Collective excitations and neutrino-nucleus reactions in relativistic point-coupling models

APCTP, Pohang

Deni Vale, Nils Paar, Tamara Nikšić, Yifei Niu

University of Zagreb, Faculty of Science, Department of Physics

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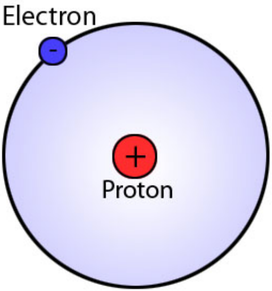
CENTER OF EXCELLENCE FOR THE THEORY OF QUANTUM AND COMPLEX SYSTEMS AND LIE ALGEBRA REPRESENTATION

Simple system - Hydrogen atom



Simple system - Hydrogen atom

Dirac Hamiltonian for central field:

$$\hat{H} = c\hat{\vec{\alpha}} \cdot \hat{\vec{p}} + \beta m_0 c^2 + V(r) \tag{1}$$

If the field has spherical symmetry, then total angular momentum operator $\hat{J}$ and operator $\hat{P}$ ($\hat{P} = \exp(i\phi)\hat{\beta}\hat{P}_0$, $P_0 : \vec{x} \to -\vec{x}$) commute with $\hat{H}$.
We assume solution:

$$\Psi_{njm} = \begin{pmatrix} \psi_{ljm}(\vec{r}, t) \\ \chi_{\bar{l}jm}(\vec{r}, t) \end{pmatrix} \tag{2}$$

Action of parity operator:

$$\hat{P}_0 \psi_{ljm}(\vec{r}, t) = \lambda_f \psi_{ljm}(\vec{r}, t) \tag{3}$$

$$-\hat{P}_0 \chi_{\bar{l}jm}(\vec{r}, t) = -\lambda_g \chi_{\bar{l}jm}(\vec{r}, t) \tag{4}$$

We must have $\lambda_f = -\lambda_g$ in order to have good parity of four-spinor.

Simple system - Hydrogen atom

$$\hat{H}\Psi_{jm}(\vec{r},t) = -i\hbar \begin{pmatrix} 0 & \hat{\vec{\sigma}} \\ \hat{\vec{\sigma}} & 0 \end{pmatrix} \nabla\Psi_{jm}(\vec{r},t) + \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} m_0 c^2 \Psi_{jm}(\vec{r},t) + V(r)\Psi_{jm}(\vec{r},t) \tag{5}$$

Rewritten in terms of bispinors:

$$-i\hbar c\vec{\sigma}\cdot\vec{\nabla}\chi_{\bar{l}jm} + m_0 c^2 \psi_{ljm} + V(r)\psi_{ljm} = E\psi_{ljm} \tag{6}$$

$$-i\hbar c\vec{\sigma}\cdot\vec{\nabla}\psi_{\bar{l}jm} - m_0 c^2 \chi_{ljm} + V(r)\chi_{ljm} = E\chi_{ljm} \tag{7}$$

For ψ

$$\psi_{ljm} = R_{nl}(r)\sum_{m_l m_s} C^{jm}_{1/2 m_s l m_l} Y_{l m_l}(\Omega)\chi_{1/2 m_s}(\vec{\sigma}) \tag{8}$$

and similar for χ.
Expansion of bispinors in spherical harmonic oscillator basis:

$$\psi_{nljm} = \sum_n C^l_n f_{nl}(r)\Omega_{ljm}(\hat{\Omega}) \tag{9}$$

$$\chi_{n\bar{l}jm} = \sum_n C^{\bar{l}}_n i g_{n\bar{l}}(r)\Omega_{\bar{l}jm}(\hat{\Omega}) \tag{10}$$

Simple system - Hydrogen atom

Matrix elements of Dirac Hamiltonian:

$$A_{fg} = -\hbar c \int_0^\infty dr r^2 f^*_{n_a l_a}(r) \frac{\partial}{\partial r} g_{n_c \bar{l}_a}(r) \tag{11}$$

$$B_{fg} = -\hbar c \int_0^\infty dr r^2 f^*_{n_a l_a}(r) \frac{1-\kappa}{r} g_{n_c \bar{l}_a}(r) \tag{12}$$

$$C^{(S)}_{ff} = \int dr r^2 f^*_{n_a l_a}(r) S(r) f_{n_c l_a}(r) \tag{13}$$

$$C^{(V)}_{ff} = \int dr r^2 f^*_{n_a l_a}(r) V(r) f_{n_c l_a}(r) \tag{14}$$

$$A_{gf} = \hbar c \int_0^\infty dr r^2 g^*_{n_a \bar{l}_a}(r) \frac{\partial}{\partial r} f_{n_c l_a}(r) \tag{15}$$

$$B_{gf} = \hbar c \int_0^\infty dr r^2 g^*_{n_a \bar{l}_a}(r) \frac{1+\kappa}{r} f_{n_c l_a}(r) \tag{16}$$

$$C^{(S)}_{gg} = -\int dr r^2 g^*_{n_a \bar{l}_a}(r) S(r) g_{n_c \bar{l}_a}(r) \tag{17}$$

$$C^{(V)}_{gg} = \int dr r^2 g^*_{n_a \bar{l}_a}(r) V(r) g_{n_c \bar{l}_a}(r) \tag{18}$$

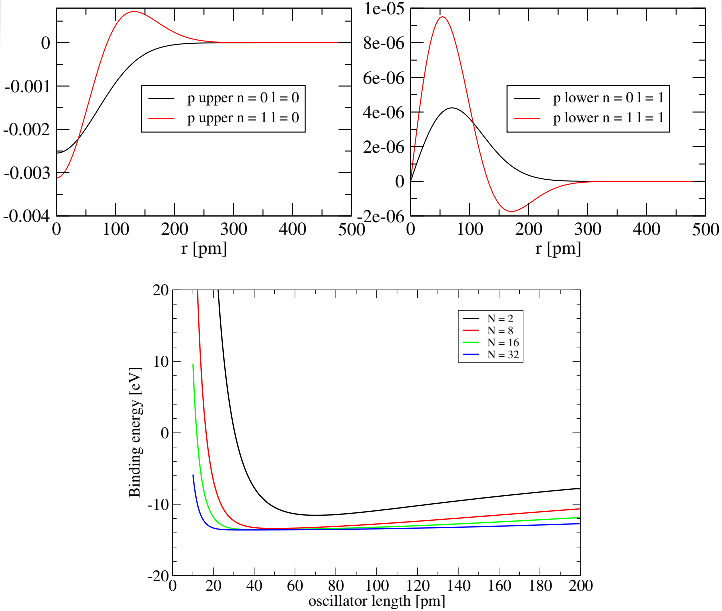
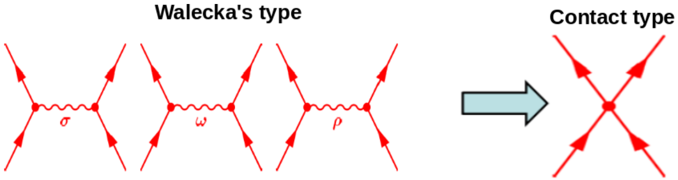


Figure 1: *Upper and lower components of spinor $s_{1/2}$. Dependence of binding energy of hydrogen atom on harmonic oscillator length for different numbers of major oscillator shells.*

Relativistic nuclear energy density functionals

Two types of nuclear models are usually present in relativistic energy density functionals:

- Walecka's type (nucleons are system of Dirac particles which interacts by exchange of mesons)
- Contact type (point-coupling; where meson propagator is replaced by contact interaction)



In nuclear models of Walecka's type we have meson propagator:

$$\frac{g_m}{-\Delta + m_m^2} \simeq \frac{g_m}{m_m^2} + g_m \frac{\Delta}{m_m^4}, \tag{19}$$

Four-fermion interaction:

$$L_{4f} = -\frac{1}{2}\alpha_S\left(\bar{\psi}\psi\right)\left(\bar{\psi}\psi\right) - \frac{1}{2}\alpha_V\left(\bar{\psi}\gamma_\mu\psi\right)\left(\bar{\psi}\gamma^\mu\psi\right) - \frac{1}{2}\alpha_{TV}\left(\bar{\psi}\vec{\tau}\gamma_\mu\psi\right)\left(\bar{\psi}\vec{\tau}\gamma^\mu\psi\right), \quad (20)$$

Derivative terms:

$$L_{der} = -\frac{1}{2}\delta_S\partial_\nu\left(\bar{\psi}\psi\right)\partial^\nu\left(\bar{\psi}\psi\right) - \frac{1}{2}\delta_V\partial_\nu\left(\bar{\psi}\gamma_\mu\psi\right)\partial^\nu\left(\bar{\psi}\gamma^\mu\psi\right) - \frac{1}{2}\delta_{TV}\partial_\nu\left(\bar{\psi}\vec{\tau}\gamma_\mu\psi\right)\partial^\nu\left(\bar{\psi}\vec{\tau}\gamma^\mu\psi\right), \quad (21)$$

We can add non-linear terms:

$$L_{hot} = -\frac{1}{3}\beta_S\left(\bar{\psi}\psi\right)^3 - \frac{1}{4}\gamma_S\left(\bar{\psi}\psi\right)^4, \quad (22)$$

Dirac Lagrangian for free nucleon:

$$L_{free} = \bar{\psi}\left(i\gamma_\mu\partial^\mu - m\right)\psi \quad (23)$$

Electromagnetic part:

$$L_{em} = -eA_\mu\bar{\psi}\left[(1-\tau_3)/2\right]\gamma^\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (24)$$

DD-PC1 parametrization

Lagrangian density:

$$\begin{aligned} L &= \bar{\psi}\left(i\gamma_\mu\partial^\mu - m\right)\psi - \frac{1}{2}\alpha_S\left(\bar{\psi}\psi\right)\left(\bar{\psi}\psi\right) - \frac{1}{2}\alpha_V\left(\bar{\psi}\gamma_\mu\psi\right) \\ &\times\left(\bar{\psi}\gamma^\mu\psi\right) - \frac{1}{2}\alpha_{TV}\left(\bar{\psi}\vec{\tau}\gamma_\mu\psi\right)\left(\bar{\psi}\vec{\tau}\gamma^\mu\psi\right) \\ &- \frac{1}{2}\delta_S\partial_\nu\left(\bar{\psi}\psi\right)\partial^\nu\left(\bar{\psi}\psi\right) - e\bar{\psi}\gamma_\mu A^\mu\frac{1-\tau_3}{2}\psi. \end{aligned} \tag{25}$$

Coupling density dependence in case of DD-PC1 parametrization:

$$f_i\left[\rho\right] = a_i + \left(b_i + c_i x\right)\exp(-d_i x), \tag{26}$$

Variation of Lagrangian with respect to $\bar{\psi}$ we obtain one-nucleon Dirac equation:

$$\left[\gamma_\mu\left(i\partial^\mu - \Sigma^\mu - \Sigma^\mu_{rearr}\right) - \left(m + \Sigma_S\right)\right]\psi = 0, \tag{27}$$

$$\Sigma^\mu = \Sigma^\mu_V + \vec{\tau}\cdot\vec{\Sigma}^\mu_{TV}, \tag{28}$$

$$\Sigma_S = \alpha_S(\rho)\rho_S + \delta_S\Delta\rho_S, \tag{29}$$

$$\Sigma^\mu_V = \alpha_V(\rho)j^\mu + e\frac{1-\tau_3}{2}A^\mu, \tag{30}$$

(31)

$$\vec{\Sigma}^{\mu}_{TV} = \alpha_{TV}(\rho)\vec{j}^{\mu}, \tag{32}$$

$$\Sigma^{\mu}_{rearr} = \frac{1}{2}\frac{j^{\mu}}{\rho}\left[\frac{\partial\alpha_S(\rho)}{\partial\rho}\rho_S^2 + \frac{\partial\alpha_V(\rho)}{\partial\rho}j_\nu j^\nu + \frac{\partial\alpha_{TV}(\rho)}{\partial\rho}\vec{j}_\nu\vec{j}^\nu\right]. \tag{33}$$

RPA matrix elements can be easily obtained from:

$$V_{abcd} = \frac{\delta h_{ac}}{\delta\rho_{db}} = \frac{\delta^2 E\left[\rho\right]}{\delta\rho_{ac}\delta\rho_{bd}}, \tag{34}$$

where

$$h = -i\boldsymbol{\alpha}\boldsymbol{\nabla} + \beta(m+\Sigma) + \beta\gamma_\mu\Sigma^\mu \tag{35}$$

General particle-hole matrix elements

$$V^{(1)}_{abcd} = \int d^3r_1 \int d^3r_2 \sum_j \bar{\psi}_a(\vec{r}_1)\Gamma^{(1)}_{j\mu} O^{(1)}_\tau \psi_c(\vec{r}_1) D_j(\vec{r}_1,\vec{r}_2) \times \bar{\psi}_b(\vec{r}_2)\Gamma^{(2)\mu}_j O^{(2)}_\tau \psi_d(\vec{r}_2) \quad (36)$$

$$V^{(2)}_{abcd} = \int d^3r_1 \int d^3r_2 \sum_j \bar{\psi}_a(\vec{r}_1)\Gamma^{(1)}_{j\mu} O^{(1)}_\tau \psi_c(\vec{r}_1) \frac{\partial D_j(\vec{r}_1,\vec{r}_2)}{\partial\rho(\vec{r}_1)} \times \rho^\mu_j(\vec{r}_2)\bar{\psi}_b(\vec{r}_2)1^{(2)}\psi_d(\vec{r}_2) \quad (37)$$

$$V^{(3)}_{abcd} = 1/2 \int d^3r_1 \int d^3r_2 \sum_j \bar{\psi}_a(\vec{r}_1)1^{(1)}\psi_c(\vec{r}_2) \frac{\partial D^2_j(\vec{r}_1,\vec{r}_2)}{\partial\rho^2(\vec{r}_1)} \times \rho_{j\mu}(\vec{r}_1)\rho^\mu_j(\vec{r}_2)\bar{\psi}_b(\vec{r}_2)1^{(2)}\psi_d(\vec{r}_2) \quad (38)$$

$$V^{(4)}_{abcd} = \int d^3r_1 \int d^3r_2 \sum_j \bar{\psi}_a(\vec{r}_1)1^{(1)}\psi_c(\vec{r}_2) \frac{\partial D_j(\vec{r}_1,\vec{r}_2)}{\partial\rho(\vec{r}_1)} \times \rho_{j\mu}(\vec{r}_1)\bar{\psi}_b(\vec{r}_1)\Gamma^{(2)\mu}_j O^{(2)}_\tau \psi_d(\vec{r}_2), \quad (39)$$

Separable pairing matrix elements

In 2009 Y. Tian, Z. Y. Ma and P. Ring introduced separable pairing in $^1S_0$ channel gap equation of symmetric nuclear matter:

$$\Delta(k) = -\int_0^\infty \frac{k'^2 dk'}{2\pi^2} \langle k | V_{sep}^{^1S_0} | k' \rangle \frac{\Delta(k')}{2E(k')}, \tag{40}$$

where

$$\langle k | V_{sep}^{^1S_0} | k' \rangle = -Gp(k)p(k'), \tag{41}$$

with Gaussian ansatz

$$p(k) = e^{-a^2k^2}. \tag{42}$$

These two parameters a and G were fitted to density dependence of the gap at the Fermi surface in nuclear matter. After transformation the separable force from momentum to coordinate space we obtained:

$$V(\vec{r}_1, \vec{r}_2, \vec{r}_1', \vec{r}_2') = -G\delta(\vec{R}_1 - \vec{R}_2)P(r)P(r')\frac{1 - \hat{P}^\sigma}{2} \tag{43}$$

with $\vec{r} = 1/\sqrt{2}(\vec{r}_1 - \vec{r}_2)$ and $\vec{R} = 1/\sqrt{2}(\vec{r}_1 + \vec{r}_2)$. Values of $G = 728$ MeV fm^3 and $a_0 = 0.644$ fm

Separable pairing matrix elements

After Fourier transformation:

$$P(r) = \frac{e^{-r^2/(2a^2)}}{(4\pi a^2)^{3/2}} \tag{44}$$

Due to coordinate transformation from laboratory to center of mass and relative coordinates we need to use Talmi-Moschinsky brackets:

$$|n_1 l_1, n_2 l_2; \lambda\mu\rangle = \sum_{NLnl} M^{NLnl}_{n_1 l_1 n_2 l_2} |NL, nl; \lambda\mu\rangle \tag{45}$$

If we work in the basis of spherical harmonic oscillator:

$$I_n = \sqrt{4\pi} \int R_{nl}(r) P(r) r^2 dr = \frac{1}{2^{2/3}\pi^{3/4} b^{3/2}} \frac{(1-\alpha^2)^n}{(1+\alpha^2)^{n+3/2}} \frac{\sqrt{2n+1}}{2^n n!}, \tag{46}$$

the coupled matrix element for $T = 1$ pairing:

$$V^{JM}_{abcd} = G \hat{j}_a \hat{j}_b \hat{j}_c \hat{j}_d (-1)^{l_b+l_d+j_a+j_c} \left\{ \begin{array}{ccc} l_a & j_a & 1/2 \\ j_b & l_b & J \end{array} \right\} \left\{ \begin{array}{ccc} l_c & j_c & 1/2 \\ j_d & l_d & J \end{array} \right\} \sum_{Nnn'} I_n I_{n'} M^{NJn0}_{n_a l_a n_b l_b} M^{NJn'0}_{n_c l_c n_d l_d} \tag{47}$$

Collective excitations

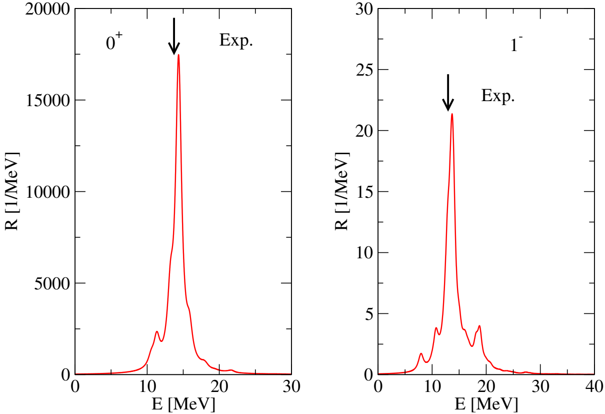


Figure 2: *The Isoscalar monopole (left) and isovector dipole (right) strength distribution for* ^{208}*Pb. ISGMR centroid energy is on 14.2 (exp.* 13.96 ± 0.20 *MeV, while for RPA IVGDR predicts the excitation energy on 13.7 (exp. 13.3 MeV).*

Isoscalar monopole collective excitation

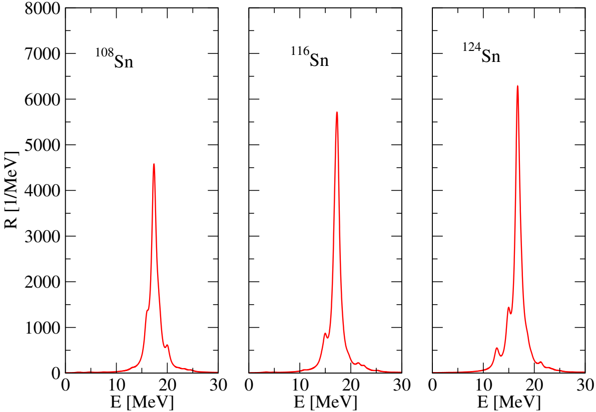


Figure 3: *The Isoscalar monopole strength distribution for even-even nuclei* $A = 108 - 124$ *with* $\Delta A = 8$.

Proton-neutron (R)QRPA

RPA equations:

$$\begin{pmatrix} A & B \\ B* & A* \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix} = E_\lambda \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \tag{48}$$

$$\begin{aligned} A_{pn,p'n'} = & H^{11}_{pp'}\delta_{nn'} + H^{11}_{nn'}\delta_{pp'} + \left(u_p v_n u_{p'} v_{n'} + v_p u_n v_{p'} u_{n'}\right) \\ & \times V^{ph}_{pn'np'} + \left(u_p u_n u_{p'} u_{n'} + v_p v_n v_{p'} v_{n'}\right) V^{pp}_{pnp'n'}, \end{aligned} \tag{49}$$

$$\begin{aligned} B_{pn,p'n'} = & \left(u_p v_n v_{p'} u_{n'} + v_p u_n u_{p'} v_{n'}\right) V^{ph}_{pp'nn'} \\ & + \left(u_p u_n v_{p'} v_{n'} + v_p v_n u_{p'} u_{n'}\right) V^{pp}_{pnp'n'}. \end{aligned} \tag{50}$$

Non-diagonal H^{11} is defined as

$$H^{11} = (u_i u_j + v_i v_j)h_{ij} + (u_i v_j - v_i u_j)\Delta_{ij} \tag{51}$$

Proton-neutron (R)QRPA

Isovector-vector part of PN-(R)QRPA survives only for $V^{(1)}$ type of matrix elements. In the case of spacelike components we have:

$$V_{abcd}^{(1s)} = -\int d^3r_1 \int d^3r_2 \psi_a^\dagger(\vec{r}_1)\left(\vec{\tau}\gamma_0\gamma_\mu\right)^{(1)}\psi_c(\vec{r}_1) \times \alpha_{TV}(\rho)\delta(\vec{r}_1-\vec{r}_2)\psi_b^\dagger(\vec{r}_2)\left(\vec{\tau}\gamma_0\gamma^\mu\right)^{(2)}\psi_d(\vec{r}_2), \quad (52)$$

and timelike components:

$$V_{abcd}^{(1t)} = \int d^3r_1 \int d^3r_2 \psi_a^\dagger(\vec{r}_1)\vec{\tau}^{(1)}\psi_c(\vec{r}_1)\alpha_{TV}(\rho) \times \delta(\vec{r}_1-\vec{r}_2)\psi_b^\dagger(\vec{r}_2)\vec{\tau}^{(2)}\psi_d(\vec{r}_2). \quad (53)$$

Isovector-vector matrix elements

If the radial part of wave function is given by:

$$\psi(r) = \begin{pmatrix} f(r) \\ ig(r) \end{pmatrix} \tag{54}$$

by coupling of angular momentum, we get coupled matrix elements for spacelike part:

$$\begin{aligned} V^{(1s)J}_{abcd} &= 2\hat{J}^{-2} \sum_L \int drr^2 \alpha_{TV} (f_a(r) g_c(r) \langle j_a || (\sigma_S Y_L)_J || \bar{j}_c \rangle \\ &\quad - g_a(r) f_c(r) \langle \bar{j}_a || (\sigma_S Y_L)_J || j_c \rangle)(f_b(r) g_d(r) \langle \bar{j}_d || (\sigma_S Y_L)_J || j_b \rangle \\ &\quad - g_b(r) f_d(r) \langle j_d || (\sigma_S Y_L)_J || \bar{j}_b \rangle), \end{aligned} \tag{55}$$

and timelike part

$$\begin{aligned} V^{(1t)J}_{abcd} &= 2J^{-2} \int drr^2 \alpha_{TV} (f_a(r) f_c(r) + g_a(r) g_c(r)) \\ &\quad (f_b(r) f_d(r) + g_b(r) g_d(r)) \langle j_a || Y_J || j_c \rangle \langle j_d || Y_J || j_b \rangle, \end{aligned} \tag{56}$$

Isovector-vector matrix elements

Angular part is given by expressions:

$$\langle j_a||Y_J||j_c\rangle = \frac{1+(-1)^{l_a+l_c+J}}{2}\frac{\hat{j}_a\hat{j}_c\hat{J}}{\sqrt{4\pi}}(-1)^{j_a-1/2}\begin{pmatrix} j_a & J & j_c \\ -1/2 & 0 & 1/2 \end{pmatrix}, \quad (57)$$

and

$$\begin{aligned}\langle j_a||(\sigma_S Y_L)_J||j_c\rangle = & \frac{1+(-1)^{l_a+l_c+J}}{2}\frac{\hat{j}_a\hat{j}_c\hat{J}\hat{L}}{\sqrt{4\pi}}(-1)^{l_a+L} \\ & \times\Bigg[(-1)^{l_c+j_c+1/2}\begin{pmatrix} 1 & L & J \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} j_a & J & j_c \\ -1/2 & 0 & 1/2 \end{pmatrix} - \\ & \sqrt{2}\begin{pmatrix} 1 & L & J \\ -1 & 0 & 1 \end{pmatrix}\begin{pmatrix} j_a & J & j_c \\ 1/2 & -1 & 1/2 \end{pmatrix}\Bigg]. \quad (58)\end{aligned}$$

Isovector-pseudovector matrix elements

In order to describe the effects of pions in multipolar transitions in PN-RQRPA we use isovector-pseudovector coupling. However, we expect that the strength of pion-nucleon in nuclei coupling should be somewhat reduced by factor of g':

$$V_{PV} = -g'\left(\frac{f_\pi}{m_\pi}\right)^2 \delta(\vec{r}_1-\vec{r}_2)\,(\gamma_0\gamma_5\gamma_\mu\vec{\tau})^{(1)}\,(\gamma_0\gamma_5\gamma^\mu\vec{\tau})^{(2)}\,, \quad (59)$$

where f_π decay constant and m_π mass of pion. The value of g' we don't know *a priori* and should be deduced from experiment.
For timelike part pseudovector matrix elements look like:

$$V^{PV(t)J}_{abcd} = 2g'\hat{J}^{-2}\left(\frac{f_\pi}{m_\pi}\right)^2 \int drr^2(f_a(r)g_c(r)-g_a(r)f_c(r)) \times (f_b(r)g_d(r)-g_b(r)f_d(r))\langle j_a||Y_J||\bar{j}_c\rangle\langle \bar{j}_d||Y_J||j_c\rangle, \quad (60)$$

Timelike matrix elements are non-zero only in case of unnatural parity transitions, like Gammow-Teller transition.

Isovector-pseudovector matrix elements

For spacelike part isovector-pseudovector matrix elements look like:

$$\begin{aligned} V_{abcd}^{PV(s)J} &= 2g' \hat{J}^{-2} \left(\frac{f_\pi}{m_\pi}\right)^2 \sum_L \int dr r^2 (f_a(r) f_c(r) \\ &\quad \times \langle j_a || (\sigma_S Y_L)_J || j_c \rangle + g_a(r) g_c(r) \langle \bar{j}_a || (\sigma_S Y_L)_J || \bar{j}_c \rangle)(f_b(r) f_d(r) \\ &\quad \times \langle j_d || (\sigma_S Y_L)_J || j_b \rangle + g_b(r) g_d(r) \langle \bar{j}_d || (\sigma_S Y_L)_J || \bar{j}_b \rangle). \end{aligned} \tag{61}$$

Spacelike isovector-pseudovector matrix elements contribute to both unnatural and natural parity transitions, but in opposite manner compared to isovector-vector matrix elements.

Separable pairing in the case of PN-(R)QRPA

Coupled pp-elements for PN-(R)QRPA are given by:

$$V_{abcd}^{JM} = -G\hat{j}_a\hat{j}_b\hat{j}_c\hat{j}_d \sum_{LS}\left(1-(-1)^{S+T}\right)\hat{S}^2\hat{L}^2 \left\{\begin{array}{ccc} l_b & 1/2 & j_b \\ l_a & 1/2 & j_a \\ L & S & J \end{array}\right\} \left\{\begin{array}{ccc} l_d & 1/2 & j_d \\ l_c & 1/2 & j_c \\ L & S & J \end{array}\right\} \sum_{nn'} I_n I'_n M_{n_a l_a n_b l_b}^{NLn0} M_{n_c l_c n_d l_d}^{NLn'0} \quad (62)$$

This is non-vanishing only for $S=0$ and $T=1$ or $S=1$ and $T=0$. Assumed form of pp-matrix elements:

$$V_{abcd}^{JM} = \langle ab|V(T=0;S=1)|cd\rangle^{JM} \times V_0 + \langle ab|V(T=1;S=0)|cd\rangle^{JM} \quad (63)$$

We don't know *a priori* the value of factor V_0. It can be somewhat reduced or enhanced compared to the case $T=1$.

Determination of parameter g'

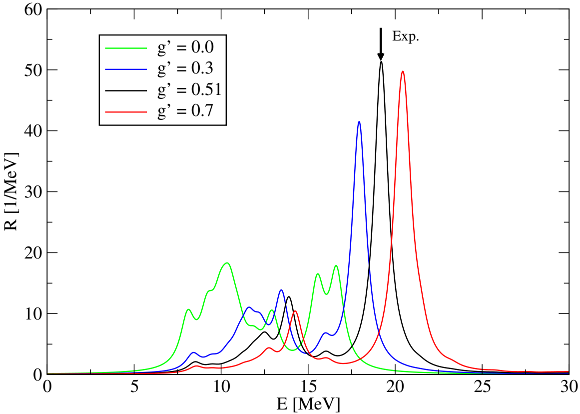


Figure 4: *The Gammow-Teller strength distribution for ^{208}Pb for different values of parameter g', calculated with DD-PC1 interaction. The experimental value of the position of GT^- main peak in ^{208}Pb is on 19.2 MeV. This corresponds to $g' = 0.51$. The width of Lorentzian is 1 MeV.*

Gammow-Teller resonance

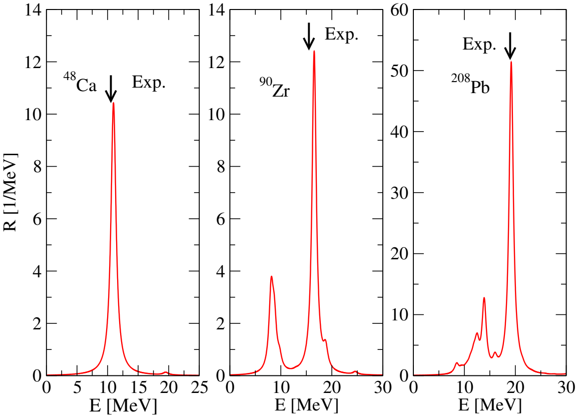


Figure 5: *The Gammow-Teller strength distribution for ^{48}Ca ^{90}Zr and ^{208}Pb, calculated by DD-PC1 interaction. The theoretical (experimental) values of central position GTR main peak are 11.0 (10.5) MeV for ^{48}Ca and 16.6 (15.6) MeV for ^{90}Zr.*

Isobaric analog resonance

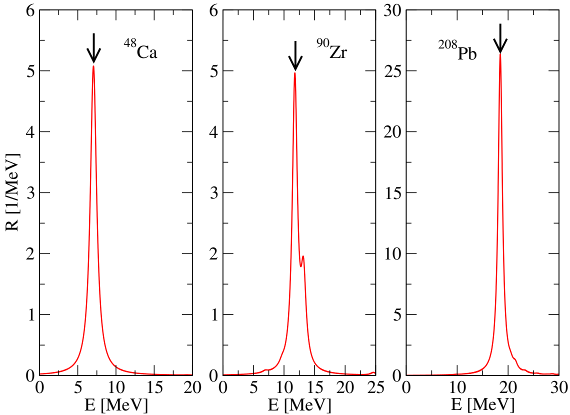


Figure 6: *The isobar analog state strength distribution for ^{48}Ca, ^{90}Zr and ^{208}Pb, calculated by DD-PC1. The theoretical (experimental) values of central position GTR main peak are 7.05 (7.17) MeV for ^{48}Ca and 11.7 (12.0±0.9) MeV for ^{90}Zr and 18.47 (18.83±0.02) MeV for ^{208}Pb.*

Isobaric analog resonance in Sn isotopes

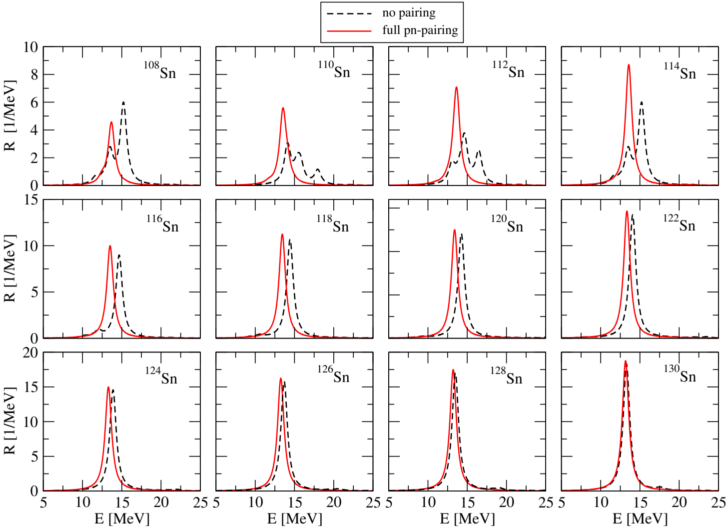


Figure 7: *PN-(R)QRPA strength distribution for even-even nuclei with* $A = 108 - 130$*, calculated by DD-PC1 with separable pairing interaction.*

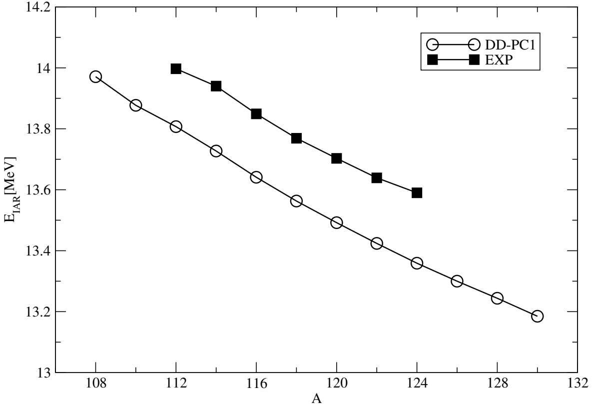


Figure 8: *Calculated and experimental IAR position for Sn isotopes.*

Gammow-Teller resonance in ^{118}Sn

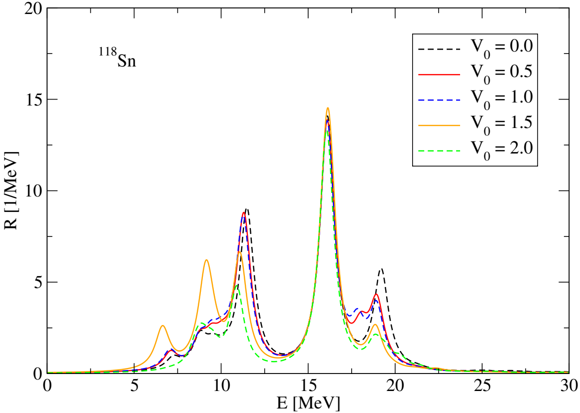


Figure 9: *The Gammow-Teller strength distribution for ^{118}Sn for different values of parameter V_0. Notice, only $T = 0$ pp matrix elements are nonvanishing.*

Standard model

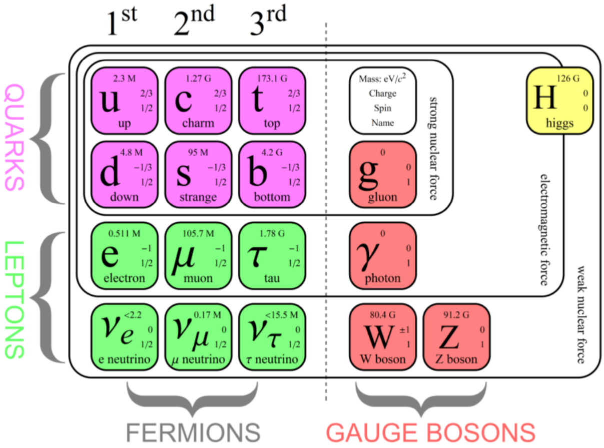


Figure 10: *Standard model.*

Why neutrino-nucleus reactions?

Neutrino mass hierarchy still remains an open problem due to insensitivity of previous and nowadays experiments on sign of difference between squares of neutrino masses.

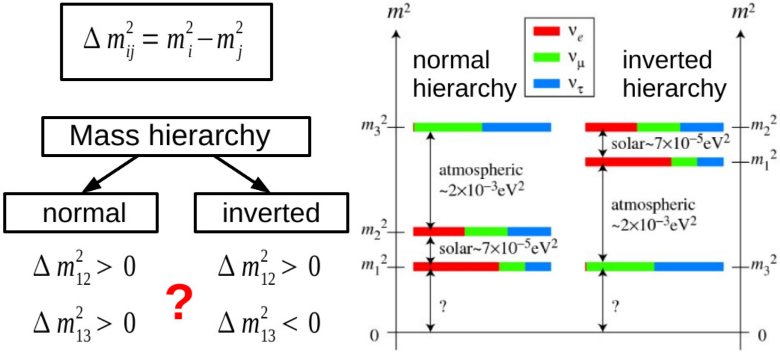


Figure 11: *Possible neutrino mass ordering (hierarchy). Degenerate case excluded from figure.*

Why neutrino-nucleus reactions?

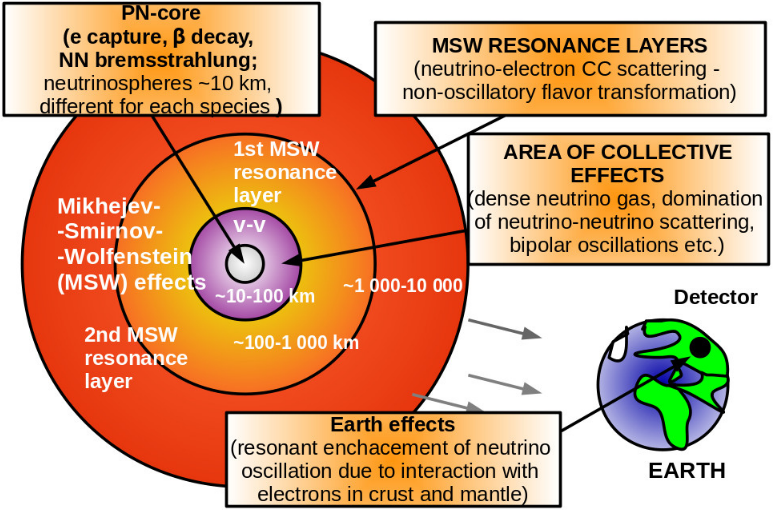


Figure 12: *Supernova from neutrino perspective.*

Why neutrino-nucleus reactions?

We need to choose adequate target material for detector in order to achieve good statistics and include or exclude particular neutrino species in a specific energy range.

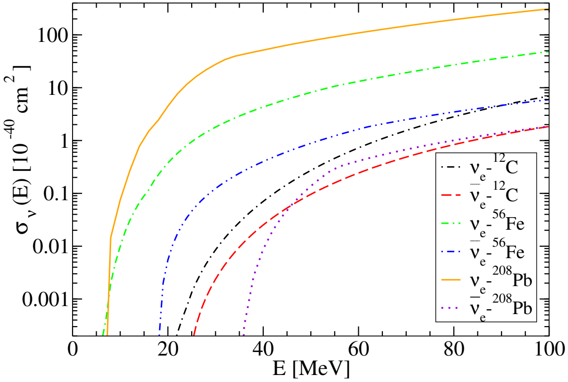


Figure 13: *The inclusive $\nu_e(\bar{\nu}_e)$ cross sections with ^{12}C, ^{56}Fe and ^{208}Pb as a function of $\nu_e(\bar{\nu}_e)$ energy (charged current reactions only). (see refs. D. Vale, N. Paar AIP Conference Proceedings 1681 (1), 050011; N. Paar, T. Marketin, D. Vale, D. Vretenar International Journal of Modern Physics E 24 (09), 1541004.*

Why neutrino-nucleus reactions?

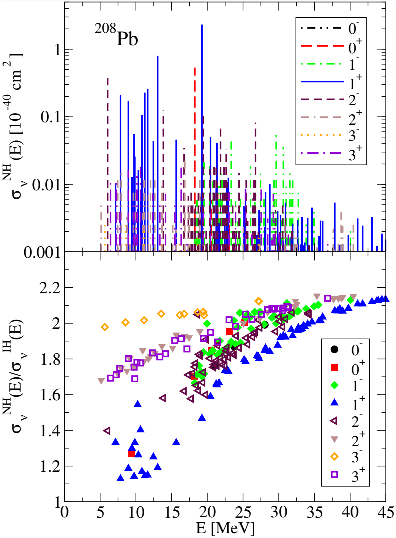


Figure 14: *Example of multipole decomposition of the flux averaged cross sections for ν_e - ^{208}Pb charged current reaction. see ref. D Vale, T Rauscher, N Paar Journal of Cosmology and Astroparticle Physics 2016 (02), 007*

Why neutrino-nucleus reactions?

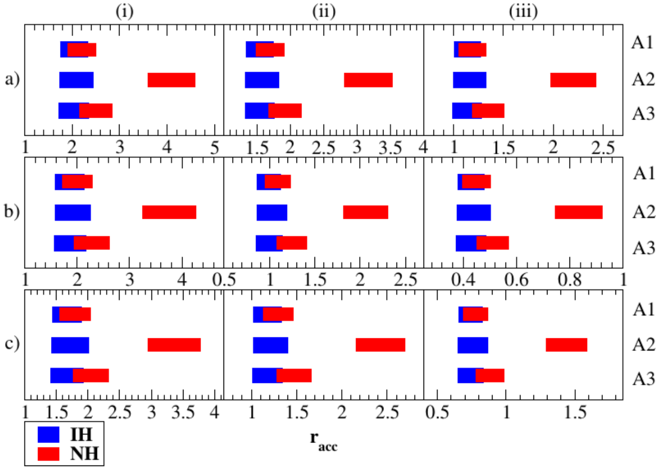


FIG. 6: The ratios r_{acc} of the number of the detector events induced in mineral oil (CH_2), water (H_2O), and ^{208}Pb for the incoming (anti)neutrino fluxes of the accretion phase in normal (NH) and inverted (IH) mass hierarchy: (a) $r^{\text{free p,Pb}}_{\text{e+,1n}}$ $[10^{-1}]$ (b) $r^{\text{free p,Pb}}_{\text{e+,2n}}$ (c) $r^{\text{free p,Pb}}_{\text{e+,tot n}}$ $[10^{-1}]$. The three columns correspond to (i) $\langle E^0_{\nu_e}\rangle = 8$ MeV, $\langle E^0_{\bar{\nu}_e}\rangle = 11$ MeV, $\langle E^0_{\nu_x}\rangle = 13$ MeV; (ii) $\langle E^0_{\nu_e}\rangle = 10$ MeV, $\langle E^0_{\bar{\nu}_e}\rangle = 13$ MeV, $\langle E^0_{\nu_x}\rangle = 15$ MeV; and (iii) $\langle E^0_{\nu_e}\rangle = 12$ MeV, $\langle E^0_{\bar{\nu}_e}\rangle = 15$ MeV, $\langle E^0_{\nu_x}\rangle = 19$ MeV. A1, A2, A3 denote the combinations of the luminosity ratios for the accretion phase given in Tab. I

Why neutrino-nucleus reactions?

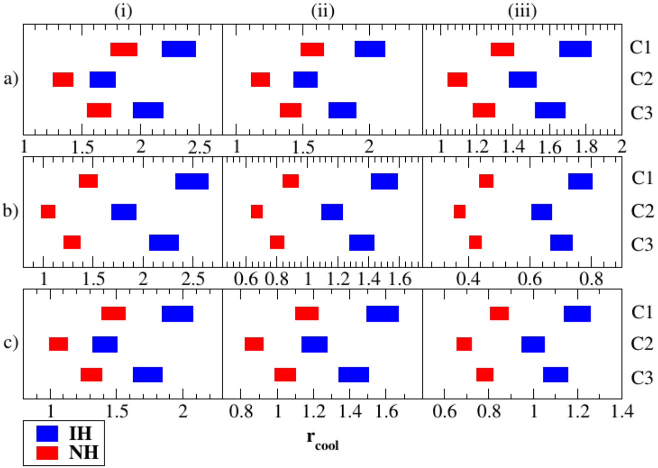


FIG. 7: The ratios r_{cool} of the number of the detector events induced in mineral oil (CH_2), water (H_2O), and ^{208}Pb for the incoming (anti)neutrino fluxes of the cooling phase in normal (NH) and inverted (IH) mass hierarchy for three configurations of initial ν average energies. The same notation as in Fig. 6 applies. C1, C2, C3 denote the combinations of the luminosity ratios for the cooling phase given in Tab. I.