Electromagnetic and axial structure of baryons in dense nuclear matter

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Motivation

Electromagnetic and Axial structure of hadrons **modified** in a nuclear medium

- Proton EM ratio G_E/G_M is **reduced** in nuclear medium
  Jefferson Lab, MAMI experiments: ^{4}He
- Nucleon axial-vector coupling constants g_A^* is **reduced** in nuclear medium
  beta-decay measurements on heavy nuclei

$\Longrightarrow$ Develop theoretical methods to study electroweak structure of baryons in dense nuclear matter: heavy-ion collisions; nucleon-nucleon collisions, coress of compact stars

Methodology: **Valence quark** degrees of freedom $\oplus$ **pion/meson cloud** dressing

- **Covariant Spectator Quark Model**
  $\Longrightarrow$ **Model for the vacuum:** calibrated by physical and lattice QCD data
- **Extension to the nuclear medium**
  Baryons as on-mass-shell particles with effective mass M_B^*
  Quark-Meson-Coupling model $\Leftarrow$ Bag Model/CBM
  Saito, Tsushima and Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)
  Modified masses and coupling constants ($g^*_{\pi B B'}$) $\Rightarrow$ Medium modifications: bare & MC

GR, K Tsushima, AW Thomas JPG 40, 015102 (2013); GR, JPBC Melo, K Tsushima PRD 100, 014030 (2019);

GR, K Tsushima, MK Cheoun PRD 111, 013002 (2025)

Octet baryon: Electromagnetic and axial transitions

EMFF: 8 transitions (N, Λ, Σ, Ξ)

Axial: Neutral Current (NC): 8 $\oplus$ $6+6$ Charged Current (CC) $\downarrow$

$|\Delta I| = 1$ $(d \to u)$

$n \to p$

$\Sigma^- \to \Lambda$

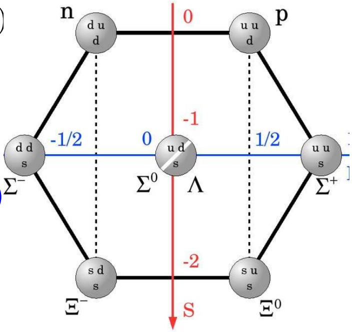
$\Sigma^+ \to \Lambda$ $(u \to d)$

$\Sigma^0 \to \Sigma^+$

$\Sigma^- \to \Sigma^0$

$\Xi^- \to \Xi^0$

6 transitions



$|\Delta S| = 1$ $(s \to u)$

$\Sigma^- \to n$

$\Sigma^0 \to p$

$\Lambda \to p$

$\Xi^- \to \Sigma^0$

$\Xi^- \to \Lambda$

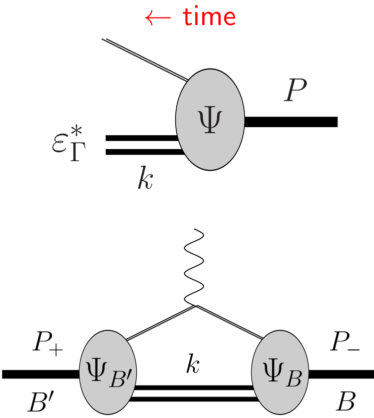
$\Xi^0 \to \Sigma^+$

6 transitions

Study Q^2-dependence of form factors & Medium modifications (ρ)

Covariant Spectator Quark Model (CSQM)

- **Covariant Spectator Theory: BARYONS**
  Active quark off-shell; 2 spectator on-shell quarks
  Stadler, Gross and Frank PRC 56, 2396 (1998); Gross and Agbakpe PRC 73, 015203 (2006)
- Integration into quark pair d.o.f.
  Reduction of system to quark-diquark system
  diquark on-shell Gross, GR and Peña PRC 77, 015202 (2008); PRD 85, 093005 (2012)
- Wave functions: relativistic generalization of $SU_S(2) \otimes SU_F(3) \otimes O(3)$ symmetries
- Radial w.f. ψ_B **determined phenomenologically** (Physical or Lattice QCD data)
- Electromagnetic interaction; relativistic impulse approximation **diquark on-shell**
  $J^\mu = 3 \sum_\Gamma \int_k \overline{\Psi}_{B'}(P_+, k) j_q^\mu \Psi_B(P_-, k)$
- Constituent quark current $j_q^\mu(q)$ $(q = u, d, s)$
  Simulate quark dressing (gluons and $q\bar{q}$ effects)



CSQM Quark Current $\oplus$ Transition current

- **Quark current:**

$$j_q^\mu(q) = j_1(q)\gamma^\mu + j_2(q)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}$$

$$j_i(q) = f_{i+}\lambda_0 + f_{i-}\lambda_3 + f_{i0}\lambda_s$$

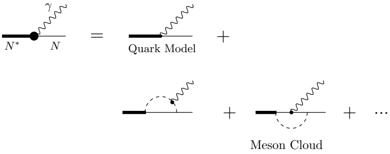
λ_l Gell-Mann matrices; $\lambda_s = \mathrm{diag}(0, 0, -2)$ [strange quark]

- Functions $f_{i\ell}$ ($\ell = 0, \pm$) determined by the nucleon and decuplet lattice QCD data
  F Gross, GR and MT Peña PRC 77, 015202 (2008);
  GR, K Tsushima, F Gross, PRD 80, 033004 (2009)
- $f_{i\ell}(q^2)$ parametrized using VMD
  Vector Meson Dominance
  Include terms in m_ω, m_ρ and m_ϕ
- Quark current can be generalized to
  - Lattice QCD regime
  - Nuclear medium
  - Inelastic TL region (decay width Γ_v)

$$m_v \to m_v - i\Gamma_v(q)$$

GR and MT Peña, PRD 80, 013008 (2009);
GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)

Transition current $\leftarrow$ time



$$J^\mu = J^\mu_{\rm Bare} + J^\mu_{\rm MC}$$

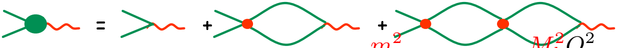
Total current $=$
[Bare (Valence Quark) current]
$+$ [Meson Cloud current]

- **Bare current: Quark model**
- **Meson cloud current:**
  Educated phenomenological parametrizations

$$G_\alpha(q^2) = G_\alpha^{\rm Bare}(q^2) + G_\alpha^{\rm MC}(q^2)$$

CSQM: Photon-Quark coupling [Extra]

- $j_q^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$, Quark form factors: $j_i = \frac{1}{2} f_{i+} \lambda_0 + \frac{1}{6} f_{i-} \lambda_3 + \frac{1}{2} f_{i0} \lambda_s$
  [parametrize gluon and $q\bar{q}$ dressing of quarks] λ_l: Gell-Mann matrices
  Vector meson dominance parameterization: PRD 80, 033004 (2009)



$$f_{1\pm} = \lambda_q + (1-\lambda_q) \frac{m_v^2}{m_v^2 + Q^2} + c_\pm \frac{M_h^2 Q^2}{(M_h^2 + Q^2)^2}$$

$$f_{10} = \lambda_q + (1-\lambda_q) \frac{m_\phi^2}{m_\phi^2 + Q^2} + c_0 \frac{M_h^2 Q^2}{(M_h^2 + Q^2)^2}$$

$$f_{2\pm} = \kappa_\pm \left\{ d_\pm \frac{m_v^2}{m_v^2 + Q^2} + (1-d_\pm) \frac{M_h^2}{M_h^2 + Q^2} \right\}$$

$$f_{20} = \kappa_0 \left\{ d_0 \frac{m_\phi^2}{m_\phi^2 + Q^2} + (1-d_0) \frac{M_h^2}{M_h^2 + Q^2} \right\}$$

Light mesons ($m_v = m_\rho$), m_ϕ and **effective** heavy meson: $M_h = 2M_N$
Fix coefficients (c_0, $c_\pm$, d_0, $d_+ = d_-$) and a. m. m. $\kappa_\pm$, κ_0, – universal parameters
Use: Nucleon EM form factors; lattice QCD data (decuplet baryon)

CSQM: **Octet** wave function (1)

S-state approximation (quark-diquark) P: Baryon; k: diquark

F Gross, GR and K Tsushima, PLB 690, 183 (2010):

$$\Psi_B(P,k) = \frac{1}{\sqrt{2}}\left[|M_S\rangle \Phi_S^0 + |M_A\rangle \Phi_S^1\right]\psi_B(P,k)$$

$|M_S\rangle, |M_A\rangle$: flavor states; $\Phi_S^{0,1}$: spin states

B	$\|M_S\rangle$	$\|M_A\rangle$
p	$\frac{1}{\sqrt{6}}\left[(ud+du)u - 2uud\right]$	$\frac{1}{\sqrt{2}}(ud-du)u$
n	$-\frac{1}{\sqrt{6}}\left[(ud+du)d - 2ddu\right]$	$\frac{1}{\sqrt{2}}(ud-du)d$
Λ^0	$\frac{1}{2}\left[(dsu-usd) + s(du-ud)\right]$	$\frac{1}{\sqrt{12}}\left[s(du-ud) - (dsu-usd) - 2(du-ud)s\right]$
Σ^+	$\frac{1}{\sqrt{6}}\left[(us+su)u - 2uus\right]$	$\frac{1}{\sqrt{2}}(us-su)u$
Σ^0	$\frac{1}{\sqrt{12}}\left[s(du+ud) + (dsu+usd) - 2(ud+du)s\right]$	$\frac{1}{2}\left[(dsu+usd) - s(ud+du)\right]$
Σ^-	$\frac{1}{\sqrt{6}}\left[(sd+ds)d - 2dds\right]$	$\frac{1}{\sqrt{2}}(ds-sd)d$
Ξ^0	$-\frac{1}{\sqrt{6}}\left[(ud+du)s - 2ssu\right]$	$\frac{1}{\sqrt{2}}(us-su)s$
Ξ^-	$-\frac{1}{\sqrt{6}}\left[(ds+sd)s - 2ssd\right]$	$\frac{1}{\sqrt{2}}(ds-sd)s$

CSQM: **Octet** wave function (2) $SU(3)$ breaking

Radial wave functions: $\psi_B[(P-k)^2]$
Defined in terms of

$$\chi_B = \frac{(M_B - m_D)^2 - (P-k)^2}{M_B m_D}$$

$$\psi_N(P,k) = \frac{N_N}{m_D(\beta_1 + \chi_N)(\beta_2 + \chi_N)}$$

$$\psi_\Lambda(P,k) = \frac{N_\Lambda}{m_D(\beta_1 + \chi_\Lambda)(\beta_3 + \chi_\Lambda)}$$

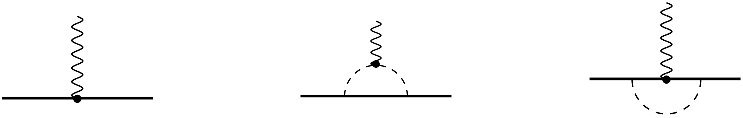
$$\psi_\Sigma(P,k) = \frac{N_\Sigma}{m_D(\beta_1 + \chi_\Sigma)(\beta_3 + \chi_\Sigma)}$$

$$\psi_\Xi(P,k) = \frac{N_\Xi}{m_D(\beta_1 + \chi_\Xi)(\beta_4 + \chi_\Xi)}$$

β_i: momentum range parameters: $\beta_4 > \beta_3 > \beta_2 > \beta_1$
long range: β_1 (all systems)
short range: β_2 (lll systems); β_3 (sll systems); β_4 (ssl systems)

Octet baryon EM form factors (Bare + Meson Cloud)

$$G_{EB} = F_{1B} - \frac{Q^2}{2M^2} F_{2B}, \qquad G_{MB} = F_{1B} + F_{2B}$$



$$F_{1B}(Q^2) = Z_B \left[\tilde{e}_{0B} + a_1 b_1(Q^2) + a_2 c_1(Q^2) + a_3 d_1(Q^2) \right]$$
$$F_{2B}(Q^2) = Z_B \left[\tilde{\kappa}_{0B} + a_1 b_2(Q^2) + a_2 c_2(Q^2) + a_3 d_2(Q^2) \right]$$

a_j combination of $\tilde{e}_{0B}$, $\tilde{\kappa}_{0B}$; b_i, c_i, d_i meson cloud functions

$$\tilde{e}_{0B} = \left(\frac{3}{2} j_1^A + \frac{1}{2} \frac{3-\tau}{1+\tau} j_1^S - 2 \frac{\tau}{1+\tau} \frac{M_B}{M_N} j_2^S \right) B, \qquad \tilde{\kappa}_{0B} = \left[\left(\frac{3}{2} j_2^A - \frac{1}{2} \frac{1-3\tau}{1+\tau} j_2^S \right) \frac{M_B}{M_N} - 2 \frac{1}{1+\tau} j_1^S \right] B$$

$$B(Q^2) = \int_k \psi_B(P',k) \psi_B(P,k), \qquad j_i^A = \langle M_A | \, j_i \, | M_A \rangle, \qquad j_i^S = \langle M_S | \, j_i \, | M_S \rangle$$

Octet baryon EM form factors in lattice QCD (p, Σ^+)

Lattice QCD (bare):

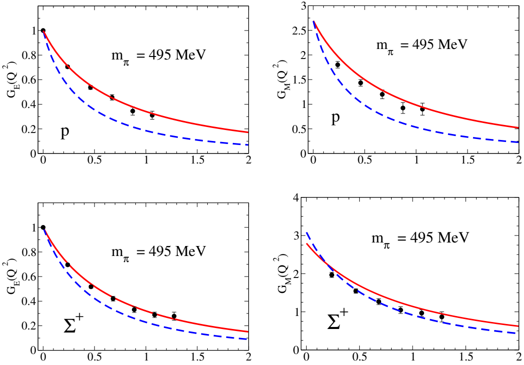
- Quark current – VMD $\ell = 0, \pm$

$$f_{i\ell}(Q^2; m_v, M_N) \to f_{i\ell}(Q^2; m_v^{\rm latt}, M_N^{\rm latt})$$

- Radial wave functions (fit):

$$\psi_B(M_B) \to \psi_B(M_B^{\rm latt})$$

GR, MT Peña, JPG 36, 115011 (2009);
PRD 80, 013008 (2009);
GR, K Tsushima, F Gross, PRD 80, 033004 (2009);
GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013)



Physical regime:

Use parametrizations derived from lattice with physical masses

—— Lattice - - - Physical

Bare parameters determined without contamination of meson cloud effects (large m_π) – radial wf

Bare contribution extrapolated to $m_\pi = m_\pi^{\rm phy}$

Octet baryon EM form factors – physical regime (p, Σ^+)

Physical Form Factors:

$G_\ell = Z_B \left[G_\ell^{\rm B} + G_\ell^\pi \right]$

$G_\ell^{\rm B}$ from lattice QCD

G_ℓ^π calibrated by

physical data

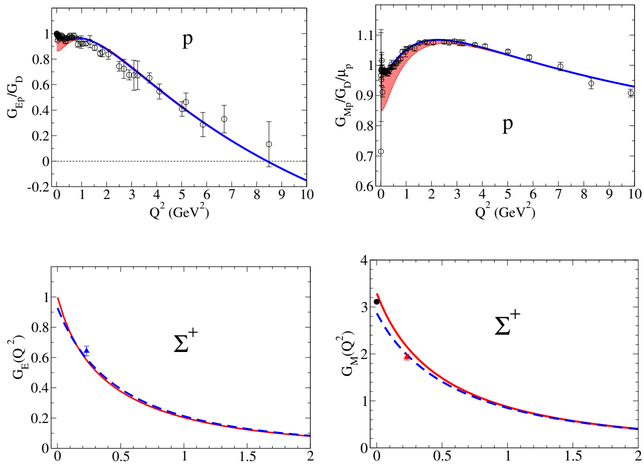
⋆Nucleon EMFF

⋆Octet baryon

magnetic moments

Model compatible with lattice QCD data and physical data

Can be used to calculate **octet baryon FF** in different regimes of Q^2



- - - Bare —— Bare + Meson Cloud

Octet baryon electromagnetic form factors in medium

GR, K Tsushima, AW Thomas JPG 40, 015102 (2013)
GR, JPBC Melo, K Tsushima PRD 100, 014030 (2019)

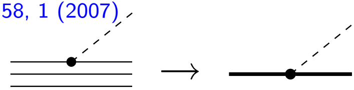
Density: $\rho = 0.5\rho_0$, ρ_0 $\qquad \rho_0 = 0.15$ fm^{-3} (normal nuclear matter)

Symmetric nuclear matter - Equation of state

Quark-Meson-Coupling model

Saito, Tsushima and Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)

$$M_H^* = M_H - g_\sigma \sigma + \dots$$



Calculate medium modifications of **masses** and **coupling constants** for $\rho = 0.5\rho_0$ and $\rho = \rho_0$ ($\rho_0 = 0.15$ fm^{-3}) – masses **reduced** in medium

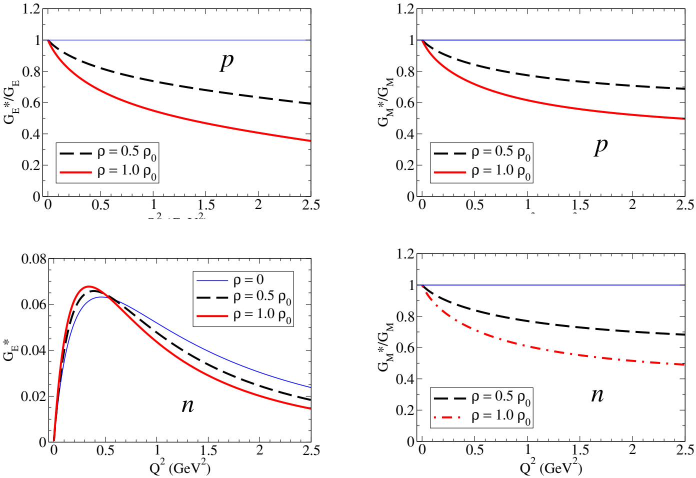
Goldberger-Treimann relation: $\frac{g^*_{\pi BB}}{g_{\pi BB}} \simeq \left(\frac{f_\pi}{f^*_\pi}\right)\left(\frac{g_A^{N*}}{g_A^N}\right)\left(\frac{M_B^*}{M_B}\right)$

Goldberger and Treiman, PRC 110, 1178 (1958)

	$\rho = 0$	$\rho = 0.5\rho_0$	$\rho = \rho_0$
M_N	939.0	831.3	754.5
M_Λ	1116.0	1043.9	992.7
M_Σ	1192.0	1121.4	1070.4
M_Ξ	1318.0	1282.2	1256.7
m_ρ	779.0	706.1	653.7
m_ϕ	1019.5	1019.1	1018.9
m_π	138.0	138.0	138.0

	$\rho = 0$	$\rho = 0.5\rho_0$	$\rho = \rho_0$
$g^*_{\pi NN}/g_{\pi NN}$	1	0.921	0.899
$g^*_{\pi\Lambda\Sigma}/g_{\pi\Lambda\Sigma}$	1	0.973	0.996
$g^*_{\pi\Sigma\Sigma}/g_{\pi\Sigma\Sigma}$	1	0.977	1.004
$g^*_{\pi\Xi\Xi}/g_{\pi\Xi\Xi}$	1	1.012	1.067

Octet baryon EM form factors

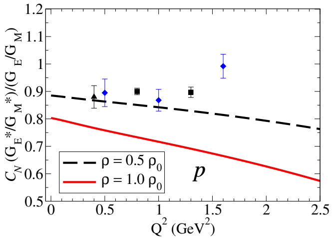


- **Proton:** G_E, G_M suppressed in medium (quenched effect)
- **Neutron:** G_E small effect; $\frac{G_E^*}{G_E} \propto \frac{r_{En}^{*2}}{r_{En}^2}$ enhancement; G_M suppress.

Octet baryon EM FF – double ratios $(G_E^*/G_M^*)/(G_E/G_E)$

Ratios $\frac{G_E^*}{G_E}$ and $\frac{G_M^*}{G_M}$ are NOT directly measured

We can measure G_E/G_M in vacuum and in medium (^{4}He)

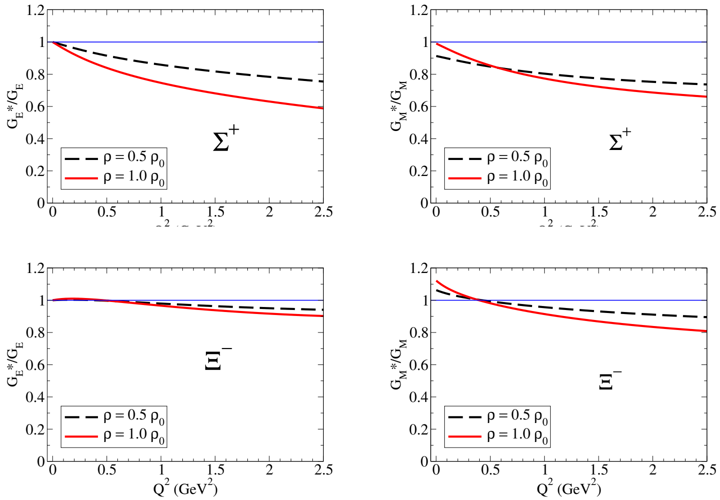


Proton: G_E/G_M is supressed in medium, Data from JLab and MAMI

Include G_M in units $\hat{\mu}_N = \frac{e}{2M_N}$ (*correction:* $C_N = \frac{M_N^*}{M_N}$) strong G_M eff.

Neutron: G_E/G_M enhanced in medium (prediction)

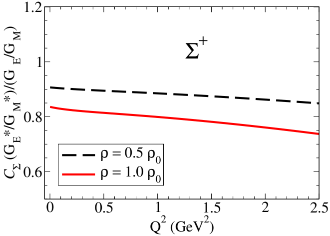
Hyperon EM form factors

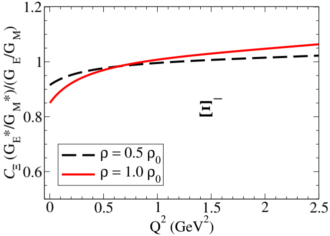


G_E: quenched (softer than p); G_M: low Q^2: enhanced; large Q^2: suppressed

Ξ^-: **Milder effects** (softer medium effects for strange quarks)

Hyperon EM FF – double ratios $(G_E^*/G_M^*)/(G_M/G_E)$





Σ^-: Quenching (softer than proton)

Ξ^-: **Low** Q^2**:** quenching (due to G_M); **Large** Q^2**: Milder** medium effects

Neutral baryons: softer medium effects (not discussed here)

Axial form factors in medium

GR, K Tsushima, MK Cheoun PRD 111, 013002 (2025)

Octet baryon: axial-vector transitions

Charged Current (CC) transitions (6 + 6)

$|\Delta I| = 1$ $(d \to u)$

$n \to p$

$\Sigma^- \to \Lambda$

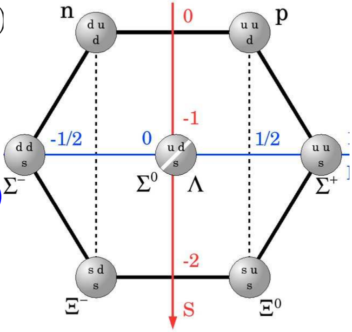
$\Sigma^+ \to \Lambda$ $(u \to d)$

$\Sigma^0 \to \Sigma^+$

$\Sigma^- \to \Sigma^0$

$\Xi^- \to \Xi^0$

6 transitions



$|\Delta S| = 1$ $(s \to u)$

$\Sigma^- \to n$

$\Sigma^0 \to p$

$\Lambda \to p$

$\Xi^- \to \Sigma^0$

$\Xi^- \to \Lambda$

$\Xi^0 \to \Sigma^+$

6 transitions

Neutral current transitions (8): $G_A(n) = -G_A(n \to p)$;
$G_A(\Sigma^+) = \sqrt{2} G_A(\Sigma^0 \to \Sigma^+)$, $G_A(\Xi^0) = G_A(\Xi^- \to \Xi^0)$

Octet baryon axial-vector form factors in vacuum

[GR and K Tsushima PRD 94, 014001 (2016)] Generalization of nucleon to octet baryon

$$(J_5^\mu)_a = \bar{u}(P_+)\left[G_A(Q^2)\gamma^\mu + G_P(Q^2)\frac{q^\mu}{2M}\right]\gamma_5 u(P_-)\,\frac{\lambda_a}{2},$$

- Extend octet model to the axial-vector transition; P-state mixture

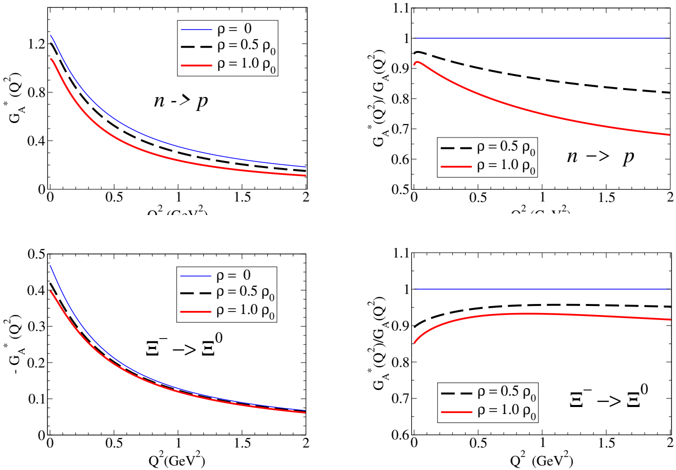
$$j_{Aq}^\mu = \left(g_A^q\gamma^\mu + g_P^q\frac{q^\mu}{2M}\right)\gamma_5\frac{\tau_a}{2}, \qquad \Psi_N = \sqrt{1-n_P^2}\,\Psi_S + n_P\Psi_P$$

- $g_A^q \equiv f_{1-}$ (isovector); g_P^q fit to the lattice QCD data for nucleon

$$G_A = G_A^B + G_A^{MC}, \qquad G_P = G_P^{\rm pole} + G_P^B + G_P^{MC}, \qquad G_P^{\rm pole} = \frac{4M^2}{\mu^2+Q^2}G_A^B$$

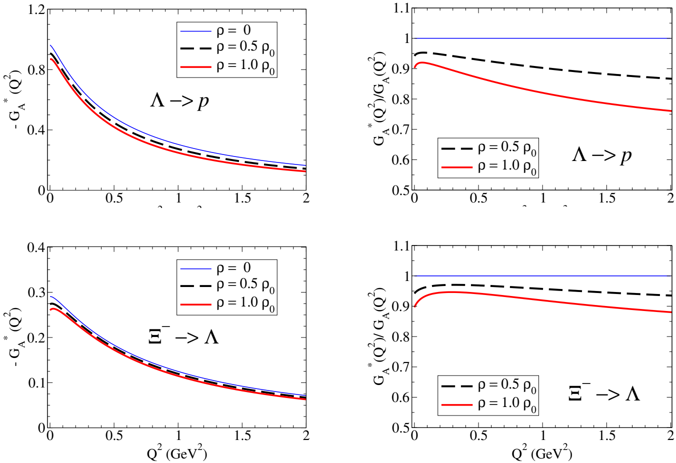
- $\mu = m_\pi$ $(\Delta S = 0)$, $\mu = m_K$ $(\Delta S = 1)$
  G_A^{MC}: $SU(3)$ effective model (D, $F \sim g_{\pi NN}^2$)
- Bare: lattice data, $SU(6)$; Meson-Cloud: nucleon and $G_A^{B,B'}(0)$ data

Axial Form Factors – $|\Delta I| = 1$



- Suppression in medium: **stronger** for **light baryons**
- Suprr. increases with Q^2 (light baryons); Heavy baryons: milder effect

Axial Form Factors – $|\Delta S| = 1$



- Similar to $|\Delta I| = 1$ case; softer effect
  Light baryons: softer falloff
- **Heavy baryons:** milder effect (**weak** Q^2 deppendence)

Applications

- Study of neutrino-nucleon and (antineutrino)-nucleon scattering in a nuclear medium (densities $0 \leq \rho \leq \rho_0$)
  Charged Currents ($B' \to BW^{\pm}$); Neutral Currents ($B \to BZ^0$)
  Form Factors $\Rightarrow$ $\left(\frac{d\sigma}{dQ^2}\right)_{\nu N}(Q^2, E_\nu)$, $\left(\frac{d\sigma}{dQ^2}\right)_{\bar{\nu} N}(Q^2, E_\nu)$
- In progress:
  - Study of ν-hyperon and $\bar{\nu}$-hyperon scattering
  - Extend calculations to higher densities ($\rho > \rho_0$)

Applications: Study of weak interactions with NC (neutral currents) and CC (charged currents)

M.K. Cheoun, K.S. Choi, S. Kim, K. Saito, T. Kajino, K. Tsushima and T. Maruyama, PRC 87, 065502 (2013)

we calculated differential cross sections of the neutrino (antineutrino) reactions on the nucleon via NC as follows [31,32]:

$$\left(\frac{d\sigma}{dQ^2}\right)^{NC}_{\nu(\bar{\nu})} = \frac{G_F^2}{2\pi}\left[\frac{1}{2}y^2(G_M)^2 + \left(1-y-\frac{M}{2E_\nu}y\right)\frac{(G_E)^2+\frac{E_\nu}{2M}y(G_M)^2}{1+\frac{E_\nu}{2M}y} + \left(\frac{1}{2}y^2+1-y+\frac{M}{2E_\nu}y\right)(G_A)^2 \mp 2y\left(1-\frac{1}{2}y\right)G_M G_A\right],$$

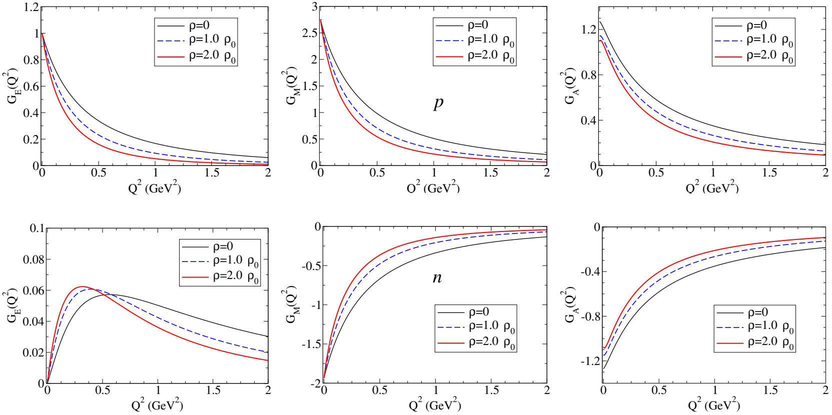
$$\left(\frac{d\sigma}{dQ^2}\right)^{CC}_{\nu(\bar{\nu})} = \left(\frac{d\sigma}{dQ^2}\right)^{NC}_{\nu(\bar{\nu})} (G_E \to G_E^{CC}, G_M \to G_M^{CC}, G_A \to G_A^{CC}), \tag{6}$$

with

$$G_E^{CC} = G_E^p(Q^2) - G_E^n(Q^2), \quad G_M^{CC} = G_M^p(Q^2) - G_M^n(Q^2). \tag{7}$$

Include EMFF G_E, G_M and Axial FF G_A (mixture of p and n), $y = \frac{Q^2}{2ME_\nu}$

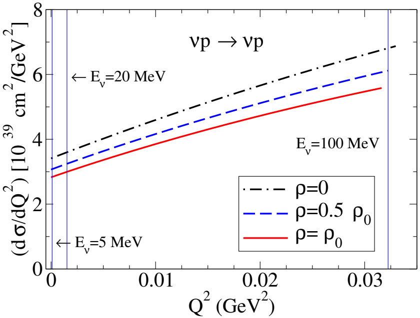
Proton and neutron FF – NC and CC transitions

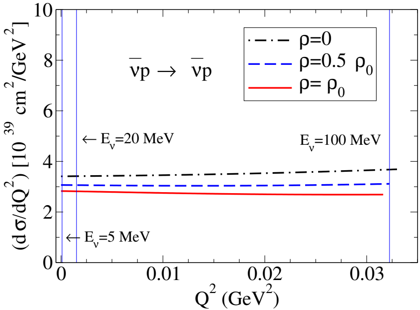


Used in calculation of $G_\ell^{\rm NC}$ $(\ell = E, M, A)$; **Include extension to** $\rho > \rho_0$

PRD 111, 013002 (2025): G_ℓ reduced in medium (except for G^*_{En})

Neutrino-nucleon cross sections in medium $E_\nu = 100$ MeV





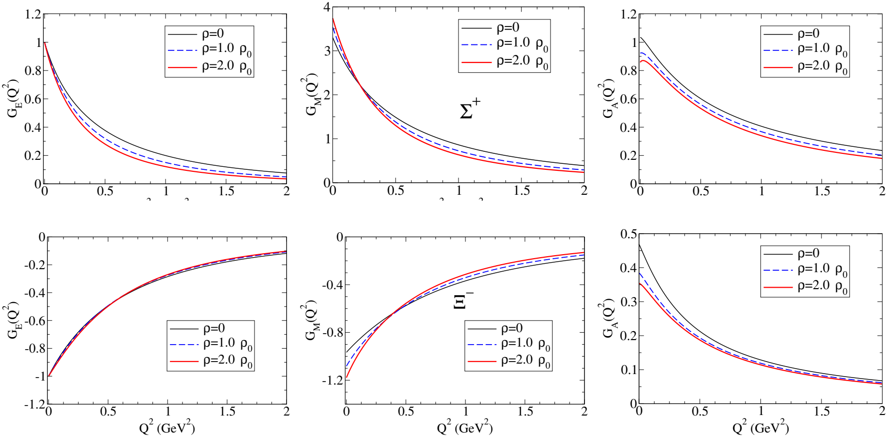
$0 \leq Q^2 \leq \frac{4E_\nu^2}{1+2\frac{E_\nu}{M}}$; Cross sections **reduced** in nuclear medium (quenched)

Cross section νp dominate over cross section $\bar{\nu} p$

Similar trend for $\nu n \to e^- p$ and $\bar{\nu} p \to e^+ n$ cross sections

Hyperon Form Factors in medium

Σ^+, Ξ^- form factors: G_A, G_E reduced; G_M^* enhanced at low Q^2



Outlook and Conclusions

- Calculations of EM and Axial form factors in-medium
  are important to study interactions in **dense nuclear matter**
- Electromagnetic and Axial form factors are modified
  in nuclear medium (quenched or enhanced) and in nucleus
  Effects increase with density
  Milder effects for hyperons with more strange quarks
  Calculations of G_P (quenched) are also available
- νN and $\bar{\nu} N$ cross sections are in general **reduced** in medium
- **In progress:**
  Extension of calculations to higher densities ($\rho > \rho_0$)
  Study of ν-hyperon and $\bar{\nu}$-hyperon cross sections in medium

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Thank you 🙂 **Arigatou**

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Thank you **Arigatou**

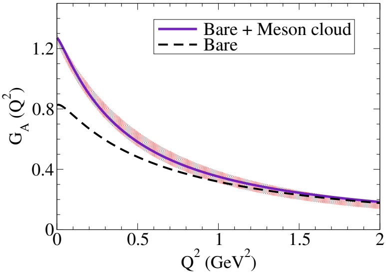
More questions: gilberto.ramalho2013@gmail.com

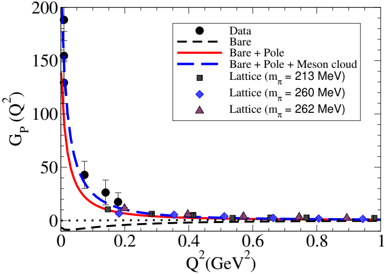
Backup slides

Axial form factors in medium

GR, K Tsushima, MK Cheoun PRD 111, 013002 (2025)

Octet Axial form factors [Nucleon $\to$ Octet]





$$G_A^{MC} = Z_N \frac{G_A^{MC0}}{\left(1+\frac{Q^2}{\Lambda^2}\right)^4} \qquad G_P = G_P^B + \frac{4M^2}{\mu^2+Q^2} G_A^B + \frac{4M^2}{\mu^2+Q^2} G_A^{MC}$$

$$G_A^{MC} = \sqrt{Z_B Z_{B'}} \frac{aF+bD}{\left(1+\frac{Q^2}{\Lambda^2}\right)^4},$$ F, D: $SU(3)$ meson cloud coefficients

Bare part: replace $f_X^{S,A}$, masses, etc. $\quad \mu = m_{\pi/K}$

Model: bare contributions $X = I_\pm, V_\pm$

$$\tilde{G}_A^B = g_A^q \mathcal{F} \left\{ \frac{3}{2} n_S^2 B_0 - 3 n_{SP} \frac{\tau}{1+\tau} B_1 + \frac{6}{5} n_P^2 \left[\tau B_2 - (1+\tau) B_4 \right] \right\}$$

$$\begin{aligned} \tilde{G}_P^B &= g_A^q \mathcal{F} \left\{ -3 n_{SP} \frac{1}{1+\tau} B_1 + \frac{3}{2} n_P^2 \left[\frac{B_5}{\tau} + 2(B_2 - B_4) \right] \right\} \\ &+ \frac{M_{BB'}}{M} g_P^q \mathcal{F} \left\{ \frac{3}{2} n_S^2 B_0 - 3 n_{SP} B_1 + \frac{3}{2} n_P^2 \left[\tau B_2 + B_3 - (2+\tau) B_4 \right] \right\} \end{aligned}$$

$$f_X^A = {}_{B'}\langle M_A | X | M_A \rangle_B \,, \qquad f_X^S = {}_{B'}\langle M_S | X | M_S \rangle_B \,, \qquad \mathcal{F} = \left(f_X^A - \frac{1}{3} f_X^S \right)$$

$n_{SP} = n_S n_P$, $M_{BB'} = \frac{1}{2}(M_B + M_{B'})$, B_l overlap integrals of ψ_S and ψ_P

Model: bare contributions: coefficients $f_X^{A,S}$

		$B \to B'$	f_X^A	f_X^S	$\mathcal{F}$
$\Delta I = 1$	(I_+)	$n \to p$	1	$-\frac{1}{3}$	$\frac{10}{9}$
	$(I_\mp)$	$\Sigma^\pm \to \Lambda$	$\pm\frac{1}{\sqrt{6}}$	$\mp\frac{1}{\sqrt{6}}$	$\pm\frac{2\sqrt{2}}{3\sqrt{3}}$
	$(I_\pm)$	$\Sigma^0 \to \Sigma^\pm$	$\frac{1}{\sqrt{2}}$	$\frac{1}{3\sqrt{2}}$	$\frac{4\sqrt{2}}{9}$
	(I_+)	$\Xi^- \to \Xi^0$	0	$\frac{2}{3}$	$-\frac{2}{9}$
$\Delta S = 1$	(V_+)	$\Lambda \to p$	$-\frac{2}{\sqrt{6}}$	0	$-\sqrt{\frac{2}{3}}$
	(V_+)	$\Sigma^- \to n$	0	$-\frac{2}{3}$	$\frac{2}{9}$
	(V_+)	$\Sigma^0 \to p$	0	$-\frac{\sqrt{2}}{3}$	$\frac{\sqrt{2}}{9}$
	(V_+)	$\Xi^- \to \Lambda$	$-\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{6}}$	$-\frac{\sqrt{2}}{3\sqrt{3}}$
	(V_+)	$\Xi^- \to \Sigma^0$	$\frac{1}{\sqrt{2}}$	$-\frac{1}{3\sqrt{2}}$	$\frac{5\sqrt{2}}{9}$
	(V_+)	$\Xi^0 \to \Sigma^+$	1	$-\frac{1}{3}$	$\frac{10}{9}$
NC	(I_0)	$N \to N$	τ_3	$-\frac{1}{3}\tau_3$	$\frac{10}{9}\tau_3$
	(I_0)	$\Sigma \to \Sigma$	I_Σ	$\frac{1}{3}I_\Sigma$	$\frac{8}{9}I_\Sigma$
	(I_0)	$\Xi \to \Xi$	0	$\frac{2}{3}\tau_3$	$-\frac{2}{9}\tau_3$

$\Delta I = 1$, $\Delta S = 1$ CC transitions; NC transitions $\nu B \to \nu B$, $\bar{\nu} B \to \bar{\nu} B$

$p \to p$: $G_A^{p\to p} \equiv G_A^{n \to p}$

Octet baryon electromagnetic form factors in medium

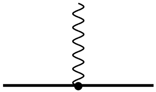
GR, K Tsushima, AW Thomas JPG 40, 015102 (2013)
GR, JPBC Melo, K Tsushima PRD 100, 014030 (2019)

Octet baryon: total electromagnetic current

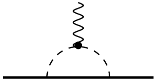
$$J^\mu = J^\mu_{0B} + J^\mu_{\pi B} + J^\mu_{\gamma B}$$

$J^\mu_{0B} \leftrightarrow$ QM

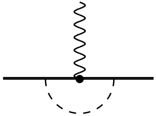
$$J^\mu_{0B} = Z_B \left[\tilde{e}_B \gamma^\mu + \tilde{\kappa}_B \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right]$$



$$J^\mu_{\pi B} = Z_B \left[\tilde{B}_1 \gamma^\mu + \tilde{B}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\pi B}$$



$$J^\mu_{\gamma B} = Z_B \left[\tilde{C}_1 \gamma^\mu + \tilde{C}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{eB} + Z_B \left[\tilde{D}_1 \gamma^\mu + \tilde{D}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\kappa B}$$



$G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ flavor part – known; $SU(3)$ functions $\tilde{B}_i, \tilde{C}_i, \tilde{D}_i$ – fited

GR and K Tsushima, PRD 84, 054014 (2011)

Pion cloud: adding PC effects †

- Projecting $G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ $\Rightarrow$ coupling constants β_B

$$\beta_N = 1, \qquad \beta_\Lambda = \frac{4}{3}\alpha^2$$
$$\beta_\Sigma = 4(1-\alpha)^2, \qquad \beta_\Xi = (1-2\alpha)^2$$

$SU(6)$ limit: $\alpha = 0.6$; and $g = g_{\pi NN}$ $\longrightarrow$ included in $\tilde{B}_i$, $\tilde{C}_i$, $\tilde{D}_i$

- Fit functions of Q^2: $\tilde{B}_i, \tilde{C}_i$, $\tilde{D}_i$ $\longrightarrow$ δG_{EB}, δG_{MB} **pion cloud**

GR and K Tsushima, PRD 84, 054014 (2011);

Bare: $\tilde{e}_B, \tilde{\kappa}_B$ F Gross, GR and MT Peña, PRC 77, 015202 (2008)

$$F_{1B} = Z_B\left[\tilde{e}_B + \delta F_{1B}\right], \qquad G_{EB} = Z_B\left[G_{E0B} + \delta G_{EB}\right]$$
$$F_{2B} = Z_B\left[\tilde{\kappa}_B + \delta F_{2B}\right], \qquad G_{MB} = Z_B\left[G_{M0B} + \delta G_{MB}\right]$$

Z_B is a normalization factor

Calibration of the model in vacuum

$$G_X(Q^2) = Z_B \left[G_X^B(Q^2) + G_X^\pi(Q^2) \right] \qquad X = E, M$$

- Calibration of model in **vacuum** by **Lattice QCD data** (radial wave functions) – bare part
- **Physical data** (N form factors, magnetic moments, baryon radii) – pion cloud part: coefficients (B_1, B_2, C_2,, D_1', D_2) $\oplus$ cutoffs Λ_1, Λ_2

$$|B\rangle = \sqrt{Z_B}\left[|qqq\rangle + |\pi B_0\rangle \right] \qquad Z_B = \frac{1}{1 + a_B B_1}$$

Normalization dependent on the photon-pion function $B_1 \equiv \tilde{B}_1(0)$ – self-energy

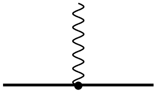
GR, Tsushima, Thomas, JPG 40, 015102 (2013); GR and K Tsushima, PRD 84, 054014 (2011)

Octet baryon: total electromagnetic current (pion) †

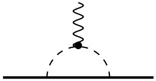
$$J^\mu = J^\mu_{0B} + J^\mu_{\pi B} + J^\mu_{\gamma B}$$

$J^\mu_{0B} \leftrightarrow$ QM

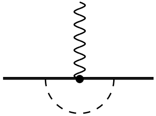
$$J^\mu_{0B} = Z_B \left[\tilde{e}_B \gamma^\mu + \tilde{\kappa}_B \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right]$$



$$J^\mu_{\pi B} = Z_B \left[\tilde{B}_1 \gamma^\mu + \tilde{B}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\pi B}$$



$$J^\mu_{\gamma B} = Z_B \left[\tilde{C}_1 \gamma^\mu + \tilde{C}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{eB} + Z_B \left[\tilde{D}_1 \gamma^\mu + \tilde{D}_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_B} \right] G_{\kappa B}$$



$G_{\pi B}, G_{eB}$ and $G_{\kappa B}$ flavor part – known; $SU(3)$ functions $\tilde{B}_i, \tilde{C}_i, \tilde{D}_i$ – fited

GR and K Tsushima, PRD 84, 054014 (2011)

Dressed form factors – Nucleon – example †

Nucleon dresssed form factors [GR and K Tsushima, PRD 84, 054014 (2011)]

$$
\begin{aligned}
F_{1p} &= Z_N \left\{ \tilde{e}_{0p} + 2\beta_N \tilde{B}_1 + \beta_N (\tilde{e}_{0p} + 2\tilde{e}_{0n}) \tilde{C}_1 + \beta_N (\tilde{\kappa}_{0p} + 2\tilde{\kappa}_{0n}) \tilde{D}_1 \right\} \\
F_{2p} &= Z_N \left\{ \tilde{\kappa}_{0p} + 2\beta_N \tilde{B}_2 + \beta_N (\tilde{e}_{0p} + 2\tilde{e}_{0n}) \tilde{C}_2 + \beta_N (\tilde{\kappa}_{0p} + 2\tilde{\kappa}_{0n}) \tilde{D}_2 \right\}
\end{aligned}
$$

$$
\begin{aligned}
F_{1n} &= Z_N \left\{ \tilde{e}_{0n} - 2\beta_N \tilde{B}_1 + \beta_N (2\tilde{e}_{0p} + \tilde{e}_{0n}) \tilde{C}_1 + \beta_N (2\tilde{\kappa}_{0p} + \tilde{\kappa}_{0n}) \tilde{D}_1 \right\} \\
F_{2n} &= Z_N \left\{ \tilde{\kappa}_{0n} - 2\beta_N \tilde{B}_2 + \beta_N (2\tilde{e}_{0p} + \tilde{e}_{0n}) \tilde{C}_2 + \beta_N (2\tilde{\kappa}_{0p} + \tilde{\kappa}_{0n}) \tilde{D}_2 \right\}
\end{aligned}
$$

F Gross, GR and K Tsushima PLB 690, 183 (2010): $Z_N = 1/(1 + 3\beta_N B_1)$

$F_{1p}(0) = 1$ and $F_{1n}(0) = 0 \Longrightarrow \tilde{D}_1(0) = 0$ and $\tilde{B}_1(0) = \tilde{C}_1(0) \equiv B_1$

Pion cloud: Normalization factor †

Z_B normalization factor; determined by the charge or self-energy

Nucleon case, using $B_1 = \tilde{B}_1(0) = \tilde{C}_1(0)$

$$G_{Ep}(0) = Z_N \left[1 + 2\beta_N B_1 + \beta_N B_1\right] = 1$$
$$G_{En}(0) = Z_N \left[0 - 2\beta_N B_1 + 2\beta_N B_1\right] = 0$$

Then $G_{Ep}(0) = 1 = Z_N[1 + 3\beta_N B_1]$:

$$Z_N = \frac{1}{1 + 3\beta_N B_1}$$

Similar for Z_Λ, Z_Σ and Z_Ξ