Neutrino Reactions on nuclei of astrophysical importance by QRPA and Deformed QRPA

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4. Summary
Motivation in theoretical description

Indirect (Two-step) Processes

$A(n(\nu), n'(\nu'))A^* \rightarrow B + \text{outgoing particles}$

$A(n(\nu_i), l(l))B^* \rightarrow C + \text{outgoing particles}$

How to describe the ground and excited states in deformed nuclei and decays with particle emissions?

How to describe the reaction on the nucleon bound in nuclei and the nucleon in matter?

SM, QRPA, Hybrid
And Deformed
QRPA

by using Hauser-Feshbach statistical model by S. Chiba

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Various roles of $\nu$'s in SN-nucleosynthesis

**$\nu p$-process:** $^{92}\text{Mo}$, $^{96}\text{Ru}$?

**MSW high-density resonance through $\theta_{13}$ at $\rho \sim 10^3 \text{ g/cm}^3$**

**$\nu$-process:** $^{6,7}\text{Li}$, $^{9}\text{Be}$, $^{10,11}\text{B}$...

**$\nu$-process:** $^{180}\text{Ta}$, $^{138}\text{La}$, $^{92}\text{Nb}$, $^{98}\text{Tc}$...

**$\nu$-process:** $^{90}\text{Mo}$, $^{96}\text{Ru}$?

**R-process:** Heavy Nuclei

**Explo. Si-burn.**

Fe-Co-Ni, $^{60}\text{Co}$, $^{55}\text{Mn}$, $^{51}\text{V}$...

**Si Layer**

**O-Ne-Mg Layer**

**He-C Layer**

From Toshitaka Kajino
Octet baryon electromagnetic form factors in nuclear medium

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FIG. 4: Proton electromagnetic form factors calculated for \(\rho = 0\) (vacuum) with a decomposition of the valence and pion cloud contributions (left panel), and the ratios to those of the \(\rho = 0\) (right panel) for \(\rho = 0.5 \rho_0\) (dashed line) and \(1.0 \rho_0\) (dash-dotted line).
2.1. Relativistic mean field Lagrangian

\[ \mathcal{L} = \sum_b \bar{\psi}_b \left[ \gamma^\mu \partial_\mu - q_b \gamma_\mu A_\mu - \frac{1}{2} \kappa_b \sigma_{\mu\nu} F^{\mu\nu} \right] \psi_b + \sum_l \bar{\psi}_l \left[ \gamma^\mu \partial_\mu - q_l \gamma_\mu A_\mu - m_l \right] \psi_l \]

\[ + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - U(\sigma) + \frac{1}{2} \partial_\mu \sigma^* \partial^\mu \sigma^* - \frac{1}{2} m_{\sigma^*}^2 \sigma_{\sigma^*}^2 \]

\[ - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \frac{1}{2} m_\omega^2 w_\mu w_\mu - \frac{1}{4} \Phi_{\mu\nu} \Phi^{\mu\nu} + \frac{1}{2} m_{\phi}^2 \phi_\mu \phi^\mu \]

\[ - \frac{1}{4} R_{i\mu\nu} R_i^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_{\mu} \rho_\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \]

(1)

FIG. 1: Electromagnetic interaction with the baryon \( B \) within the one-pion loop level through the intermediate baryon states \( B' \). A diagram including a contact vertex \( \gamma \pi BB' \), as described in Ref. [20], is not represented explicitly, since the isospin structure is the same as diagram (a). See Ref. [20] for details.
Effective Mass in nuclear medium

**FIG. 4:** The effective mass $M^*(\rho)$ in terms of finite density $\rho/\rho_0$. 
\[ \frac{\text{QMC(medium)}}{\text{QMC(vacuum)}} \] for $g_A$.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{Change of the axial coupling constant normalized to that in free space, $g_A(\rho, Q^2)/g_A(\rho = 0, Q^2)$, with finite momentum transfer in nuclear medium. From the uppermost (vacuum), density ratios are increased by 0.1 $\rho_0$. Lowermost curve is for $\rho = \rho_0$.}
\end{figure}

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[QMC(medium)]/[QMC(vacuum)] for $F_1$.

\[ F_1^V(Q^2) = F_{1p}(Q^2) - F_{1n}(Q^2), \]
\[ F_2^V(Q^2) = F_{2p}(Q^2) - F_{2n}(Q^2). \]

**FIG. 2:** Change of the weak coupling constant ratio, $F_1(\rho, Q^2)/F_1(\rho = 0, Q^2)$, with finite momentum transfer in nuclear medium. From the lowermost (vacuum), density ratios are increased by 0.1 $\rho_0$. Uppermost curve is for $\rho = \rho_0$. 
[QMC(medium)]/[QMC(vacuum)] for F2.

\[ F_1^V(Q^2) = F_{1p}(Q^2) - F_{1n}(Q^2), \]
\[ F_2^V(Q^2) = F_{2p}(Q^2) - F_{2n}(Q^2). \]

FIG. 3: Changed of the weak coupling constant ratio, \( F_2(\rho, Q^2)/F_2(\rho = 0, Q^2) \), with finite momentum transfer in nuclear medium. From the lowermost (vacuum), density ratios are increased by 0.1 \( \rho_0 \). Uppermost curve is for \( \rho = \rho_0 \).
Neutrino X-section on the nucleon in dense matter

FIG. 5: Density dependence of electro-neutrino cross sections on a proton. The y axis is $10^{-41} \text{cm}^2$ and x-axis is the incident neutrino energy in the units of MeV. Red curve is the result in free space. The cross sections are decreased with the increase of the density by $0.1 \rho/\rho_0$, but it is increased suddenly at $3 \rho_0$.

About 10 (normal) - 40 %(3 \rho_0) decrease of the cross sections on a proton!!
Density dependence of X-section on 12C via CC

FIG. 6: Density dependence of electro-neutrino cross sections on $^{12}$C. The y axis is $10^{-41} \text{cm}^2$ and x-axis is the incident neutrino energy in the units of MeV. The cross sections are decreased with the increase of the density by 0.1 $\rho/\rho_0$.

About 10 (normal) - 15 %($3 \rho_0$) decrease of the cross section s for 12 C!!
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4. Summary
Motivation

Neutrino Energy

Cross Section

Giant Resonance

Quasi Elastic Region

Delta

Discrete Excited states

Dip Region

Pion Threshold

Typical cross section by incident electron

\[ T(\nu_e) = 3.2 \text{ MeV} < T(\bar{\nu}_e) = 5.0 \text{ MeV} < T(\nu_{\mu,\tau}) = T(\bar{\nu}_{\mu,\tau}) = 6.0 \text{ MeV} \]
FLOW of Computer Program (DQRPA)

1. Hartree Fock Field (Mean Field Potential)

2. Deformed Bardeen Cooper Schriffer (DBCS) Theory

3. Hartree Fock Bogoliubov (HFB) Theory

4. Deformed Quasi-particle RPA (DQRPA)

5. Beta Decay, Proton capture, Photo-disintegration, ...

6. Network Calculations for rp Nucleosynthesis

Particle-Hole Interaction (Long Range)

Quasi-Particle (ph, pp, hh interactions) and Deformations

Pairing Correlations among different states

Excited States

With G-matrix for NN interaction in nuclei
\[ \frac{d\sigma_{\nu}}{d\Omega} \left( \nu/\bar{\nu} \right) = \frac{G_F^2 \epsilon k}{\pi (2J_i + 1)} \left[ \sum_{J=0} \left( 1 + \vec{\nu} \cdot \vec{\beta} \right) \left| < J_f || \hat{M}_J || J_i > \right|^2 + (1 - \vec{\nu} \cdot \vec{\beta} + 2(\vec{\nu} \cdot \vec{q})(\vec{q} \cdot \vec{\beta})) \left| < J_f || \hat{L}_J || J_i > \right|^2 \right. \\
\left. - \hat{q} \cdot (\vec{\nu} + \vec{\beta}) 2 \text{Re} \left( < J_f || \hat{L}_J || J_i > < J_f || \hat{M}_J || J_i >^* \right) \right. \\
\left. + \sum_{J=1} \left( 1 - (\vec{\nu} \cdot \hat{q})(\vec{q} \cdot \vec{\beta}) \right) \left( \left| < J_f || \hat{T}^{el}_J || J_i > \right|^2 + \left| < J_f || \hat{T}^{mag}_J || J_i > \right|^2 \right) \right. \\
\left. \pm \sum_{J=1} \hat{q} \cdot (\vec{\nu} - \vec{\beta}) 2 \text{Re} \left[ < J_f || \hat{T}^{mag}_J || J_i > < J_f || \hat{T}^{el}_J || J_i >^* \right] \right) , \]

\[ \sigma(E_{\nu}) = \frac{G_F^2 \cos^2 \theta_c}{\pi \hbar^4 c^3} \sum_i k_i \epsilon_i F(Z, \epsilon_i) [B_i(GT) + B_i(F)] , \tag{8} \]

where \( k_i \) and \( \epsilon_i \) refer to the momentum and total energy of the outgoing electron and \( F(Z, \epsilon_i) \).

\[ R_T(q, \omega) = \sum_{J=0} \left| < J_f || \hat{T}^{el}_J(q) || J_i > \right|^2 + \left| < J_f || \hat{T}^{mag}_J(q) || J_i > \right|^2 , \]

\[ R_I(q, \omega) = \sum_{J=0} 2 \text{Re} \left( < J_f || \hat{T}^{el}_J(q) || J_i > < J_f || \hat{T}^{mag}_J(q) || J_i > \right) , \]

\[ \left( \frac{d\sigma_{\nu}}{d\Omega} \right)_{ERL} = \frac{2G_F^2 \epsilon \cos^2 \left( \frac{\theta}{2} \right)}{\nu \left( 2J_i + 1 \right)} \left[ R_T(q, \omega) + C(\theta, q) R_I(q, \omega) \mp \tan \left( \frac{\theta}{2} \right) C(\theta, q) R_I(q, \omega) \right] \]
Difference between two formalism for nu X-section

FIG. 8:
Neutrino-induced reactions data on $^{12}\text{C}$

$\text{LSND}: \nu_e^{12}\text{C} \rightarrow e^- + ^{12}\text{N}^*$

1. We need more data on nu-reactions! Neutrino beam from pion or
2. GT transitions by CEX are largely appreciated!
   Roles of RIF for unstable nuclei are important for unstable nuclei!
3. Multi-pole transitions as well as GT should be considered!
4. Coulomb distortion beyond Fermi function for beta decay may work!
5. Contributions from higher energy tails,
6. How are effects from the bound nucleon in nuclei?
   Already discussed.
7. How to treat the deformed nuclei?
GT Results for 90Zr

90Zr: beta- = 6111 KeV, beta+ = 2280 KeV

1. Peak positions on high-lying GT states are well pointed.
2. ISR is nicely reproduced.
3. 2p-2h mixings are vital for the high-lying GT states.

ISR is recovered by high-lying GT excitation coming from 2p-2h correlations. Then, g_A quenching problem??

States are well pointed. High-lying GT states.
In spherical basis, $J$ is a good quantum number. But in deformed basis, a projection of $J$ on the nuclear symmetric axis $z$, $\Omega$, is a good quantum number.

Deformed states. $\pm 5/2$, $\pm 3/2$, and $\pm 1/2$, are separated from the spherical state $d_{5/2}$.

Figure 1.2. Various shapes observed or expected in nuclei. Exotic orbitals that appear in regions far from the stability line may provide some new types of deformation. The superdeformation (top) and pear shape (bottom) have been observed experimentally, the oblate superdeformation has been predicted but not observed—less deformed oblate shapes are, however, quite common. The hyperdeformation (second from the top) has been seen in certain nuclei. The octupole banana-type deformation has not been observed in such extreme form, but vibrations of this kind are well known.

➢ Single particle states in deformed nucleus become more complex.
Deformed QRPA

From spherical basis to Nilsson basis

\[ |\alpha\Omega_\alpha> = \sum B^\alpha a |\alpha\Omega_\alpha> \]

\[ B^\alpha = \sum_{Nn_z\Sigma} C^\alpha_{l\Lambda_\Sigma} A^{nrl}_{Nn_z\Lambda} b_{Nn_z\Sigma} . \quad A^{nrl}_{Nn_z\Lambda} = \langle n_{r\Lambda}|Nn_z\Lambda \rangle \]

\[ |\alpha\beta> = \sum_{abJ} F^{JK}_{\alpha\alpha|ab} |\alpha\beta> \quad JK = \sum J C^{JK}_{j_{\alpha\beta}} |\alpha\beta> \quad \text{and} \quad F^{JK}_{\alpha\beta} = B^\alpha B^\beta (-1)^{j_{\beta} - \Omega_{\beta}} C^{JK}_{j_{\alpha\beta}} \]

Normal-parity orbits:

\[ |[411 3/2]> = 0.926 |411 3/2> + \ldots \]
\[ = 0.418 |g_{9/2}> - 0.140 |g_{7/2}> + 0.864 |d_{5/2}> + 0.246 |d_{3/2}> \]

\[ |[411 1/2]> = 0.900 |411 1/2> + \ldots \]
\[ = -0.163 |g_{9/2}> + 0.396 |g_{7/2}> - 0.099 |d_{5/2}> + 0.848 |d_{3/2}> + 0.297 |s_{1/2}> \]

\[ |[400 1/2]> = 0.968 |400 1/2> + \ldots \]
\[ = 0.147 |g_{9/2}> - 0.072 |g_{7/2}> + 0.539 |d_{5/2}> - 0.160 |d_{3/2}> + 0.811 |s_{1/2}> \]
Result 1

Gamow-Teller Strengths on $^{26-34}\text{Mg}$ isotopes by the Deformed Quasi-particle RPA
1. N = 20 magic number disappeared in $^{32}$Mg. But N = 28 is still there.

2. $^{30}$Ne shows degeneracy of fp shells.
Deformed QRPA

GT strength distributions on 26 Mg

$^{26}\text{Mg} (^{3}\text{He},t)$

(a) Exp. Zegers (PRC.2006)

(b) $\beta_2 = -0.1$

(120%, 50.54%)

(c) $\beta_2 = -0.2$

(109.44%, 60.6%)

Beta_2 = 0.296, -0.261

Oblate deformation leads to high lying GT states. ! Nothing in prolate.
The more neutrons you have, the more High-lying GT states appear.
Neutrino X-section on deformed 26 Mg which show a change about tens of % compared to the result by small deformation
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Result 3

High-lying Gamow-Teller excited states in the deformed nuclei of $^{76}\text{Ge}$ and $^{82}\text{Se}$ by the Deformed Quasi-particle RPA

Calculated GT states on $^{76}$Ge and $^{82}$Se.
Deformed QRPA GT strength distributions on 76 Ge and 82 Se

Deformation $\rightarrow$

Fermi energy increase $\rightarrow$

Wide Fermi smearing $\rightarrow$

2p-2h mixing $\rightarrow$

High-lying excitations are intimately associated with the deformation!!

FIG. 1: (Color online) Occupation probability of the neutron of $^{82}$Se with two deformation parameters $\beta_2$ as a function of the single particle energy given as Nilsson basis.
Summary

1. More data are necessary for understanding neutrino-induced reactions. DIF of pions or Beta beam neutrinos from RI are plausible sources of neutrinos on the lab. on Earth.

2. GT transitions are welcome because they dominate low energy X-section. In specific, RIB Facilities may greatly contribute to the CEX on the unstable nuclei.

3. Multi-pole transitions as well as GT should be considered!

4. Coulomb distortion beyond Fermi function for beta decay may work!

5. Contributions from higher energy tails, high-lying excited states beyond 1 nucleon threshold, also contribute. More CEX data beyond 1 nucleon threshold are necessary.

6. To treat density dependence is also necessary.

7. DQRPA is a quite useful for the nu-reaction description of deformed nuclei.
Thanks for your attention, and NAOJ for this workshop!