Weak Interactions in Nuclear Matter

Myung-Ki Cheoun (SSU & OMEG)
(Soongsil University, OMEG Institute & Dept. of Physics, Seoul, Korea)
https://omeg.ssu.ac.kr/

T. Miyatsu, K. Saito, G. Gamalho, K. Tsushima

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Koichi Saito (Tokyo U. of Sci.), Tsuyoshi Miyatsu (SoongSil U.), Myung-Ki Cheoun (SoongSil U.) (Sep 23, 2024)

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Electromagnetic |GE/GM| ratios of hyperons at large timelike q2

G. Ramalho (SoongSil U.), M.T. Peña (LIP, Lisbon and Espirito Santo U.), K. Tsushima (Cruzeiro do Sul U.), Myung-Ki Cheoun (SoongSil U.) 2024)

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Weak interaction axial form factors of the octet baryons in nuclear medium

G. Ramalho (SoongSil U.), K. Tsushima (Cruzeiro do Sul U.), Myung-Ki Cheoun (SoongSil U.) (Jun 12, 2024)

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4-1. Understanding of beta decay and Cabibbo angle

Since the **weak interaction couples to weak eigenstates**, we express the down-type quarks in terms of mass eigenstates via the **CKM matrix**:

$$d' = V_{ud} d + V_{us} s + V_{ub} b$$

For neutron beta decay ($n \to p$), only the $V_{ud} d$ term is relevant. Thus, the weak Lagrangian simplifies to:

$$\mathcal{L}_{\text{weak}} = -\frac{g}{\sqrt{2}} V_{ud} \left[\bar{u}\gamma^\mu (1-\gamma^5) d\right] W_\mu^+$$

---

2. Integrating Out the W-Boson

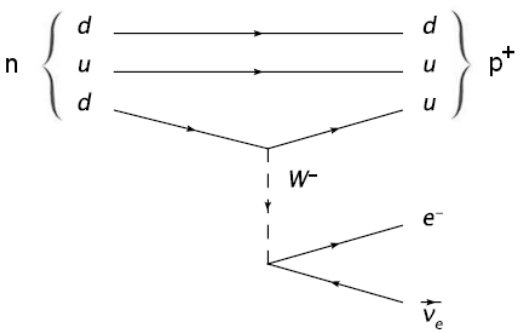
At **low energies** ($E \ll M_W$), we can replace the W^+-boson by an effective f interaction using the relation:

$$\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$$

which gives the **effective weak Lagrangian**:

$$\mathcal{L}_{\text{eff}} = \frac{G_F V_{ud}}{\sqrt{2}} \left[\bar{u}\gamma^\mu (1-\gamma^5) d\right] \left[\bar{e}\gamma_\mu (1-\gamma^5)\nu_e\right]$$

This is the **quark-level** interaction responsible for neutron beta decay.



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3. Transition to the Nucleon Level

Since the neutron (n) consists of **(udd)** and the proton (p) consists of **(uud)**, the quark current:

$$\bar{u}\gamma^\mu (1-\gamma^5) d$$

is embedded inside the neutron and proton wavefunctions. We define the **hadronic matrix element**:

$$\langle p|\bar{u}\gamma^\mu (1-\gamma^5) d|n\rangle = g_V \bar{p}\gamma^\mu n - g_A \bar{p}\gamma^\mu \gamma^5 n$$

where:

- $g_V \approx 1.0$ (vector coupling, assuming **Conserved Vector Current (CVC)**),
- $g_A \approx 1.27$ (axial coupling, extracted from neutron decay).

1. Effective Hamiltonian for Beta Decay (Charged Current Interaction)

At **low energies**, the charged current weak interaction can be written as a four-fermion interaction by integrating out the heavy $W^\pm$ bosons:

$$\mathcal{H}_{\text{weak}}^{(\text{CC, nucleon})} = \frac{G_F V_{ud}}{\sqrt{2}} \left[\bar{p}\gamma^\mu (g_V - g_A\gamma^5) n\right] \left[\bar{e}\gamma_\mu (1-\gamma^5)\nu_e\right]$$

where:

- $G_F = 1.166 \times 10^{-5}$ GeV^{-2} is the **Fermi constant**.
- $V_{ud} \approx 0.974$ is the **CKM matrix element** for up-down quark mixing.
- $g_V \approx 1.0$ is the **vector coupling constant** (assuming conserved vector current (CVC) hypothesis).
- $g_A \approx 1.27$ is the **axial-vector coupling constant** (from neutron beta decay).
- p, n, e, ν_e are the **proton, neutron, electron, and neutrino fields**.
- The term $(1-\gamma^5)$ ensures that only **left-handed particles** participate in the weak interaction.

This Hamiltonian governs **nuclear beta decay**, including:

1. **Neutron beta decay**:
2. **Electron capture**:
3. **Beta-plus decay**:

$$\Gamma = \frac{G_F^2 |V_{ud}|^2}{2\pi^3} (g_V^2 + 3g_A^2) m_n^5 f$$

where:

- f is the **Fermi integral**, which depends on the electron energy and phase space effects,
- m_n is the neutron mass.

Numerically, for neutron decay:

$$\Gamma_n = 1.13 \times 10^{-3}\,\text{s}^{-1}$$

which gives a **neutron lifetime**:

$$\tau_n = \frac{1}{\Gamma_n} \approx 880\,\text{seconds}$$

4-1. Understanding of beta decay : neutral current

3. Effective Hamiltonian for Neutral Current Interactions

For **neutral current** weak interactions (mediated by the Z^0 boson), the Hamiltonian takes the form:

$$\mathcal{H}_{\text{weak}}^{(\text{NC, nucleon})} = \frac{G_F}{\sqrt{2}} \bar{N} \gamma^\mu \left(g_V^N - g_A^N \gamma^5 \right) N Z_\mu$$

where:

- g_V^N and g_A^N are the **vector and axial couplings** for nucleons.
- This describes **neutrino-nucleon interactions**, such as:

$$\nu + N \to \nu + N$$

The vector and axial couplings depend on the nucleon content:

- For a proton:

$$g_V^p = \frac{1}{2} - 2\sin^2\theta_W, \quad g_A^p = \frac{1}{2}$$

- For a neutron:

$$g_V^n = -\frac{1}{2}, \quad g_A^n = -\frac{1}{2}$$

where $\sin^2\theta_W \approx 0.231$ is the **Weinberg angle**.

4-2. Weak interaction and CKM matrix

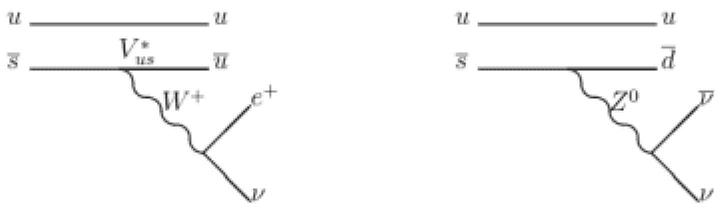
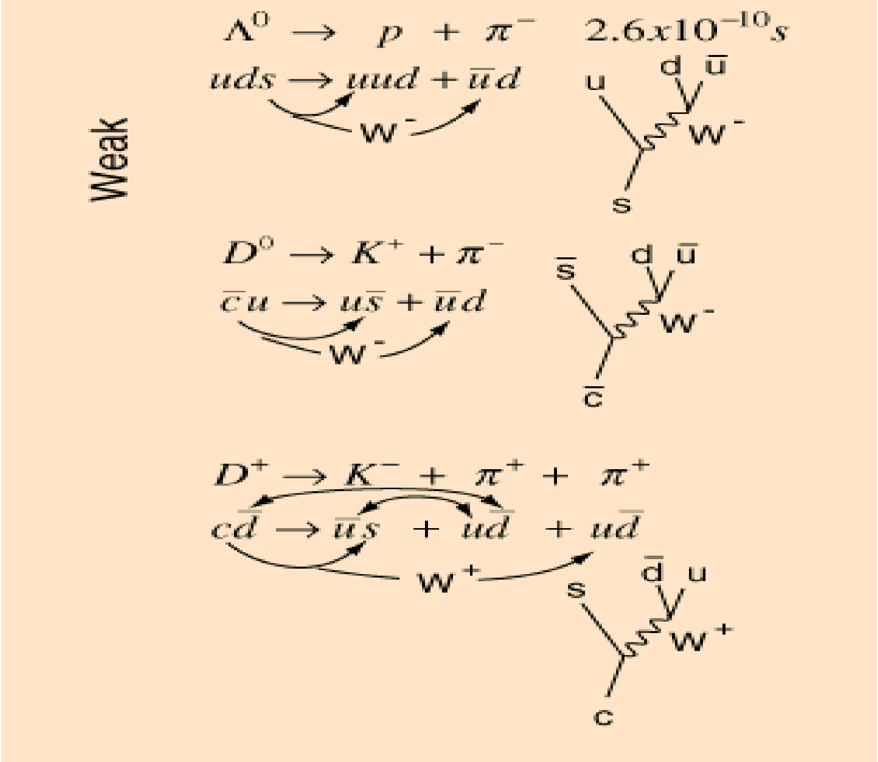


Figure 1.4: The first Feynman diagram describes a first order weak $K^+ \to \pi^0 e^+ \nu_e$ decay, which is allowed in the Standard Model. The second describes a first order weak $K^+ \to \pi^+ \nu\bar{\nu}$ decay, which is not allowed.



Beta Decay
Microscopic picture

When a quark decays, the new quark does not have a definite flavor. For instance:

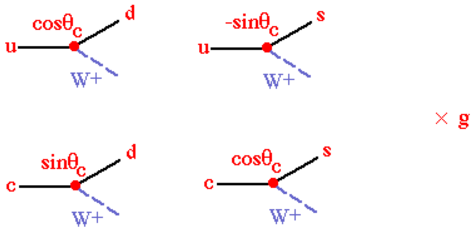
$$u \to d' = d\cos\theta_c + s\sin\theta_c$$ **Cabibbo angle**

However, the observed weak transitions are between quarks of definite flavor. The strong-interaction quark eigenstates

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

are different from weak interaction eigenstates).

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$



This means that the observed beta-decay strength in reactions is modified by the mixing angle.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo _Kobayashi-Maskawa (CKM) matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}, \quad (11.27)$$

4-3. Motivation: SU(3) symmetry (Charge symmetry) breaking effect in CKM matrix

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Effect of isoscalar and isovector scalar fields on baryon semileptonic decays in nuclear matter

Koichi Saito*
Department of Physics and Astronomy, Tokyo University of Science, Noda 278-8510, Japan

Tsuyoshi Miyatsu† and Myung-Ki Cheoun‡
Department of Physics and OMEG Institute, Soongsil University, Seoul 06978, Republic of Korea

The precise determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements is very important because it could be a clue to new physics beyond Standard Model. This is particular true of V_{ud} because it is the main contribution to the unitary condition of the CKM matrix elements. The level of accuracy for the test of the unitarity involving the element V_{ud} is now of the order of 10^{-4}. Because the precise data for V_{ud} is usually extracted from superallowed nuclear β decay, it is quite significant to investigate the breaking of SU(3) flavor symmetry on the weak vector coupling constant in nuclear matter. The purpose of this paper is to investigate how the isoscalar scalar (σ) and the isovector scalar (δ or a_0) mean-fields affect the weak vector and axial-vector coupling constants for semileptonic baryon (neutron, Λ, or Ξ^-) decay in asymmetric nuclear matter. To do so, we use the quark-meson coupling (QMC) model, where nuclear matter consists of nucleons including quark degrees of freedom bound by the self-consistent exchange of scalar and vector mesons. We pay careful attention to the center of mass correction to the quark currents in matter. We then find that, for neutron β decay in asymmetric nuclear matter, the defect of the vector coupling constant due to the δ field can be of the order of 10^{-4} at the nuclear saturation density, which is the same amount as the level of the current uncertainty in the measurements. It is also interesting

Meson	Type	Isospin	Spin-Parity	Role in NN Interaction
π (Pion)	Pseudoscalar	1	0^-	Long-range nuclear force
σ (Sigma)	Scalar	0	0^+	Medium-range attraction
a_0 (980)	Scalar	1	0^+	Short-range repulsion
ρ (Rho)	Vector	1	1^-	Spin-orbit interactions
ω (Omega)	Vector	0	1^-	Short-range repulsion

PDG 2010

$$V_{\rm CKM} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}, \quad (11.27)$$

By Including the isovector scalar meson in the QMC model,
we try to examine the CSB
in the Cabbibo angle !!

CKM Unitarity Test and Scalar Current Search with ^{10}C Superallowed Beta Decay Measurement

Poster

- Unitarity test for the Cabbibo-Kobayashi-Maskawa (CKM) matrix:**precise corrected *ft* value of the superallowed β-decay**
- **^{10}C is the lightest nuclide** exploited for the test, and linked to the scalar current search, Fierz interference term
- For ^{10}C, the **branching ratio has largest uncertainty** in corrected *ft*

Yonghyn Son

4-4. Starting from QMC model to describe the CSB

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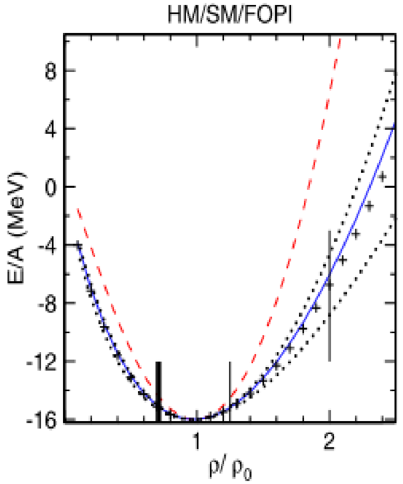

Fig. 4. Various symmetric nuclear matter EOS. Dashed (red) curve, HM; full (blue) curve, SM. The dotted curves and the thin vertical bars delimit the FOPI EOS (crosses) constraints. The thick vertical bar is the density relevant for the GMR according to [40]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

HM: Stiff momentum dependent EoS
SM: Soft momentum dependent EoS
Dotted lines: IQMD based on Skyrme and ...

Why nucleon mass becomes small than that in free space ?

Yes, the mass of a nucleon (such as a proton or neutron) can be smaller in certain environments compared to its mass in free space. This phenomenon is primarily observed under conditions like those inside atomic nuclei or in high-energy physics scenarios.

In a free space, the mass of a proton, for example, is about 938 MeV/c^2. However, inside a nucleus, the nucleon mass can be lower due to the binding energy of the nucleus. The binding energy is the energy required to break a nucleus into its constituent nucleons. This energy is released when the nucleons come together to form the nucleus, leading to a reduction in the effective mass of the nucleons in the bound state.

This decrease in mass is due to the strong nuclear force, which acts between nucleons and can bind them in a nucleus. The effective mass of the nucleons inside a nucleus is typically lower than their free-space mass because the system as a whole has a lower total energy than if the nucleons were free. This concept is connected to the idea of mass-energy equivalence, where energy contributes to the mass of a system.

In high-energy particle physics, under extreme conditions like those found in heavy-ion collisions or at the beginning of the universe, nucleons can also experience mass modifications due to factors such as the quark-gluon plasma, where quarks and gluons are no longer confined within individual nucleons.

Decrease below normal density: Might stem from the reduction of **effective nucleon mass**
Increase after: Perhaps come from the repulsion of NN force

4-5. Quark Mean Field model for nuclear matter

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Quark mean field model for nuclear matter and finite nuclei

H. Shen*
CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China
and Department of Physics, Nankai University, Tianjin 300071, China

H. Toki†
Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan
(Received 15 November 1999; published 17 March 2000)

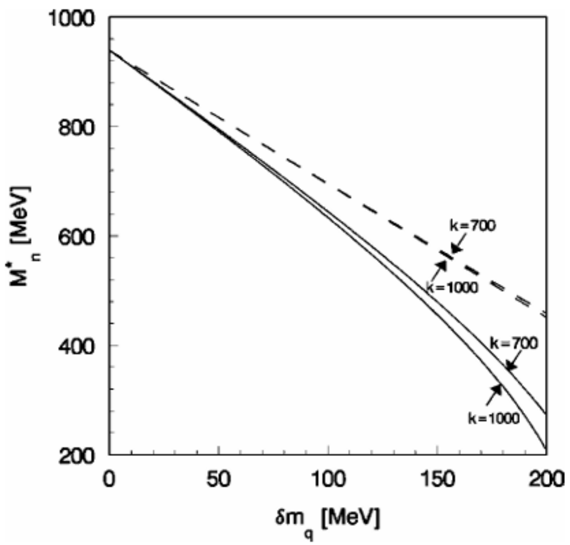

FIG. 1. The effective nucleon mass M_n^* as functions of the quark mass correction δm_q. The results in the QMF model with $\chi_c=\frac{1}{2}kr^2$ are shown by solid curves, while those with $\chi_c=\frac{1}{2}kr^2(1+\gamma^0)/2$ are shown by dashed curves. For each potential shown are the two results for two confining strengths.

The first step is to generate the nucleon system under the influence of the meson mean fields. In the constituent quark model, the quarks in a nucleon satisfy the following Dirac equation:

$$[i\gamma_\mu\partial^\mu - m_q - \chi_c - g_\sigma^q\sigma(r) - g_\omega^q\omega(r)\gamma^0 - g_\rho^q\rho(r)\tau_3\gamma^0]q(r) = 0, \quad (2)$$

where τ_3 is the isospin matrix in our nuclear physics convention. Assuming the meson mean fields are constant within the small nucleon volume, we can then write the Dirac equation as

$$[-i\vec{\alpha}\cdot\vec{\nabla} + \beta m_q^* + \beta\chi_c]q(r) = e^* q(r), \quad (3)$$

where $m_q^* = m_q + g_\sigma^q\sigma$ and $e^* = e - g_\omega^q\omega - g_\rho^q\rho\tau_3$, with σ, ω, and ρ being the mean fields at the middle of the nucleon. e is the energy of the quark under the influence of the σ, ω, and ρ mean fields. The quark mass is modified to m_q^* due to the presence of the σ mean field. Here, g_σ^q, g_ω^q, and g_ρ^q are the coupling constants of the σ, ω, and ρ mesons with quarks, respectively. We take into account the spin correlations, $E_{\rm spin}$, due to gluons and pions so that the mass difference between Δ and nucleon arises. Hence, the nucleon energy is expressed as $E_n^* = 3e^* + E_{\rm spin}$, where the vector contribution is removed here. There exists the spurious center of mass motion, which is removed in the standard method by $M_n^* = \sqrt{E_n^{*2} - \langle p_{\rm c.m.}^2\rangle}$, where $\langle p_{\rm c.m.}^2\rangle = \Sigma_{i=1}^3\langle p_i^2\rangle$, since the three constituent quarks are moving in the confining potential independently.

We now move to the second step, in which the nuclear many body system will be solved with the change of the nucleon properties obtained in the first step. We assume the following QMF Lagrangian,

$$\mathcal{L}_{\rm QMF} = \bar{\psi}[i\gamma_\mu\partial^\mu - M_n^* - g_\omega\omega\gamma^0 - g_\rho\rho\tau_3\gamma^0]\psi + \mathcal{L}_M(\sigma,\omega,\rho). \quad (4)$$

TABLE I. The nuclear matter properties used to determine the five free parameters in the present model. The saturation density and the energy per particle are denoted by ρ_0 and E/A, and the incompressibility by k, the effective mass by M_n^*, and the symmetry energy by a_{sym}.

ρ_0 (fm^{-3})	E/A (MeV)	k (MeV)	M_n^*/M_n	$a_{\rm sym}$ (MeV)
0.145	−16.3	280	0.63	35

III. PROPERTIES OF NUCLEAR MATTER

We calculate first the change of the nucleon properties as a function of the quark mass correction, δm_q, which is defined as $\delta m_q = m_q - m_q^* = -g_\sigma^q\sigma$. Here, the constituent quark mass is taken to be one third of the nucleon mass; $m_q = M_n/3 = 313$ MeV. We take into account confinement in terms of the harmonic oscillator potential together with two Lorentz structures: (1) scalar potential $\chi_c = \frac{1}{2}kr^2$ and (2) scalar-vector potential $\chi_c = \frac{1}{2}kr^2(1+\gamma^0)/2$. As pointed out in Ref. [25], the quark cannot be confined when the vector potential is larger than the scalar one. Here, we just take two extreme types, since the Lorentz structure of the confinement is not established. As for the strength of the confining potential, we take $k=700$ and 1000 MeV/fm^2, in order to see the results depending on this factor. The spin correlation, $E_{\rm spin}$, is fixed by the free nucleon mass as $M_n = \sqrt{(3e + E_{\rm spin})^2 - \langle p_{\rm c.m.}^2\rangle} = 939$ MeV. We assume further that the confining interaction and the spin correlations do not change in the nuclear medium.

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4-6. Quark Mean Field model for nuclear matter with delta meson in free space

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IV. QUARK-MESON COUPLING MODEL FOR ASYMMETRIC NUCLEAR MATTER

In this section, we introduce the quark-meson coupling (QMC) model [22–26], which starts with confined quarks as the degrees of freedom, with the relativistic confinement potential of the scalar-vector HO type [see Eq. (1)]. We assume that the strength parameter c in the potential does not change in matter.

We here consider the mean fields of σ, ω, ρ and δ mesons, which interact with the confined quarks, in uniformly distributed, asymmetric nuclear matter. Let the mean-field values for the σ, ω (the time component), ρ (the time component in the 3rd direction of isospin) and δ (in the 3rd direction of isospin) fields be $\bar{\sigma}$, $\bar{\omega}$, $\bar{\rho}$ and $\bar{\delta}$, respectively. The Dirac equation for the quark field ψ_i ($i = u$, d or s) is then given by [32]

$$\left[i\gamma \cdot \partial - (m_i - V_s) - \gamma_0 V_0 - \frac{c}{2}(1+\gamma_0)r^2\right]\psi_i(\vec{r}, t) = 0, \tag{19}$$

where $V_s = g^q_\sigma \bar{\sigma} + \tau_3 g^q_\delta \bar{\delta}$ and $V_0 = g^q_\omega \bar{\omega} + \tau_3 g^q_\rho \bar{\rho}$ [$\tau_3 = \pm 1$ for $\binom{u}{d}$ quark] with the quark-meson coupling constants, g^q_σ, g^q_δ, g^q_ω and g^q_ρ. Motivated by the Okubo-Zweig-Iizuka (OZI) rule, we here assume that the σ, ω, ρ and δ mesons couple to the u and d quarks only, not to the s quark. This breaks SU(3) symmetry explicitly. Furthermore, the isoscalar σ meson couples to the u and d quarks *equally*, while the isovector δ meson couples to the u and d quarks *oppositely*. This breaks isospin symmetry. Now we respectively define the effective quark mass and the effective single-particle energy as $m_i^* \equiv m_i - V_s = m_i - g^q_\sigma \bar{\sigma} \mp g^q_\delta \bar{\delta}$ and $\epsilon_i^* \equiv \epsilon_i - V_0 = \epsilon_i - g^q_\omega \bar{\omega} \mp g^q_\rho \bar{\rho}$ for $\binom{u}{d}$ quark, where ϵ_i is the eigenenergy of Eq. (19). Note that $m_s^* = m_s$ and $\epsilon_s^* = \epsilon_s$.

The static, lowest-state wave function in matter is presented by

$$\psi_i(\vec{r}, t) = \exp[-i\epsilon_i t]\psi_i(\vec{r}). \tag{20}$$

The wave function $\psi_i(\vec{r})$ is then given by Eqs. (2) and (3), in which ϵ_i, m_i, λ_i and a_i are replaced with ϵ_i^*, m_i^*, λ_i^* and a_i^*, and the effective energy ϵ_i^* is determined by $\sqrt{\epsilon_i^* + m_i^*}(\epsilon_i^* - m_i^*) = 3\sqrt{c}$ [see Eq. (4)].

The zeroth-order energy E_B^{0*} of the low-lying baryon is thus given by

$$E_B^{0*} = \sum_i \epsilon_i^*, \tag{21}$$

and we have the effective baryon mass in matter

$$M_B^* = E_B^{0*} + E_B^{\rm spin} - E_B^{c.m.*}. \tag{22}$$

In this model, we have eight parameters: c, m_u, m_d, m_s, $E_p^{\rm spin}$, $E_n^{\rm spin}$, $E_\Lambda^{\rm spin}$, $E_{\Xi^-}^{\rm spin}$. In order to reduce the number of parameters, we assume $E_N^{\rm spin} = E_p^{\rm spin} = E_n^{\rm spin}$, and consider the three cases:

(i) case 1; $m_u = 250$ MeV, $m_s = 450$ MeV,
(ii) case 2; $m_u = 300$ MeV, $m_s = 500$ MeV,
(iii) case 3; $m_u = 350$ MeV, $m_s = 550$ MeV.

The remaining five parameters, c, m_d, $E_N^{\rm spin}$, $E_\Lambda^{\rm spin}$, and $E_{\Xi^-}^{\rm spin}$, are determined so as to reproduce the proton charge radius $\langle r^2 \rangle_p^{1/2} = 0.841$ fm [3] and the baryon masses: $M_p = 937.64$ MeV, $M_n = 939.70$ MeV, $M_\Lambda = 1115.68$ MeV, and $M_{\Xi^-} = 1321.71$ MeV. Here, the electromagnetic self-energy for proton or neutron is subtracted from the observed mass [32].

TABLE I. Parameters and quark energies in vacuum.

Case	m_u [a]	m_d	m_s [a]	ϵ_u	ϵ_d	ϵ_s	$E_N^{\rm spin}$	$E_\Lambda^{\rm spin}$	$E_{\Xi^-}^{\rm spin}$	c
	(MeV)						(MeV)			(fm^{-3})
1	250	252.63	450	493.1	495.0	649.8	−236.8	−227.7	−190.2	0.635
2	300	302.48	500	517.8	519.7	681.2	−334.5	−331.3	−299.8	0.561
3	350	352.38	550	546.4	548.3	715.3	−441.9	−443.3	−416.5	0.500

[a] Input.

4-6. Quark Mean Field model for nuclear matter with delta meson in symmetric and asymmetric matter

Here, we assume that the spin correlation $E_B^{\rm spin}$ does not change in matter, and the c.m. correction $E_B^{c.m.*}$ is given by Eqs. (5)–(8) with ϵ_i^* and m_i^*, instead of ϵ_i and m_i.

For describing asymmetric nuclear matter, we now start from the following Lagrangian density in mean-field approximation

$$\mathcal{L} = \bar{\psi}_N[i\gamma\cdot\partial - M_N^*(\bar{\sigma},\bar{\delta}) - g_\omega\gamma_0\bar{\omega} - g_\rho\gamma_0\tau_3\bar{\rho}]\psi_N - \frac{m_\sigma^2}{2}\bar{\sigma}^2 - \frac{m_\delta^2}{2}\bar{\delta}^2 + \frac{m_\omega^2}{2}\bar{\omega}^2 + \frac{m_\rho^2}{2}\bar{\rho}^2 - \frac{g_2}{3}\bar{\sigma}^3 \quad (23)$$

with ψ_N the (isodoublet) nucleon field, τ_3 the 3rd component of Pauli matrix and $M_N^*(\bar{\sigma},\bar{\delta})$ the mass matrix whose component is given by Eq. (22). The nucleon-meson coupling constants, g_σ, g_ω, g_ρ, and g_δ, are respectively related to the quark-meson coupling constants as $g_\sigma = 3g_\sigma^q$, $g_\omega = 3g_\omega^q$, $g_\rho = g_\rho^q$, and $g_\delta = g_\delta^q$. The meson masses are taken to be $m_\sigma = 550$ MeV, $m_\omega = 783$ MeV, $m_\rho = 770$ MeV, and $m_\delta = 983$ MeV. We add the last term to the Lagrangian, which is the nonlinear, self-coupling term of σ meson, in order to reproduce the properties of nuclear matter as discussed later. Here, we do not include the nonlinear term $\frac{1}{4}g_3\sigma^4$, because it plays similar roles as $\frac{1}{3}g_2\sigma^3$.

The total energy per nucleon of asymmetric nuclear matter is then obtained by

$$E = \sum_{j=p,n}\frac{1}{\pi^2\rho_N}\int_0^{k_{F_j}} dk\, k^2\sqrt{M_j^{*2}+k^2} + g_\omega\bar{\omega} + g_\rho\left(\frac{\rho_3}{\rho_N}\right)\bar{\rho} + \frac{1}{2\rho_N}(m_\sigma^2\bar{\sigma}^2 - m_\omega^2\bar{\omega}^2 + m_\delta^2\bar{\delta}^2 - m_\rho^2\bar{\rho}^2) + \frac{1}{3\rho_N}g_2\bar{\sigma}^3, \quad (24)$$

where $k_{F_{p(n)}}$ is the Fermi momentum for protons (neutrons), and this is related to the density of protons (neutrons), $\rho_{p(n)}$, through $\rho_{p(n)} = k_{F_{p(n)}}^3/(3\pi^2)$. The total nucleon density is given by $\rho_N = \rho_p + \rho_n$, and the difference in proton and neutron densities is defined by $\rho_3 \equiv \rho_p - \rho_n$. Using Eq. (24), we can calculate pressure by $P = \rho_N^2(\partial E/\partial\rho_N)$. Then, the binding energy per nucleon, E_b, is defined by

$$E_b(\rho_N,\alpha) \equiv E(\rho_N,\alpha) - \frac{1}{2}[(M_n+M_p) + (M_n - M_p)\alpha] \quad (25)$$

where $\alpha = (\rho_n - \rho_p)/\rho_N$ and $E(\rho_N,\alpha)$ is given by Eq. (24).

$$(m_\sigma^2 + g_2\bar{\sigma})\bar{\sigma} = -\sum_{j=p,n}\left(\frac{\partial M_j^*}{\partial\bar{\sigma}}\right)\rho_j^s \equiv g_\sigma\sum_j G_{\sigma j}(\bar{\sigma},\bar{\delta})\rho_j^s$$

$$m_\omega^2\bar{\omega} = g_\omega\rho_N, \quad (27)$$

$$m_\delta^2\bar{\delta} = -\sum_j\left(\frac{\partial M_j^*}{\partial\bar{\delta}}\right)\rho_j^s \equiv g_\delta\sum_j G_{\delta j}(\bar{\sigma},\bar{\delta})\rho_j^s, \quad (28)$$

$$m_\rho^2\bar{\rho} = g_\rho\rho_3, \quad (29)$$

with $G_{\sigma j}$ ($G_{\delta j}$) the isoscalar (isovector) quark scalar density in j (= proton or neutron) (see Appendix C), and ρ_j^s the scalar density of j in matter

$$\rho_j^s = \frac{1}{\pi^2}\int_0^{k_{F_j}} dk\, k^2\frac{M_j^*}{\sqrt{M_j^{*2}+k^2}}. \quad (30)$$

TABLE IV. Coupling constants. For detail, see the text.

Model	Case	g_σ	g_ω	g_δ	g_ρ	g_2 (fm^{-1})
NL0	1	10.34	7.34	···	4.37	23.61
	2	9.98	7.69	···	4.35	24.97
	3	9.72	7.95	···	4.33	25.67
NLA	1	10.34	7.34	4.04	4.83	23.61
	2	9.98	7.69	4.04	4.90	24.97
	3	9.72	7.95	4.04	4.96	25.67
NLB	1	10.34	7.34	5.59	5.16	23.61
	2	9.98	7.69	5.59	5.31	24.97
	3	9.72	7.95	5.59	5.43	25.67
NLC	1	10.34	7.34	7.70	5.65	23.61
	2	9.98	7.69	7.70	5.93	24.97
	3	9.72	7.95	7.70	6.16	25.67

4-7. Results for u and d quark mass in matter

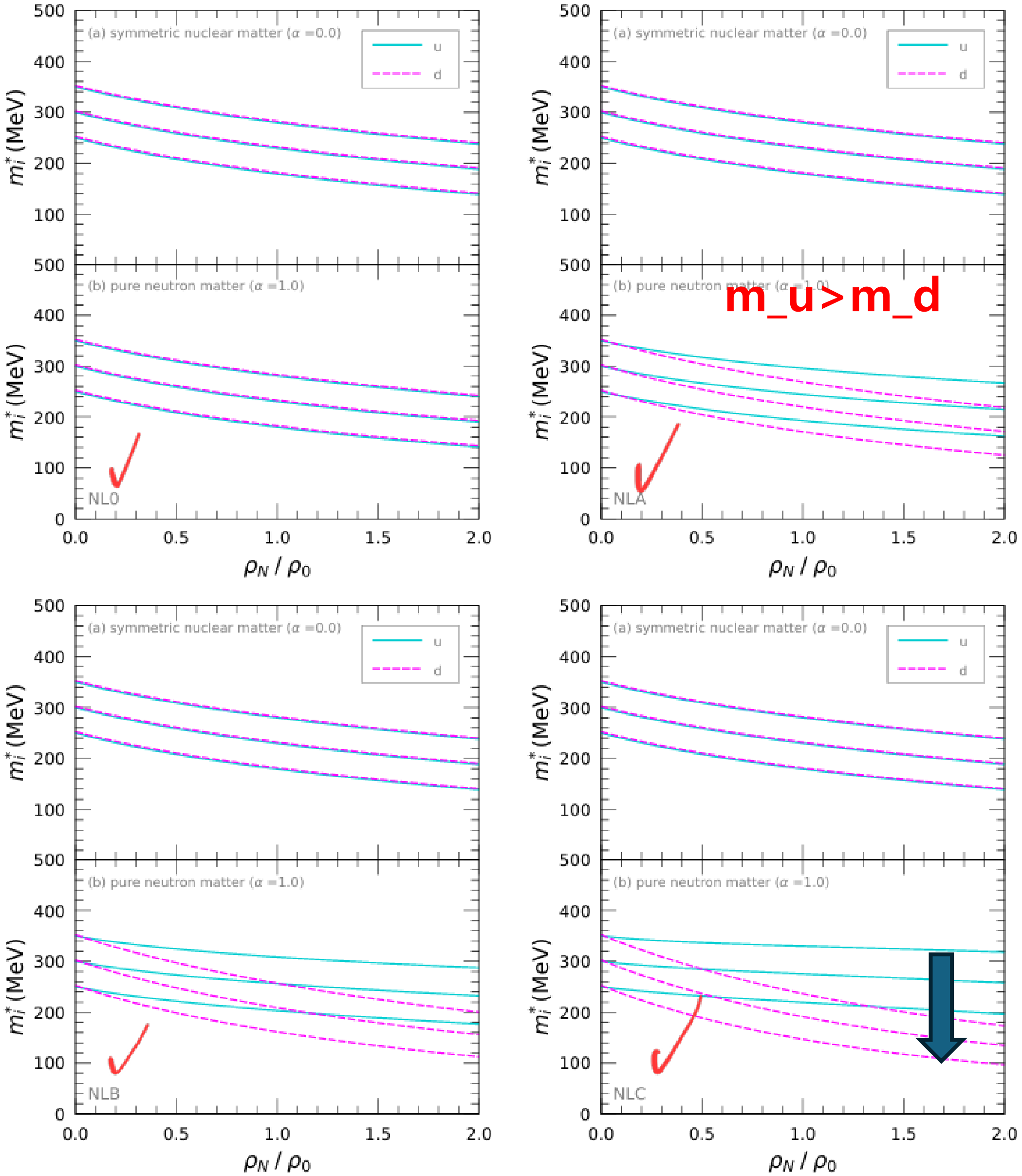

FIG. 2. Effective quark mass ($i = u$ or d) as a function of ρ_N/ρ_0.

$$\Delta^*_{du} = m^*_d - m^*_u = \Delta_{du} + 2 g_\delta \bar{\delta},$$

the effective quark mass and the effective single-p
energy as $m_i^* \equiv m_i - V_s = m_i - g^q_\sigma \bar{\sigma} \mp g^q_\delta \bar{\delta}$ and ϵ_i^*
$V_0 = \epsilon_i - g^q_\omega \bar{\omega} \mp g^q_\rho \bar{\rho}$ for $\binom{u}{d}$ quark, where ϵ_i is th

In symmetric matter, delta meson effect is very small.
But, in neutron rich matter delta meson field becomes negative

TABLE VI. Mean-field values of the meson fields (in MeV) at the saturation density. The ρ meson field vanishes in symmetric nuclear matter.

Model	Case	$\bar{\sigma}$	$\bar{\omega}$	$\bar{\delta}$
NL0	1	20.54	13.80	...
	2	21.15	14.46	...
	3	21.61	14.94	...
NLA	1	20.54	13.80	−0.023
	2	21.15	14.46	−0.017
	3	21.61	14.94	−0.012
NLB	1	20.54	13.80	−0.030
	2	21.15	14.46	−0.022
	3	21.61	14.94	−0.016
NLC	1	20.54	13.80	−0.037
	2	21.15	14.46	−0.028
	3	21.61	14.94	−0.020

EFFECT OF ISOSCALAR AND ISOVECTOR SCALAR FIELDS ... PHYS. REV. D **110,** 113001 (2024)

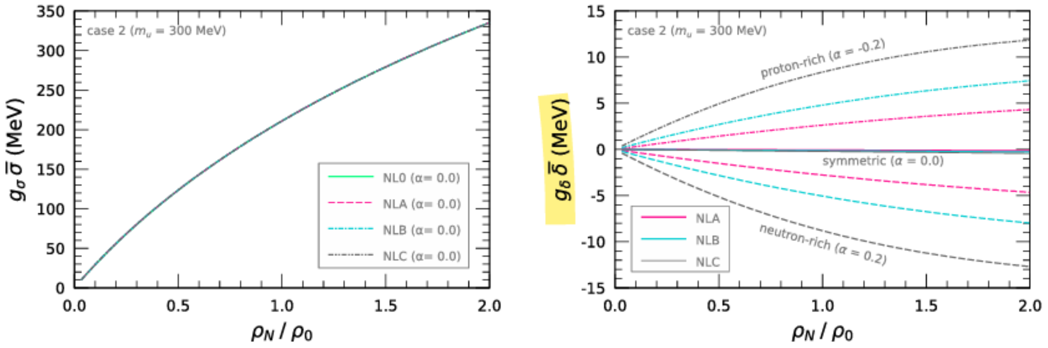

FIG. 2. Mean-field values of the meson fields as a function of ρ_N/ρ_0. We show the results in case 2 only in Table VI. The left panel is for the σ field in symmetric nuclear matter. The model dependence of the σ field is very small. The right panel is for the δ field in case of $\alpha = -0.2$ (the dot-dashed curves), 0 (the solid curves), or 0.2 (the dashed curves). Note that $\alpha = 0.2$ corresponds to $^{208}_{82}$Pb.

4-9. Results for nucleon masses in matter

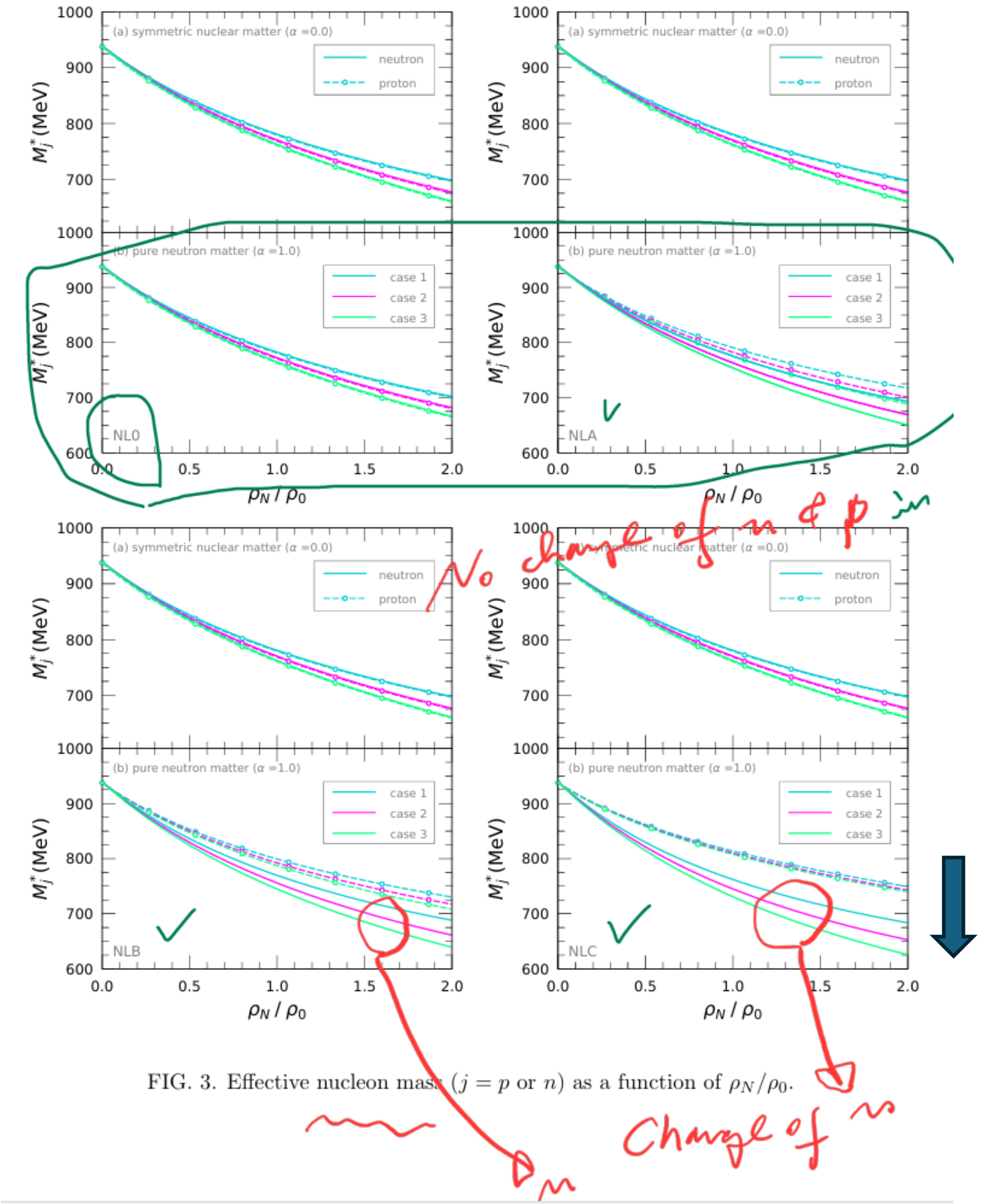

FIG. 3. Effective nucleon mass ($j = p$ or n) as a function of ρ_N/ρ_0.

4-10. Results of weak coupling constants in matter

III. WEAK COUPLING CONSTANTS IN VACUUM

We are interested in calculating the weak form factors. The transition matrix element for the decay of an initial baryon B_1 to a final baryon B_2 and lepton l with its antineutrino $\bar{\nu}_l$, that is $B_1 \to B_2 + l + \bar{\nu}_l$, is proportional to the matrix element of the baryon weak current $J^\mu(x)$, which consists of the vector and axial-vector currents, as

$$\langle B_2 | J^\mu(x) | B_1 \rangle = C \left[\langle B_2 | V^\mu(x) | B_1 \rangle + \langle B_2 | A^\mu(x) | B_1 \rangle \right], \tag{12}$$

and

$$\langle B_2 | V^\mu(x) | B_1 \rangle = \bar{u}_2(p_2) \left[f_1(q^2) \gamma^\mu + \cdots \right] u_1(p_1) e^{iq\cdot x}, \tag{13}$$

$$\langle B_2 | A^\mu(x) | B_1 \rangle = \bar{u}_2(p_2) \left[g_1(q^2) \gamma^\mu \gamma_5 + \cdots \right] u_1(p_1) e^{iq\cdot x}, \tag{14}$$

where $C = \cos\theta_c (\sin\theta_c)$ is the Cabibbo angle for t 1), and $p_{1(2)}$ is the four-momentum of baryon 1(2) transfer squared, which is generally quite small for

$$\psi_i(\vec{r}) = \frac{N_i}{\sqrt{4\pi} a_i} \begin{pmatrix} 1 \\ i\vec{\sigma}\cdot\hat{r}\frac{1}{\lambda_i a_i}\left(\frac{r}{a_i}\right) \end{pmatrix} e^{-r^2/2a_i^2} \chi_i, \tag{2}$$

$$N_i^2 = \frac{8}{\sqrt{\pi} a_i} \frac{\lambda_i^2 a_i^2}{2\lambda_i^2 a_i^2 + 3}, \qquad \lambda_i = \epsilon_i + m_i,$$

$$a_i^2 = \frac{1}{\sqrt{c\lambda_i}} = \frac{3}{\epsilon_i^2 - m_i^2}, \tag{3}$$

where m_i is the constituent quark mass, a_i is the length scale, and χ_i is the quark spinor. Here, the single-particle quark energy, ϵ_i, is determined by

$$\sqrt{\epsilon_i + m_i}(\epsilon_i - m_i) = 3\sqrt{c}. \tag{4}$$

The zeroth-order energy of the low-lying baryon, E_B^0, is then simply given by a sum of the quark energies, $E_B^0 = \sum_i \epsilon_i$. Now we should take into account some corrections to the baryon energy such as the spin correlations, $E_B^{\rm spin}$, due to the quark-gluon and quark-pion interactions [47,48], and the c.m. correction, $E_B^{c.m.}$. Here we do not calculate the spin correlation explicitly, but we assume that it can be treated as a constant parameter which is fixed so as to reproduce the baryon mass [33,34]. The c.m. correction to the spurious motion can be calculated analytically (for detail, see Appendix A.1). In the present

and (14) refer to additional vector and axial-vector currents, which contribute to the decay rates only in order q/M_B or higher. Therefore, in order to focus on the leading form factors $f_1(0)$ (vector coupling constant) and $g_1(0)$ (axial-vector coupling constant), we only consider the $\mu = 0$ component of V^μ and the $\mu = 3$ component of A^μ (all baryons are treated with spin up).

The β decay of the octet baryons, $B_1 \to B_2 + e^- + \bar{\nu}_e$, can be interpreted as the quark β decays like $q_i \to q_j + e^- + \bar{\nu}_e$ inside the baryon, where $j = u$ and i could be d or s quarks. The weak coupling constants without the cm correction, $f_1^{(0)}$ and $g_1^{(0)}$, are calculated by the quark model

$$f_1^{(0)} = \int d\vec{r}\, \langle B_2 | V^0(x) | B_1 \rangle, \quad g_1^{(0)} = \int d\vec{r}\, \langle B_2 | A^3(x) | B_1 \rangle. \tag{15}$$

Then, they are rewritten by

$$\begin{aligned} f_1^{(0)} &= f_1^{\rm SU(3)} \times \int d\vec{r}\, \bar{\psi}_j(\vec{r}) \gamma_0 \psi_i(\vec{r}) \\ &= f_1^{\rm SU(3)} \times 2^{5/2} \left(\frac{a_i a_j}{a_i^2 + a_j^2} \right)^{3/2} \frac{\lambda_i a_i \lambda_j a_j + 3 a_i a_j/(a_i^2 + a_j^2)}{\sqrt{2\lambda_i^2 a_i^2 + 3}\sqrt{2\lambda_j^2 a_j^2 + 3}} \\ &\equiv f_1^{\rm SU(3)} \times (1 + \delta f_1^{(0)}) \end{aligned} \tag{16}$$

SU(3) sym. bre.

and

$$\begin{aligned} g_1^{(0)} &= g_1^{\rm SU(3)} \times \int d\vec{r}\, \bar{\psi}_j(\vec{r}) \gamma^3 \gamma_5 \psi_i(\vec{r}), \\ &= g_1^{\rm SU(3)} \times 2^{5/2} \left(\frac{a_i a_j}{a_i^2 + a_j^2} \right)^{3/2} \frac{\lambda_i a_i \lambda_j a_j - a_i a_j/(a_i^2 + a_j^2)}{\sqrt{2\lambda_i^2 a_i^2 + 3}\sqrt{2\lambda_j^2 a_j^2 + 3}} \\ &\equiv g_1^{\rm SU(3)} \times (1 - \delta g_1^{(0)}) \end{aligned} \tag{17}$$

where in both cases the superscript ${}^{\rm SU(3)}$ indicates the usual value obtained in exact SU(3) [46] (for example, in case of neutron β decay, $f_1^{\rm SU(3)} = 1$ and $g_1^{\rm SU(3)} = 5/3$). Furthermore, using Eq. (4), we can easily verify that the vector coupling $f_1^{(0)}$ obeys the BSAG theorem, namely $\delta f_1^{(0)} = \mathcal{O}(\Delta_{ij}^2)$.

4-9. Weak coupling constants in vacuum

In this model, we have eight parameters: c, m_u, m_d, m_s, $E_p^{\rm spin}$, $E_n^{\rm spin}$, $E_\Lambda^{\rm spin}$, $E_{\Xi^-}^{\rm spin}$. In order to reduce the number of parameters, we assume $E_N^{\rm spin} = E_p^{\rm spin} = E_n^{\rm spin}$, and consider the three cases:

(i) case 1; $m_u = 250$ MeV, $m_s = 450$ MeV,
(ii) case 2; $m_u = 300$ MeV, $m_s = 500$ MeV,
(iii) case 3; $m_u = 350$ MeV, $m_s = 550$ MeV.

The remaining five parameters, c, m_d, $E_N^{\rm spin}$, $E_\Lambda^{\rm spin}$, and $E_{\Xi^-}^{\rm spin}$, are determined so as to reproduce the proton charge radius $\langle r^2\rangle_p^{1/2} = 0.841$ fm [3] and the baryon masses: $M_p = 937.64$ MeV, $M_n = 939.70$ MeV, $M_\Lambda = 1115.68$ MeV, and $M_{\Xi^-} = 1321.71$ MeV. Here, the electromagnetic self-energy for proton or neutron is subtracted from the observed mass [32].

TABLE III. Weak coupling constants in vacuum.

		$n \to p$				
case	$\delta f_1^{(0)} \times 10^6$	ρ_V	$\delta f_1 \times 10^6$	$\delta g_1^{(0)}$	ρ_A	δg_1
1	3.12	0.999999789	2.91	0.187	0.9177	0.114
2	2.28	0.999999810	2.08	0.156	0.9195	0.082
3	1.71	0.999999825	1.54	0.131	0.9209	0.057
		$\Lambda \to p$				
case	$\delta f_1^{(0)}$	ρ_V	δf_1	$\delta g_1^{(0)}$	ρ_A	δg_1
1	0.012	0.9988	0.011	0.154	0.9254	0.086
2	0.010	0.9989	0.009	0.131	0.9271	0.062
3	0.008	0.9990	0.007	0.111	0.9285	0.043
		$\Xi^- \to \Lambda$				
case	$\delta f_1^{(0)}$	ρ_V	δf_1	$\delta g_1^{(0)}$	ρ_A	δg_1
1	0.012	0.9973	0.009	0.154	0.9404	0.101
2	0.010	0.9975	0.007	0.131	0.9420	0.077
3	0.008	0.9976	0.006	0.111	0.9433	0.058

in the case 2, we find that $\delta f_1^{(0)} \simeq 2.3 \times 10^{-6}$ and $\delta g_1^{(0)} \simeq 0.16$ in the neutron β decay. It is not surprising that $\delta f_1^{(0)}$ is of the order of 10^{-6}, because the present calculation does not involve the breaking of SU(3) symmetry due to gluons and pions [21]. In contrast, we find that $\delta f_1^{(0)} \simeq 0.01$ and $\delta g_1^{(0)} \simeq 0.13$ in the Λ or Ξ^- decay. Here, $\delta g_1^{(0)}$ in the hyperon decay is smaller than that in the neutron decay, which is caused by the fact that the s quark is heavier than the d quark and thus the lower component of the s-quark wave function in hyperon is smaller than that of the d-quark wave function in neutron.

4-9. Weak coupling constants in matter

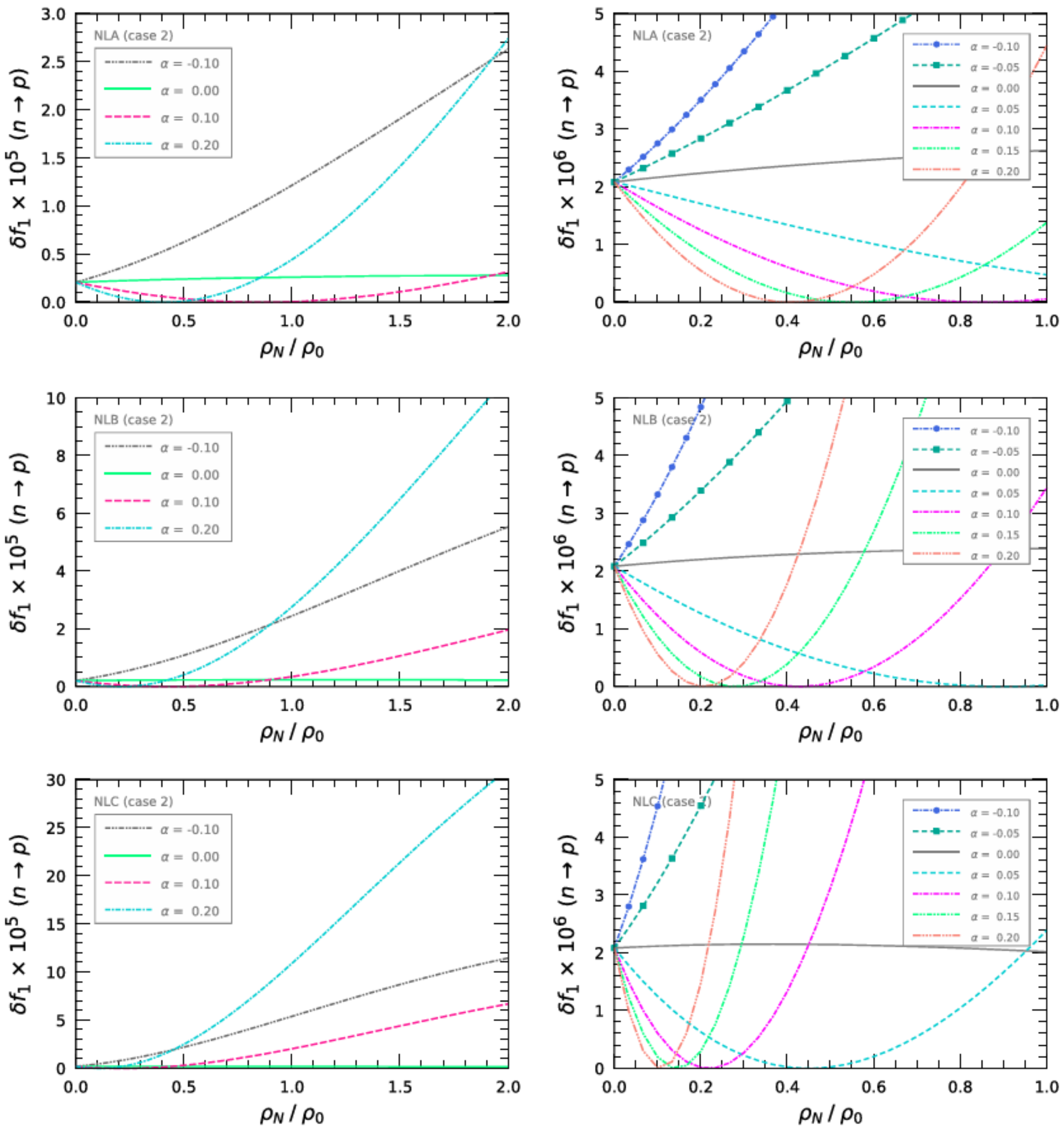

FIG. 9. Deviation, δf_1, for the neutron β decay in the NLA, NLB, or NLC model. We show the results in case 2. In the left panels, the nuclear density varies up to $\rho_N/\rho_0 = 2.0$. In the right panels, δf_1 at low density is magnified.

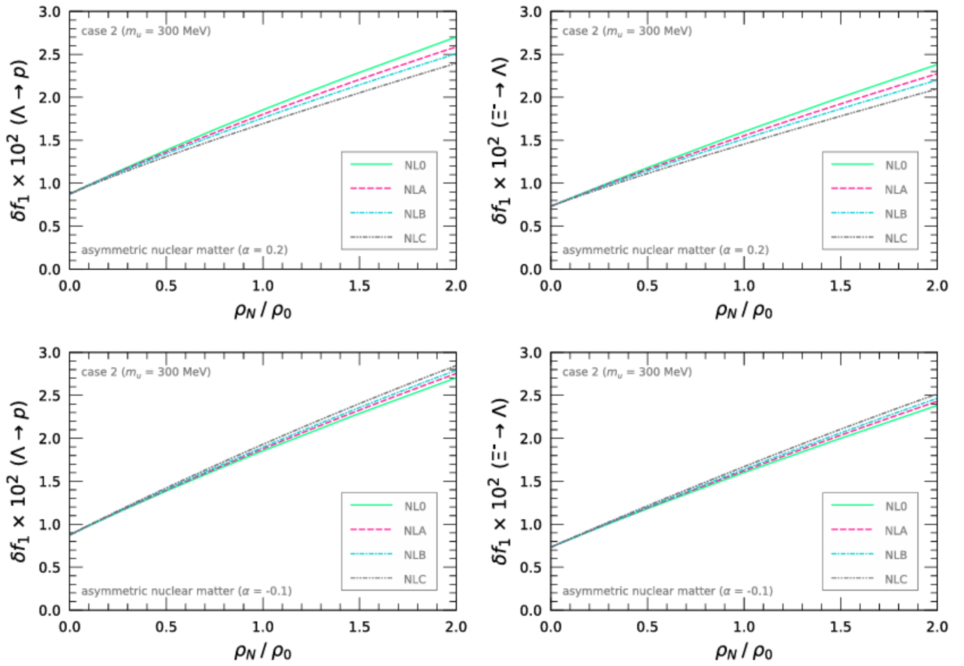

FIG. 10. Deviation, δf_1, for the hyperon β decay in the NL0, NLA, NLB, or NLC model. We show the results in case 2 only. The left (right) two panels are for the Λ (Ξ^-) decay. The top (bottom) two panels are for $\alpha = 0.2$ (-0.1).

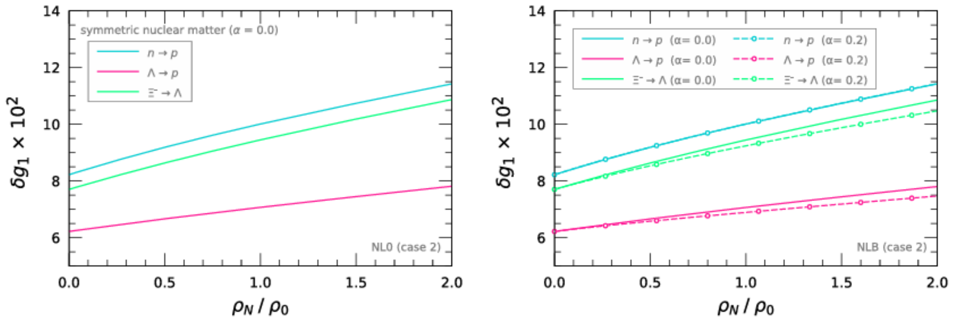

FIG. 11. Deviation, δg_1, in the axial-vector coupling constant as a function of ρ_N/ρ_0. We show the results in case 2. In the left panel, δg_1 in the NL0 model is displayed, in which the δ field is not included. Because the dependence of δg_1 on α is quite small in this model, we show the result with $\alpha = 0$ only. In the right panel, δg_1 in the NLB model is presented. In the neutron β decay, the results with $\alpha = 0$ and 0.2 are very close to each other.

4-10. Summary I

1. We investigated effects of the isoscalar scalar (sigma) and isovector scalar (delta) fields on the semi-leptonic decay in free space and nuclear matter.
2. The evolution of u and d quark masses (m_d>m_u) in nuclear matter are evaluated. The smaller d quark mass than u quark mass are found with the increase of density.

$$\Delta^*_{du} = m^*_d - m^*_u = \Delta_{du} + 2g_\delta\bar{\delta},$$

$$\Delta^*_{su} = m^*_s - m^*_u = \Delta_{su} + \frac{g_\sigma}{3}\bar{\sigma} + g_\delta\bar{\delta},$$

where Δ_{du} and Δ_{du} are the original breaking in vacuum, and the meson-field terms are the additional ones in matter. It should be noticed that the mean field $\bar{\delta}$ is negative (positive) in neutron-rich (proton-rich) matter. Because the

3. We found that the deviation of vector CC from the SU symmetry amounts to $O(10^{-6})$ for SU(2), but it is **$O(10^{-2})$ for SU(3).** For axial CC, they are up to $O(10^{-1})$ for SU(2), but it is **$O(10^{-2})$ for SU(3).**

4. Main reason of the deviation for the vector CC comes from SU(3) symmetry breaking, but the axial CC stems from the relativistic effect due to the lower component of the wave function.

Electromagnetic |GE/GM| ratios of hyperons at large timelike q2

G. Ramalho (SoongSil U.), M.T. Peña (LIP, Lisbon and Espirito Santo U.), K. Tsushima (Cruzeiro do Sul U.), Myung-Ki Cheoun (SoongSil U.)
2024)

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Weak interaction axial form factors of the octet baryons in nuclear medium

G. Ramalho (SoongSil U.), K. Tsushima (Cruzeiro do Sul U.), Myung-Ki Cheoun (SoongSil U.) (Jun 12, 2024) (PRD 111 013002 (2025))

e-Print: 2406.07958 [hep-ph]

4-11. Covariant spectator quark model

A Covariant spectator quark model

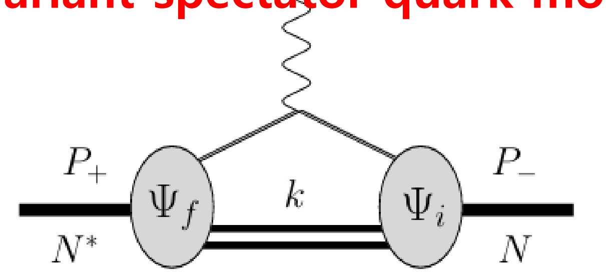
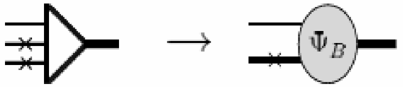


Fig. 1. $\gamma N \to N^*$ transition in the covariant spectator quark model (diquark on-shell) in relativistic impulse approximation. P_+ (P_-) represents the final (initial) baryon momentum and k the intermediate diquark momentum. The baryon wave functions are represented by Ψ_f and Ψ_i for the final and initial states, respectively.

- Baryon: 3 constituent quark system
- Covariant Spectator Theory: wave function Ψ_B defined in terms of a 3-quark vertex Γ with 2 on-mass-shell quarks – integrate into quark-pair degrees of freedom



$$\int_{k_1}\int_{k_2} = \int_{4m_q^2}^{+\infty} ds \sqrt{\frac{s-4m_q^2}{s}} \int \frac{d^3\mathbf{k}}{2\sqrt{s+\mathbf{k}^2}}$$

Mean value theorem: $s=(k_1+k_2)^2 \to m_D^2$; effective diquark mass m_D

Gross and Agbakpe PRC 73, 015203 (2006); Gross, GR and Peña PRC 77, 015202 (2008)

The electromagnetic current associated with the final state N^* in the covariant spectator quark model (see Fig. 1) is determined by

$$J^\mu = 3\sum_\lambda \int_k \overline{\Psi}_f(P_+,k) j_I^\mu \Psi_i(P_-,k). \quad (4)$$

In the above, $\int_k$ represents the covariant integral with respect to the on-mass-shell diquark momentum and λ the diquark polarization. For simplicity, diquark and baryon polarization indices are suppressed.

The quark electromagnetic current j_I^μ is given by the Dirac and Pauli structures:

$$j_I^\mu = \left(\frac{1}{6}f_{1+} + \frac{1}{2}f_{1-}\tau_3\right)\left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2}\right) + \left(\frac{1}{6}f_{2+} + \frac{1}{2}f_{2-}\tau_3\right)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}, \quad (1)$$

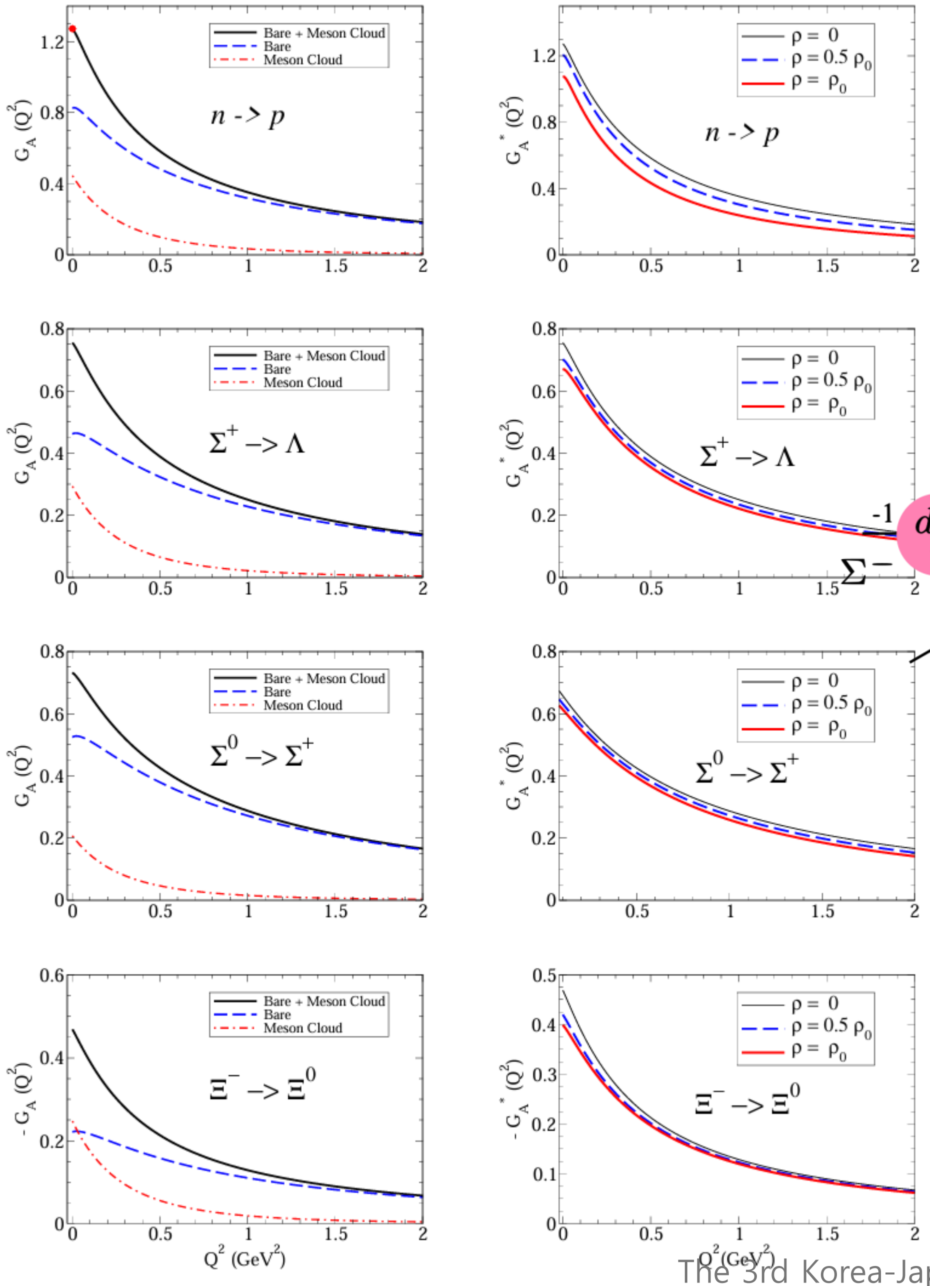
where M_N is the nucleon mass, $f_{1\pm}$ and $f_{2\pm}$ are the quark form factors as functions of Q^2, and τ_3 the isospin operator. To represent the quark structure we adopt a vector meson dominance motivated parametrization, where the form factors are written in terms of two vector meson poles:

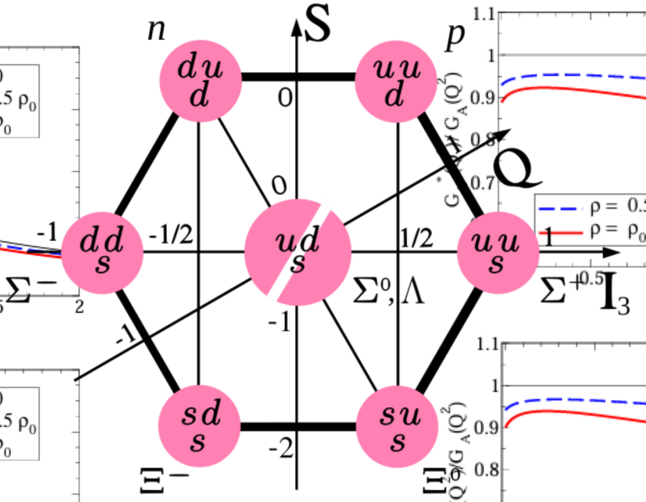
$$f_{1\pm}(Q^2) = \lambda_q + (1-\lambda_q)\frac{m_v^2}{m_v^2+Q^2} + c_\pm \frac{Q^2 M_h^2}{(M_h^2+Q^2)^2} \quad (2)$$

$$f_{2\pm}(Q^2) = \kappa_\pm \left\{ d_\pm \frac{m_v^2}{m_v^2+Q^2} + (1-d_\pm)\frac{Q^2}{M_h^2+Q^2} \right\}. \quad (3)$$

In the above $m_v = m_\rho$ is a light vector meson mass that effectively represents the ρ and ω poles and M_h is the an effective heavy vector meson mass, that takes into account the short range phenomenology. We chose $M_h = 2M_N$ in the present study. The isoscalar κ_+ and isovector κ_- quark anomalous moments are fixed by the nucleon magnetic moments. The adjustable parameters are λ_q and the mixture coefficients $c_\pm$ and $d_\pm$. In the study of the nucleon properties, it turned out that $d_+ = d_-$ gives a very good description of the nucleon electromagnetic form factor [10]. This reduces the number of adjustable parameters to 4. The quality of the model description for the nucleon form factors is illustrated in Fig. 2. The quark current fixed by the nucleon form factors will be used for all other applications discussed below.

4-12. Results of Covariant spectator quark model and quenching





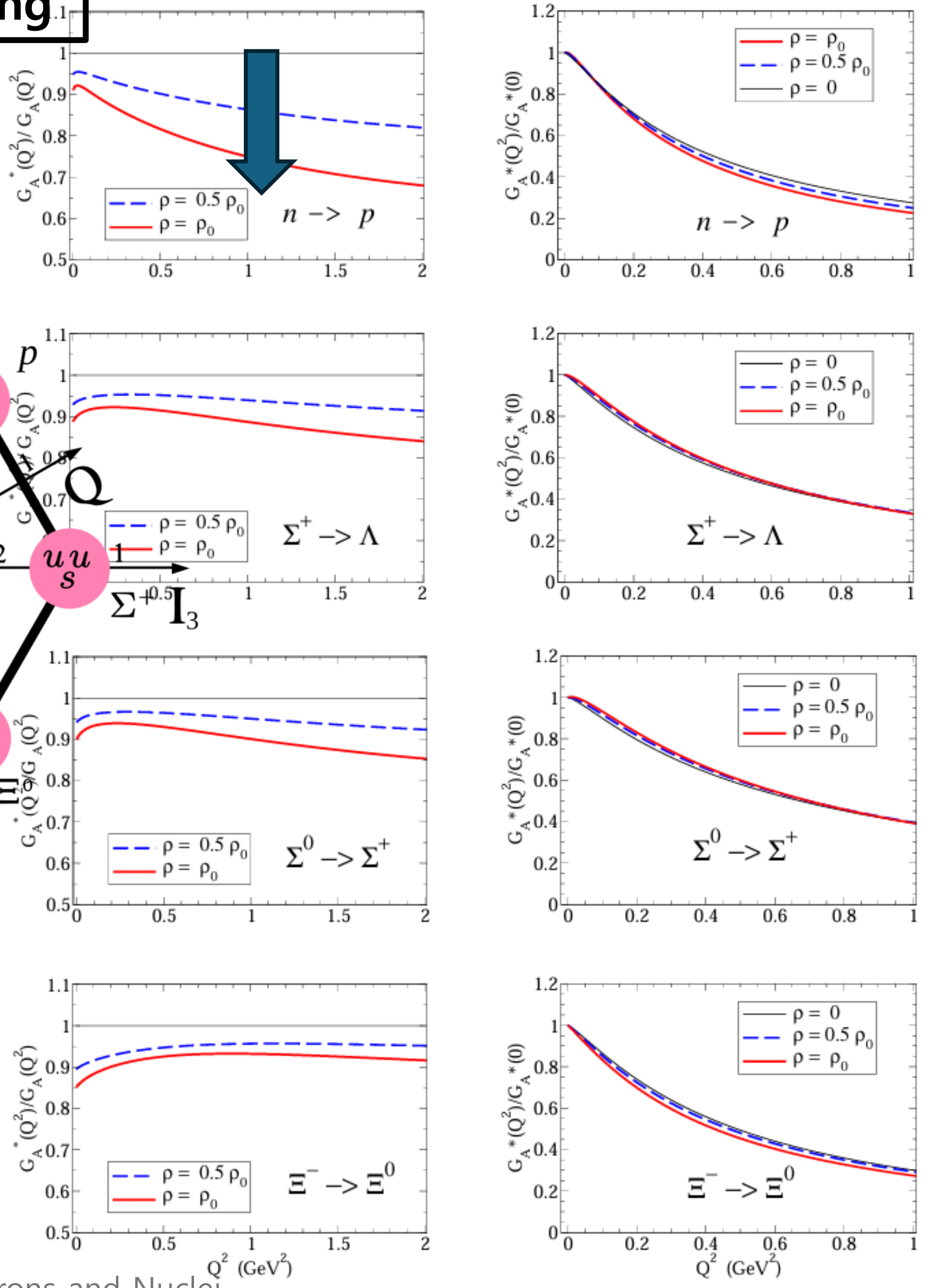
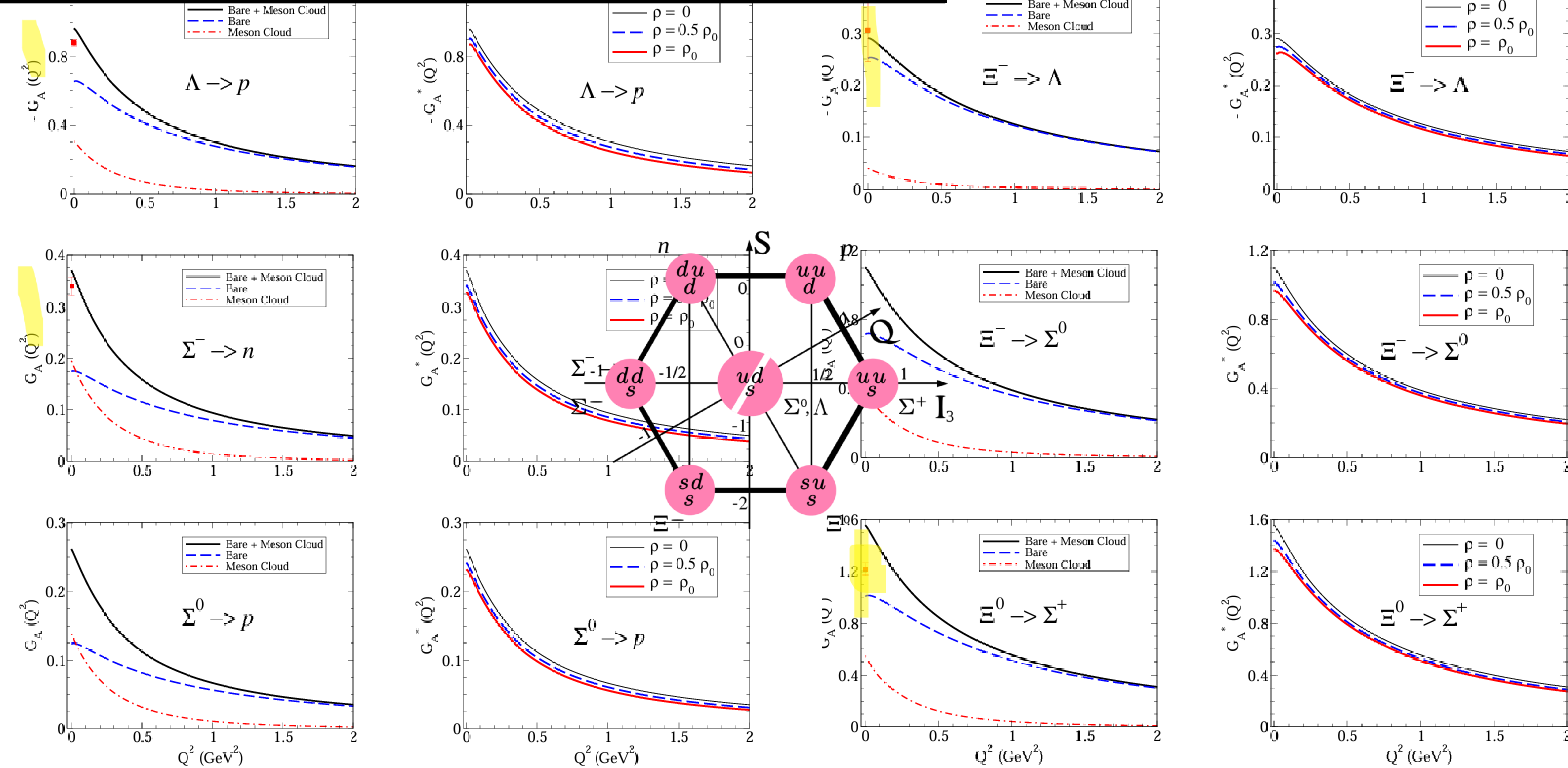


FIG. 3. Axial-vector form factor G_A for $\Delta I = 1$ transitions. **Left panel:** results in vacuum (bare, meson cloud and total). **Right panel:** total results for the medium $\rho = 0.5\rho_0$ and ρ_0 compared with vacuum ($\rho = 0$).

FIG. 9. Axial-vector form factor G_A for $\Delta I = 1$ transitions. Ratios G_A^*/G_A and $G_A^*(Q^2)/G_A^*(0)$.

4-13. Results of Covariant spectator quark model and quenching



. 4. Axial-vector form factor G_A for $\Delta S = 1$ transitions (part 1). **Left panel:** results in vacuum (bare, meson cloud and total). ht **panel:** total results for the medium $\rho = 0.5\rho_0$ and ρ_0 compared with vacuum ($\rho = 0$).

Axial-vector form factor G_A for $\Delta S = 1$ transitions (part 2). **Left panel:** results in vacuum (bare, meson cloud an nel: total results for the medium $\rho = 0.5\rho_0$ and ρ_0 compared with vacuum ($\rho = 0$).

1. We investigated effects of the isoscalar scalar (sigma) and isovector scalar (delta) fields on the semi-leptonic decay in free space and nuclear matter.
2. The evolution of u and d quark masses (m_d>m_u) in nuclear matter are evaluated. The smaller d quark mass than u quark mass are found with the increase of density.

$$\Delta^*_{du} = m^*_d - m^*_u = \Delta_{du} + 2g_\delta\bar{\delta},$$
$$\Delta^*_{su} = m^*_s - m^*_u = \Delta_{su} + \frac{g_\sigma}{3}\bar{\sigma} + g_\delta\bar{\delta},$$

where Δ_{du} and Δ_{du} are the original breaking in vacuum, and the meson-field terms are the additional ones in matter. It should be noticed that the mean field $\bar{\delta}$ is negative (positive) in neutron-rich (proton-rich) matter. Because the

3. We found that the deviation of vector CC from the SU symmetry amounts to $O(10^{-6})$ for SU(2), but it is **$O(10^{-2})$ for SU(3).** For axial CC, they are up to $O(10^{-1})$ for SU(2), but it is **$O(10^{-2})$ for SU(3).**

4. Main reason of the deviation for the vector CC comes from SU(3) symmetry breaking, but the axial CC stems from the relativistic effect due to the lower component of the wave function.
This was also confirmed by using a different quark model, covariant spectator quark model.

5. In nuclear matter, the deviation becomes larger with increase of the density.

6. Now we are applying this evolution of axial and vectorial CC to the supernovae evolution and BBC.

GR1D : Relativistic Boltzmann equation

$$p^{\alpha}\left[\frac{\partial f_{\nu_i}}{\partial x^{\alpha}} - \Gamma^{\beta}_{\alpha\gamma}\, p^{\gamma}\,\frac{\partial f_{\nu}}{\partial p^{\beta}}\right] = \left[\frac{df_{\nu}}{d\tau}\right]_{coll}$$

$\Gamma^{\beta}_{\alpha\gamma}$: connection coefficients-Christoffel symbols

f_{ν} : distribution function

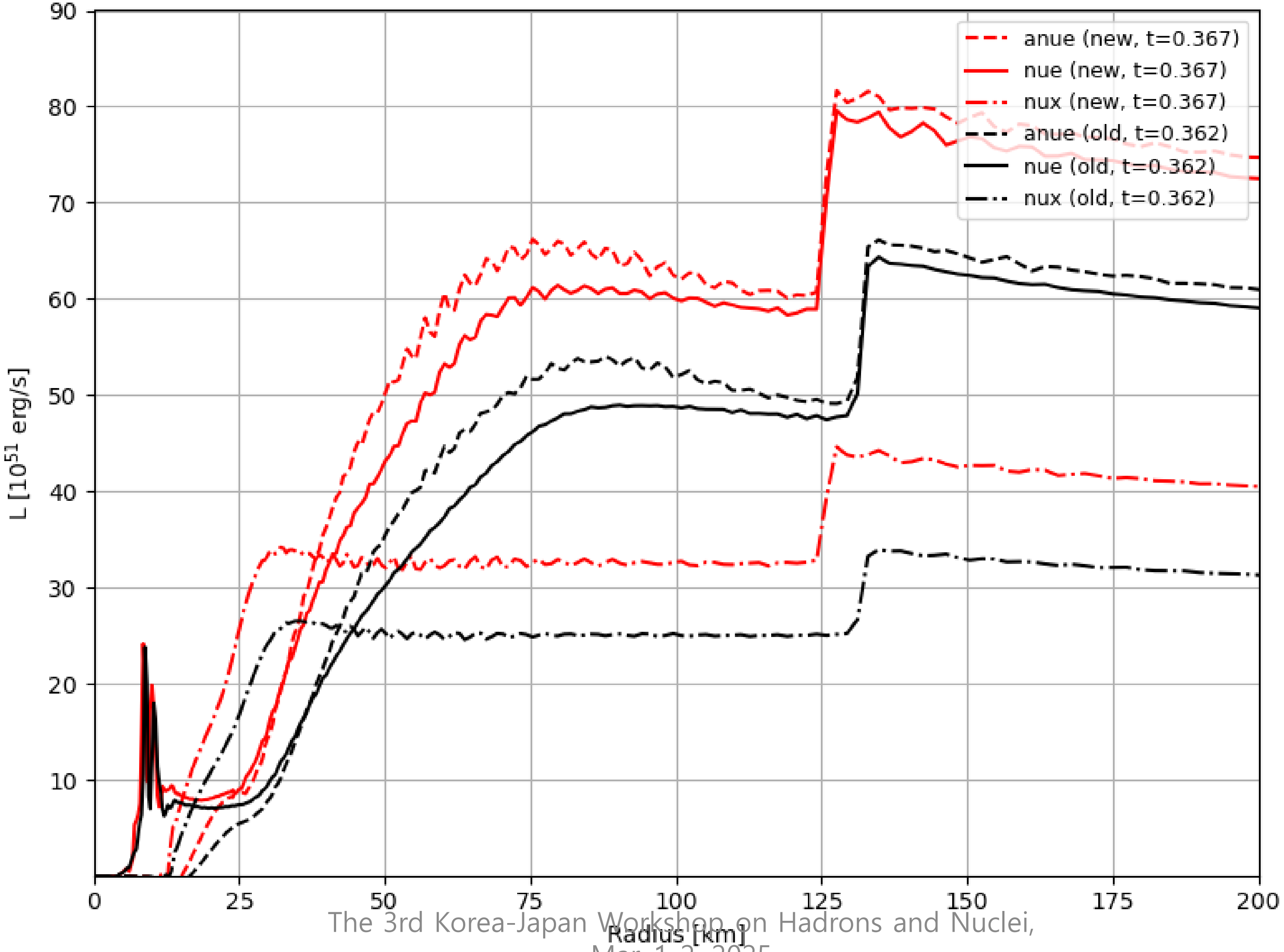
$\tau \rightarrow \frac{dx^{\alpha}}{d\tau} = p^{\alpha}$

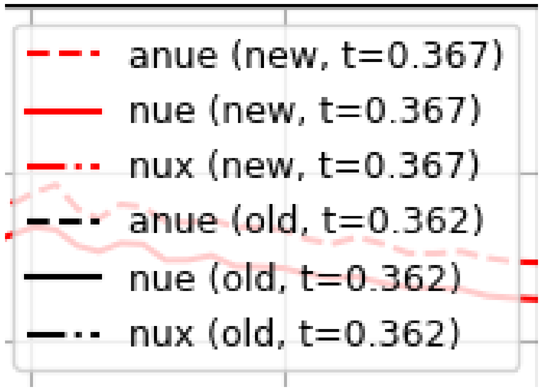
$\left[\frac{df_{\nu}}{d\tau}\right]_{coll}$ = collision term

Neutrinos in supernovae is **High energy + not equilibrium**

→ use relativistic Boltzmann equation

Preliminary data : (g_A =1) vs (g_A =1.27) data





Bounce time = 0.267s

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Thanks for your attention !!