and $\delta d = -(0.1\text{-}0.4)$

First experimental extraction @ $Q^2 = 0.4$ GeV^2

$\delta u = 0.46^{+0.30}_{-0.23}$ and $\delta d = -0.19^{+0.30}_{-0.23}$

[Anselmino & *al.*, Phys.Rev. D75 (2007) 054032]

[Cloët, Bentz & Thomas, arXiv:0708.3246]

Summary of Results for Tensor Charges (s)

[M. Mekhfi, Phys.Rev. D72 (2005) 114014]

Model	δs
VSQMM	-0.02
CQP	-0.13
Latt.	-0.05
χQSM1	-0.01
χQSM3	-0.01

Quadrupolar Effect

Proton $5Q$ (discrete level) contribution

$$\Delta u = \frac{6}{25}\left[453K^A_{\sigma\sigma} + 137K^A_{\pi\pi} + 14(3K^A_{33} - K^A_{\pi\pi})\right]$$
$$\delta u = \frac{6}{25}\left[453K^T_{\sigma\sigma} + 137K^T_{\pi\pi} - 7(3K^T_{33} - K^T_{\pi\pi})\right]$$

$$\Delta d = \frac{-4}{25}\left[159K^A_{\sigma\sigma} + 91K^A_{\pi\pi} - 38(3K^A_{33} - K^A_{\pi\pi})\right]$$
$$\delta d = \frac{-4}{25}\left[159K^T_{\sigma\sigma} + 91K^T_{\pi\pi} + 19(3K^T_{33} - K^T_{\pi\pi})\right]$$

$$\Delta s = \frac{-4}{25}\left[3K^A_{\sigma\sigma} + 17K^A_{\pi\pi} - 16(3K^A_{33} - K^A_{\pi\pi})\right]$$
$$\delta s = \frac{-4}{25}\left[3K^T_{\sigma\sigma} + 17K^T_{\pi\pi} + 8(3K^T_{33} - K^T_{\pi\pi})\right]$$

$(3K_{33} - K_{\pi\pi}) = \int \mathrm{d}^3q\, \frac{3q_z^2 - \mathbf{q}^2}{\mathbf{q}^2} f(\mathbf{q})$ quadrupole!

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$$(3K_{33} - K_{\pi\pi}) = \int \mathrm{d}^3q\, \frac{3q_z^2 - \mathbf{q}^2}{\mathbf{q}^2}\, f(\mathbf{q}) \quad \text{quadrupole!}$$

Conclusion

- Light-cone approach within a chiral model χQSM
- Explicit baryon wave functions
- Expansion in Fock space ($3Q$, $5Q$, ...)
- Static properties: vector, axial & tensor charges, and magnetic moments
- Explicit quadrupolar distortion
- *Ab initio* calculations

Problems ($\Rightarrow$ outlook)

- Theoretical errors?
- $SU(3)$ breaking?
- Discrete level distortion due to the sea?