Weak-interaction Process in Nuclear Structure and Nuclear Astrophysics

— $0\nu\beta\beta$-decay, electron-capture and Urca cooling —

Long-Jun Wang

School of Physical Science and Technology, Southwest University

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Outline

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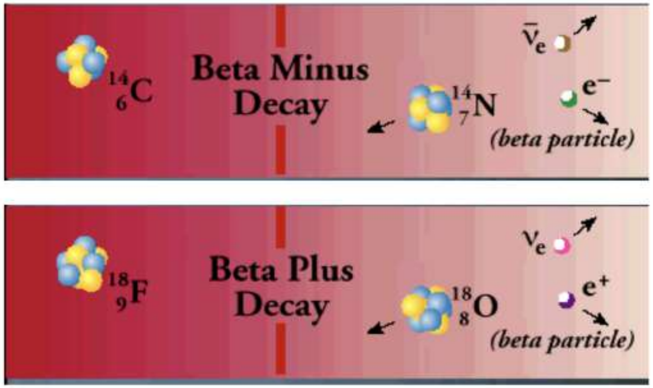
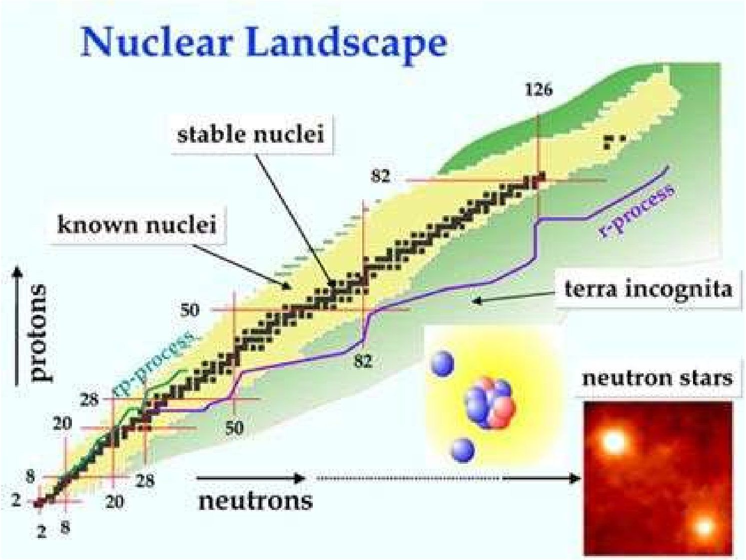
Nuclear weak-interaction process

- Single β-decays:





Nuclear weak-interaction process

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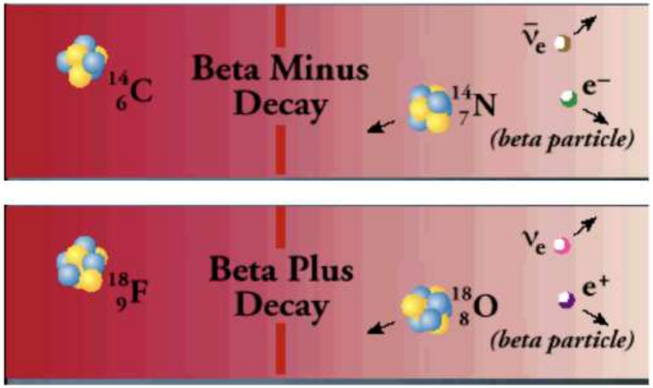

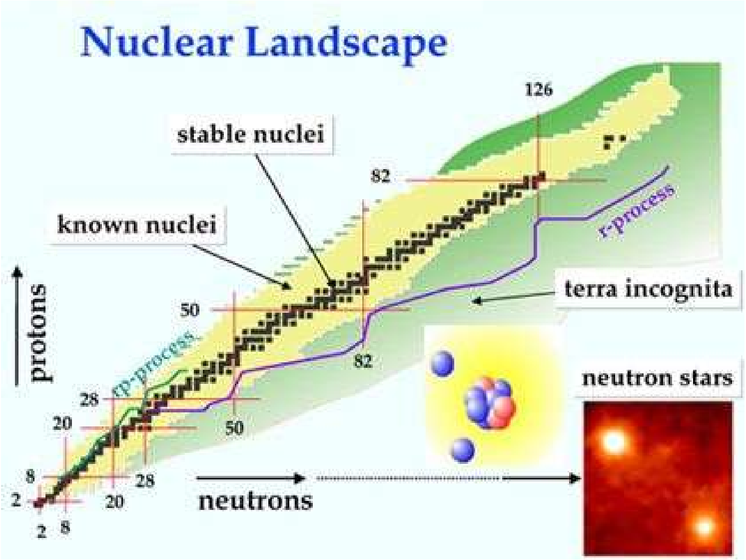

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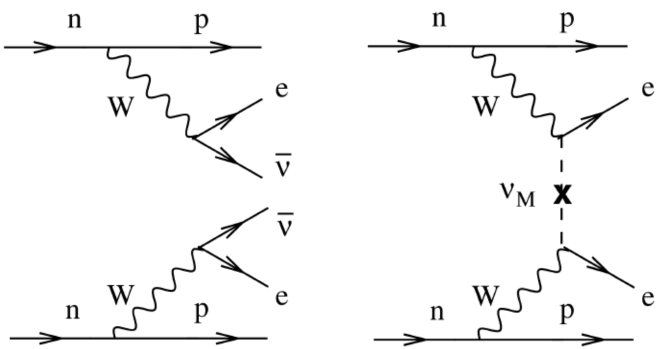
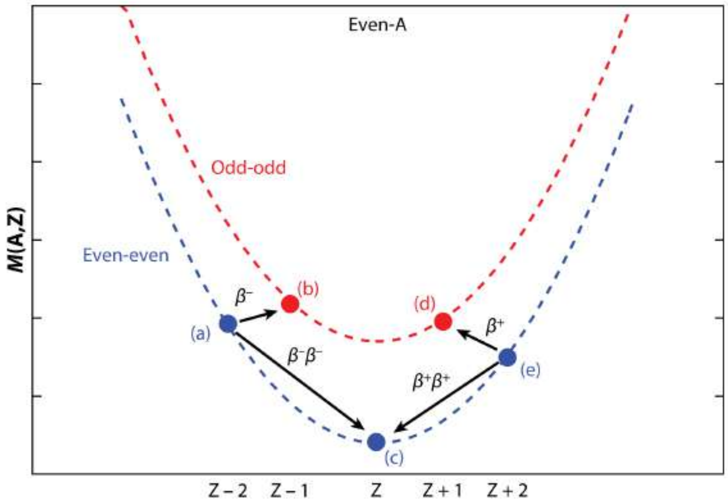
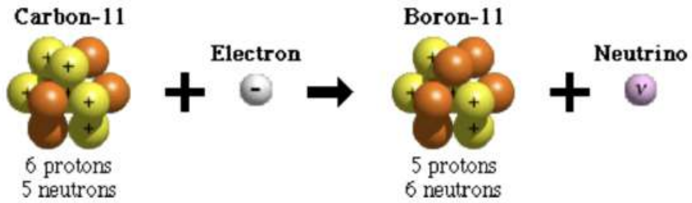


Majorana or Dirac ?



Nuclear weak-interaction process

- Single electron captures:



$${}^{A}_{Z}\mathsf{X} + e^{+} \rightarrow {}^{A}_{Z+1}\mathsf{Y} + \bar{\nu}$$

$${}^{A}_{Z}\mathsf{X} + e^{-} \rightarrow {}^{A}_{Z-1}\mathsf{Y} + \nu$$

Nuclear weak-interaction process

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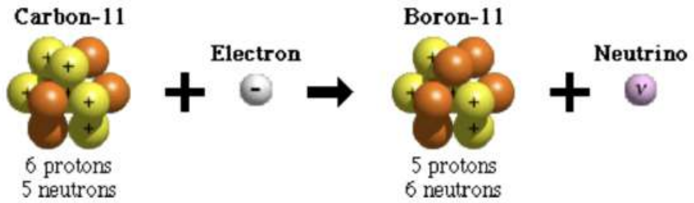

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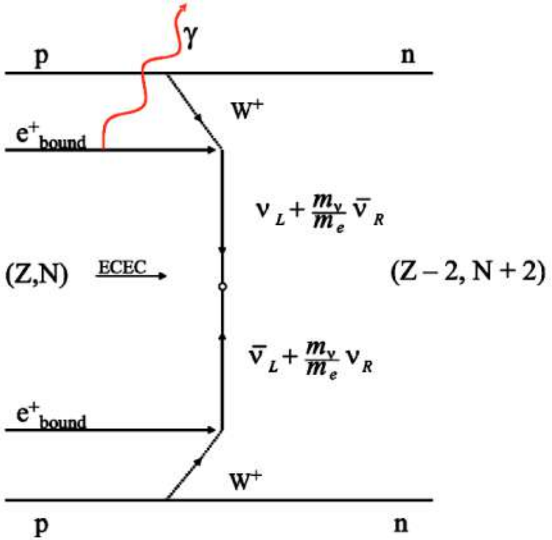
$${}^{A}_{Z}\mathsf{X} + e^{-} \rightarrow {}_{Z-1}^{\;A}\mathsf{Y} + \nu$$

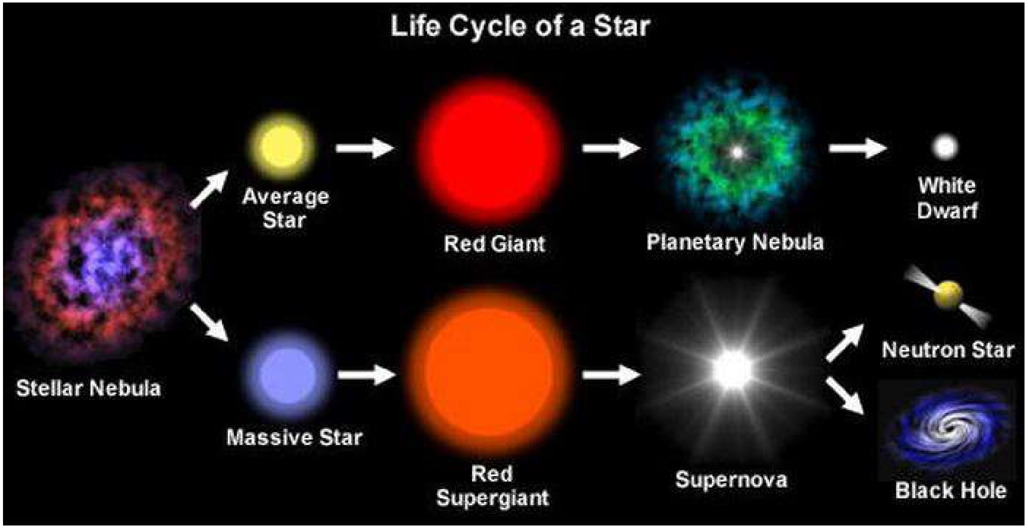
- (neutrinoless) Double-electron capture:

$${}^{A}_{Z}\mathsf{X} + e^{-} + e^{-} \rightarrow {}_{Z-2}^{\;A}\mathsf{Y}^{*}$$

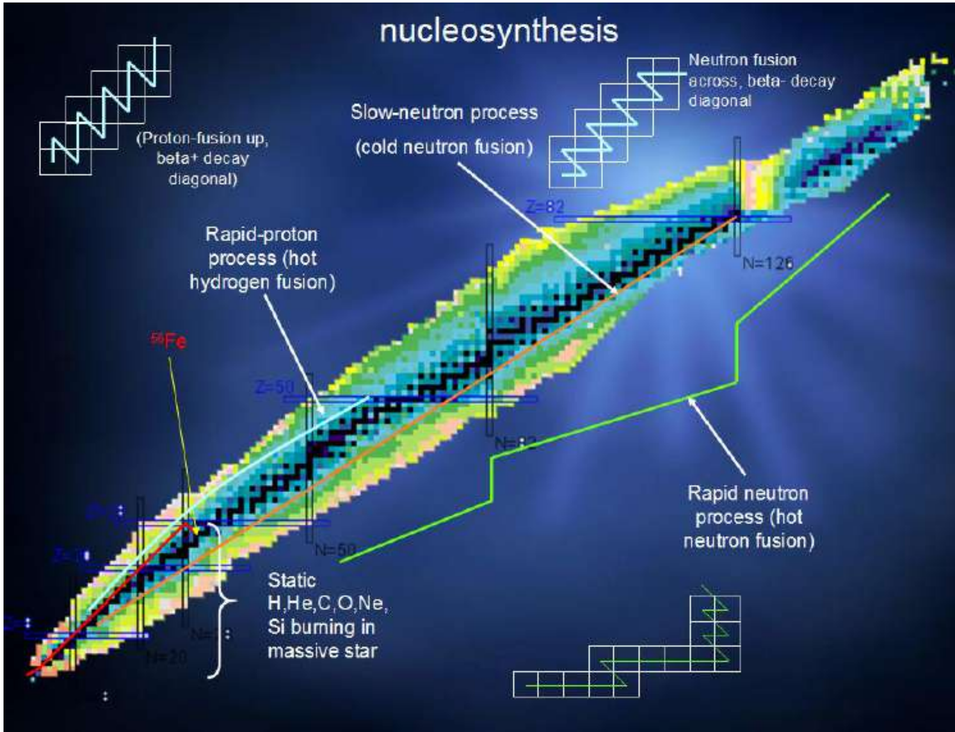
Majorana or Dirac ?



Weak processes in astrophysics



- Electron capture in supernova

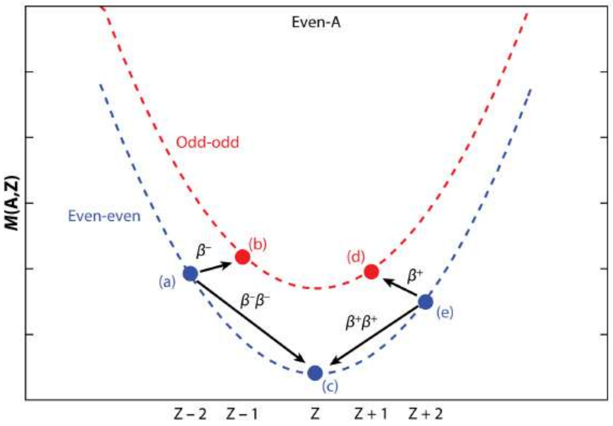


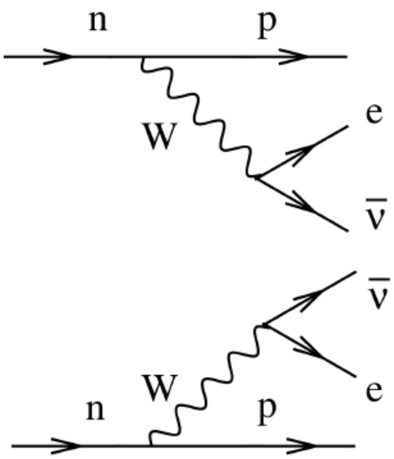
- β-decay for nucleosynthesis
- neutrino cooling (Urca)

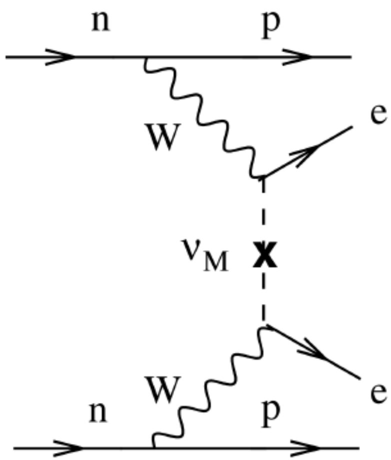
Outline

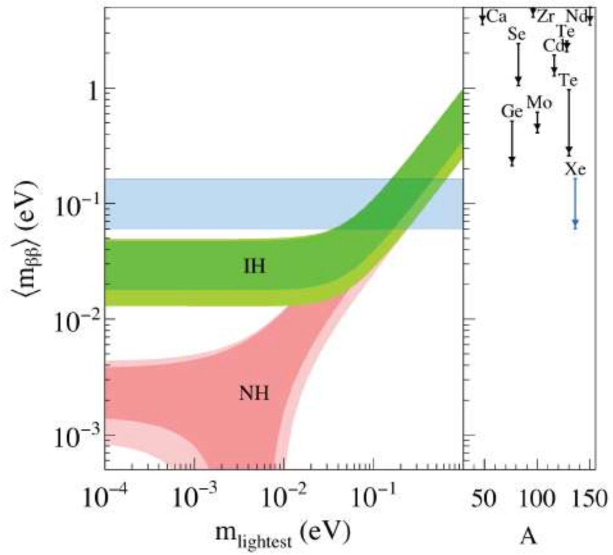
Neutrinoless double beta ($0\nu\beta\beta$) decay

- Nuclear decays: α-decay, β-decay, γ-transition, $\beta\beta$-decay.









$0\nu\beta\beta$ matrix elements: Uncertainties

- Neutrinoless double beta decay ($0\nu\beta\beta$) half-life:

$$\left[T_{1/2}^{0\nu\beta\beta}(0_i^+ \rightarrow 0_f^+)\right]^{-1} = G^{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \langle m_\nu \rangle^2 \quad (1)$$

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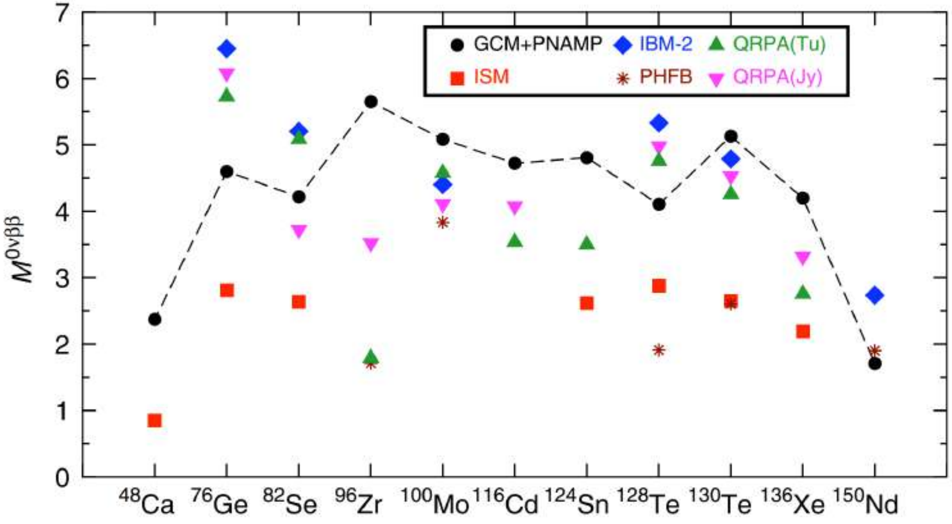
- Model dependent

Rodriguez and Martinez-Piendo: PRL (2010)

Vogel: JPG (2012)



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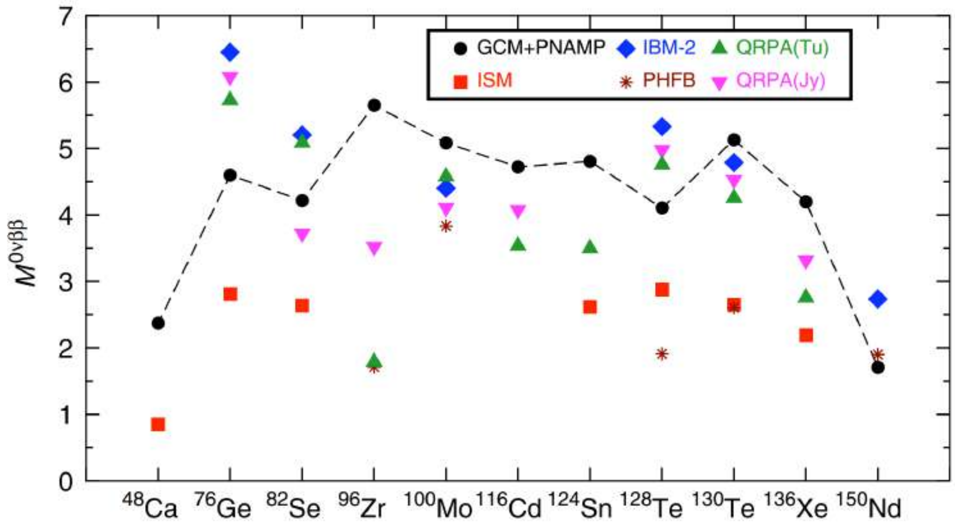

- Uncertainties: Wave function vs Transition operator

$$M^{0\nu\beta\beta} = \langle 0_f^+ |\ \hat{O}^{0\nu\beta\beta}\ | 0_i^+ \rangle \quad (2)$$

✓ Wave function: $\hat{H}$, model space, method → SM vs lmSRG vs GCM vs QRPA ...

✓ **Transition operator: two-body currents ...**

Transition operators

- "g_A-quenching" for single-β decay and $2\nu\beta\beta$-decay

- quenching in magnetic dipole transitions

  Martinez-Piendo et al: PRC (1996)

  Caurier et al: RMP (2005); Barea et al: PRC (2015); Ichimura et al: PPNP (2006)

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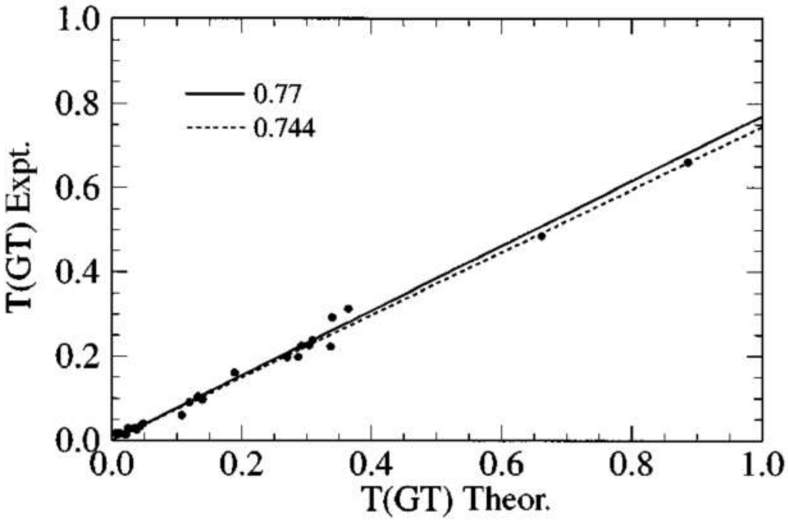
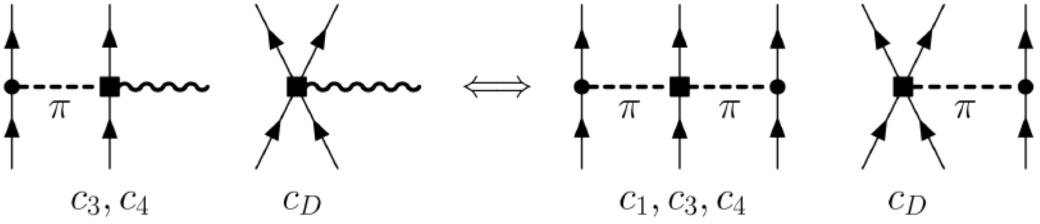


- Similar quenching in $0\nu\beta\beta$ decay ???

- Corrections by Chiral EFT: two-body currents



E. Epelbaum et al: RMP (2009); Menendez, Gazit and Schwenk: PRL (2011)

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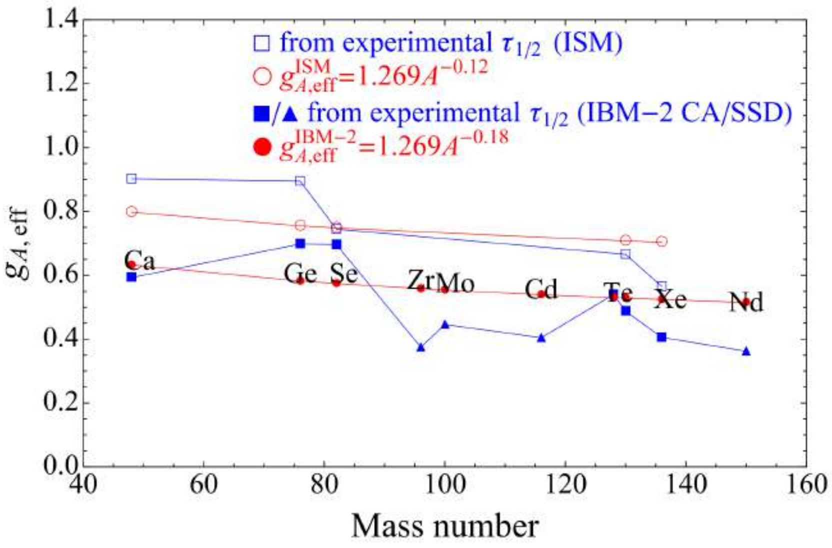

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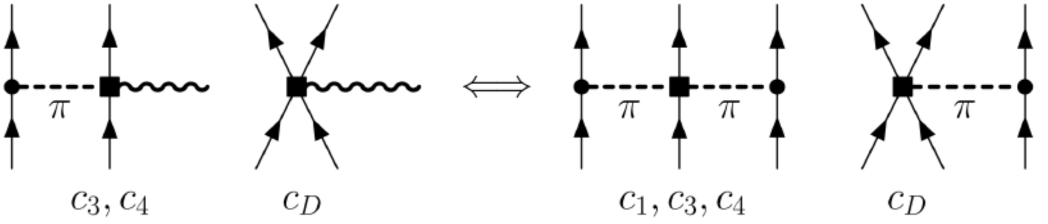

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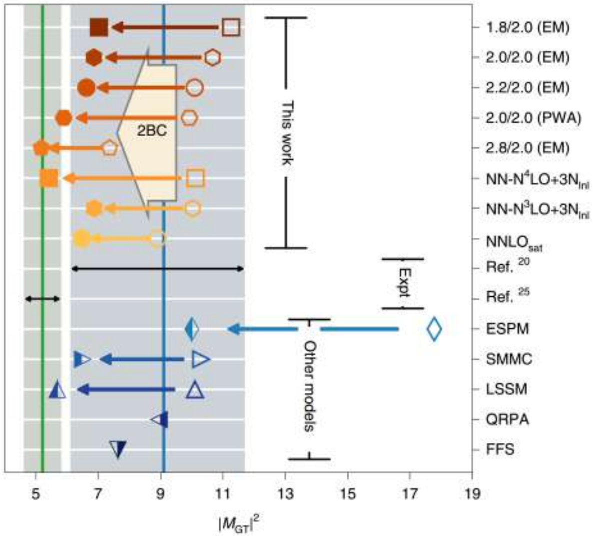

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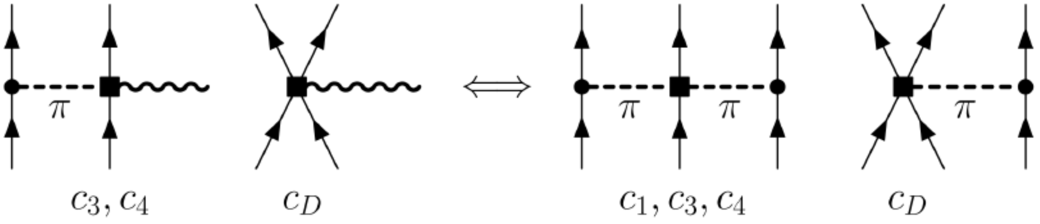

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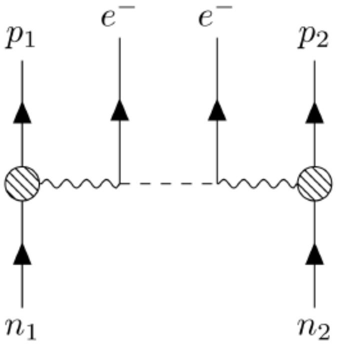
$0\nu\beta\beta$ matrix element: currents

closure approximation

$$\mathcal{M}^{0\nu} = \frac{4\pi R}{g_A^2(2\pi)^3}\int d\boldsymbol{x}_1 d\boldsymbol{x}_2 \int d\boldsymbol{q} \frac{e^{i\boldsymbol{q}\cdot(\boldsymbol{x}_1-\boldsymbol{x}_2)}}{q(q+E_d)}\left\langle 0_F^+ \middle| \hat{\mathcal{J}}^\mu(\boldsymbol{x}_1)\hat{\mathcal{J}}_\mu(\boldsymbol{x}_2) \middle| 0_I^+ \right\rangle,$$



(a) Double 1B

$$\hat{\mathcal{J}}^\mu_{1b}(\boldsymbol{x}) = \sum_{n=1}^{A}\left[g_{\mu 0}J_0(q^2) + g_{\mu j}\boldsymbol{J}_{n,j}(q^2)\right]\boldsymbol{\tau}_n^-\delta(\boldsymbol{x}-\boldsymbol{r}_n),$$

$$J_0(q^2) = g_V(q^2),$$

$$\boldsymbol{J}_n(q^2) = g_M(q^2)i\frac{\boldsymbol{\sigma}_n \times \boldsymbol{q}}{2m_p} + g_A(q^2)\boldsymbol{\sigma}_n - g_P(q^2)\frac{\boldsymbol{q}\boldsymbol{\sigma}_n \cdot \boldsymbol{q}}{2m_p}$$

$0\nu\beta\beta$ matrix element: currents

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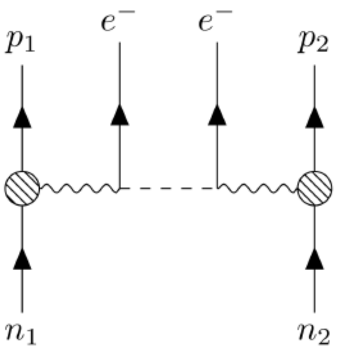

(a) Double 1B

$$\mathcal{O}_{\text{GT}} \propto \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_m \tau_n^- \tau_m^-$$

$$\mathcal{O}_{\text{Fermi}} \propto \tau_n^- \tau_m^-$$

$$\mathcal{O}_{\text{Tensor}} \propto \left[(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{r}}_{nm})(\boldsymbol{\sigma}_m \cdot \hat{\boldsymbol{r}}_{nm}) - \frac{\boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_m}{3} \right] \tau_n^- \tau_m^-$$

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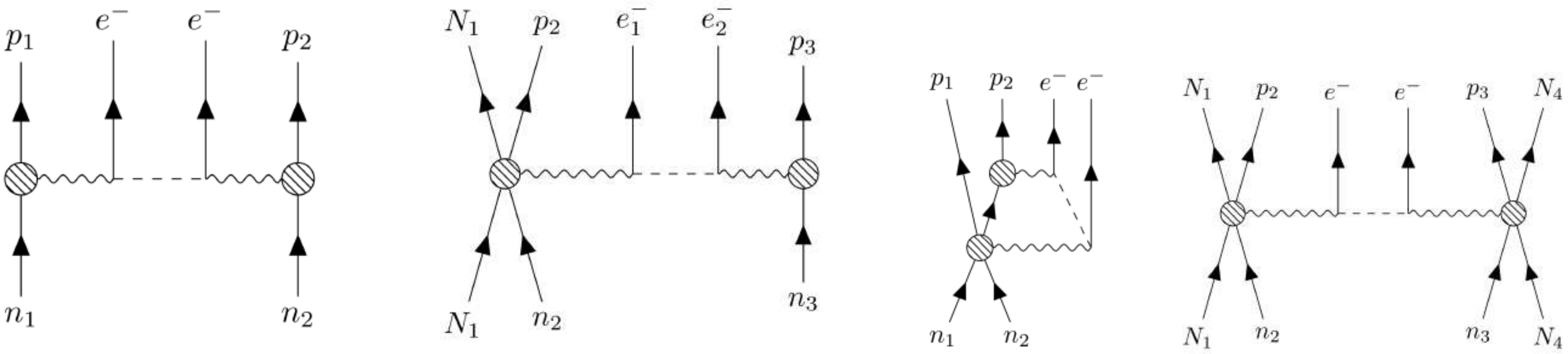

(a) Double 1B (b) 1B plus 2B (c) 1B then 2B (d) Double 2B

$$\hat{\mathcal{J}}_{2\mathrm{b}}(\boldsymbol{x}) = \sum_{k<l}^{A}\boldsymbol{J}_{kl}(\boldsymbol{x}),$$

$$\begin{aligned}\boldsymbol{J}_{kl}(\boldsymbol{x}) = {} & \frac{2c_3 g_A(q^2)}{m_N F_\pi^2}\left[m_\pi^2\left(\left(\frac{\boldsymbol{\sigma}_l}{3}-\boldsymbol{\sigma}_l\cdot\hat{\boldsymbol{r}}\hat{\boldsymbol{r}}\right)Y_2(r)-\frac{\boldsymbol{\sigma}_l}{3}Y_0(r)\right)+\frac{\boldsymbol{\sigma}_l}{3}\delta(\boldsymbol{r})\right]\boldsymbol{\tau}_l^-\delta(\boldsymbol{x}-\boldsymbol{r}_k) \ + \ (k\leftrightarrow l) \\ & + \left(c_4+\frac{1}{4}\right)\frac{g_A(q^2)}{2m_N F_\pi^2}\left[m_\pi^2\left(\left(\frac{\boldsymbol{\sigma}_\times}{3}-\boldsymbol{\sigma}_k\times\hat{\boldsymbol{r}}\boldsymbol{\sigma}_l\cdot\hat{\boldsymbol{r}}\right)Y_2(r)-\frac{\boldsymbol{\sigma}_\times}{3}Y_0(r)\right)+\frac{\boldsymbol{\sigma}_\times}{3}\delta(\boldsymbol{r})\right]\boldsymbol{\tau}_\times^-\delta(\boldsymbol{x}-\boldsymbol{r}_k) \ + \ (k\leftrightarrow l) \\ & - \frac{g_A(q^2)}{4m_N F_\pi^2}\left[2\hat{d}_1(\boldsymbol{\sigma}_k\boldsymbol{\tau}_k^-+\boldsymbol{\sigma}_l\boldsymbol{\tau}_l^-)+\hat{d}_2\boldsymbol{\sigma}_\times\boldsymbol{\tau}_\times^-\right]\delta(\boldsymbol{r})\delta(\boldsymbol{x}-\boldsymbol{r}_k).\end{aligned}$$

Only prior (pioneering) work: normal-ordering

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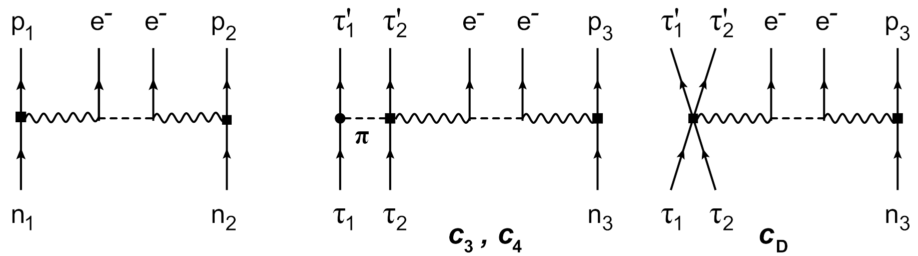
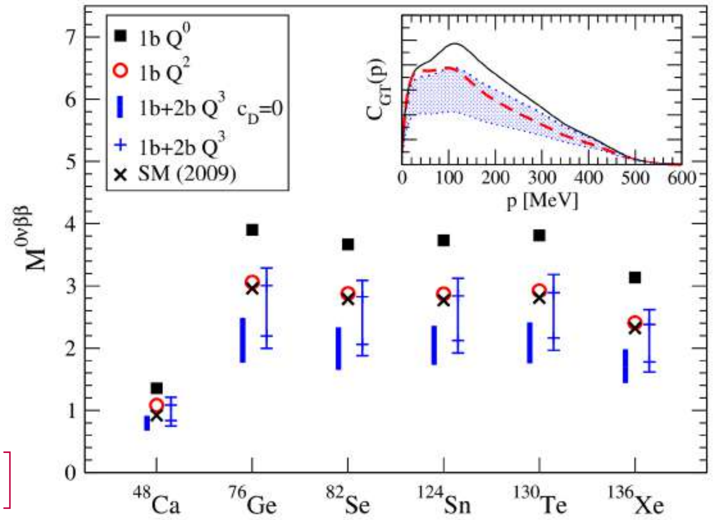


(a) Double 1-body (b) 1-body plus 2-body

Normal-ordering approximation *J. Menéndez, D. Gazit and A. Schwenk: PRL 107, 062501 (2011)*

- ✓ Fermi-gas approximation (analytically)
- ✓ Neglected $\boldsymbol{q} \neq 0$ & pion-pole terms
- ✓ Neglected inter-current contractions
- ✓ Neglected two-body operator pieces

$$\boldsymbol{J}^{\text{eff}}_{i,2b} = -g_A\boldsymbol{\sigma}_i\boldsymbol{\tau}_i^-\frac{\rho}{F_\pi^2}\left[\frac{c_D}{g_A\Lambda_\chi}+\frac{2}{3}c_3\frac{\boldsymbol{q}^2}{4m_\pi^2+\boldsymbol{q}^2}+I(\rho,P)\left(\frac{2c_4-c_3}{3}+\frac{1}{6m}\right)\right]$$



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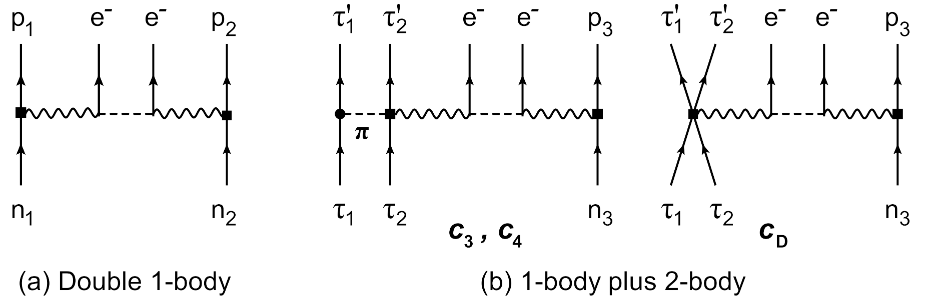

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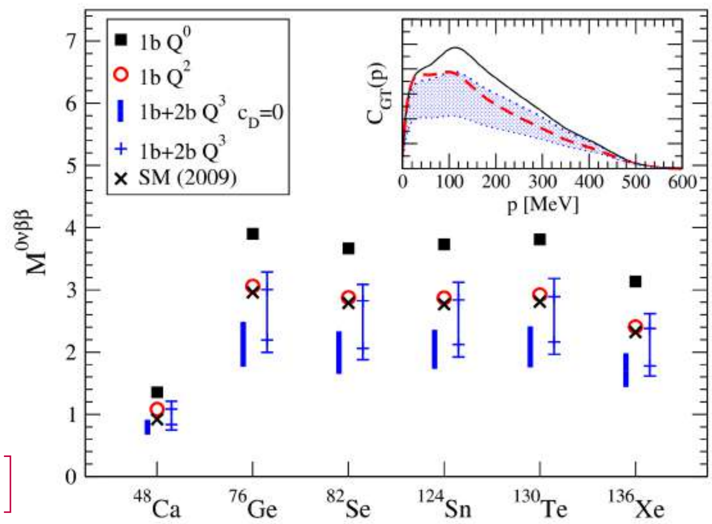
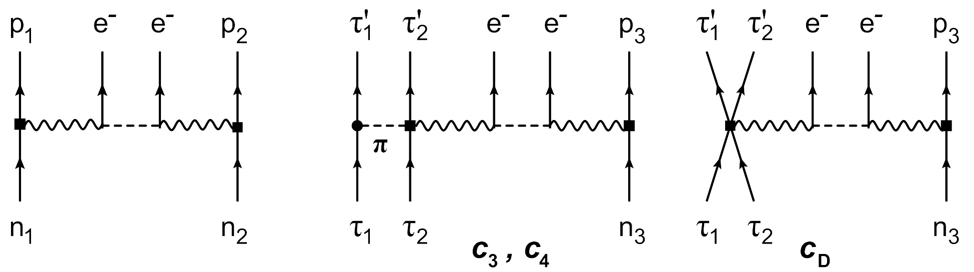


From -35% to 10%: should be included in all calculations!

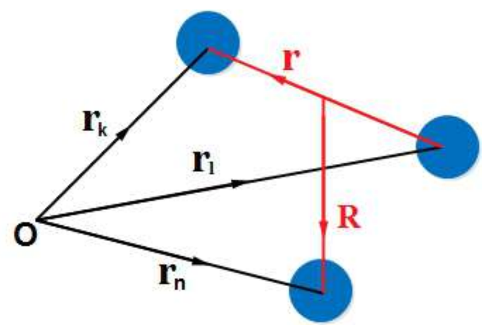
Our work: no more approx.



(a) Double 1-body (b) 1-body plus 2-body

- Pure 3-body operator parts (>7,000 CPU days):

$$\delta \text{NME}^{3b} = -\sum_{\bar{a}\bar{b}\bar{c}\bar{d}\bar{e}\bar{f}} \sum_{J_{ab}J_{de}J} \frac{\hat{J}}{2} \left\langle \left[\bar{a}\bar{b}\right]^{J_{ab}} \bar{c} \right|^{J} \hat{O}_{3b}(k,l,n) \left| \left[\bar{d}\bar{e}\right]^{J_{de}} \bar{f} \right\rangle^{J} \rho^{T}_{3b}, \quad (3)$$



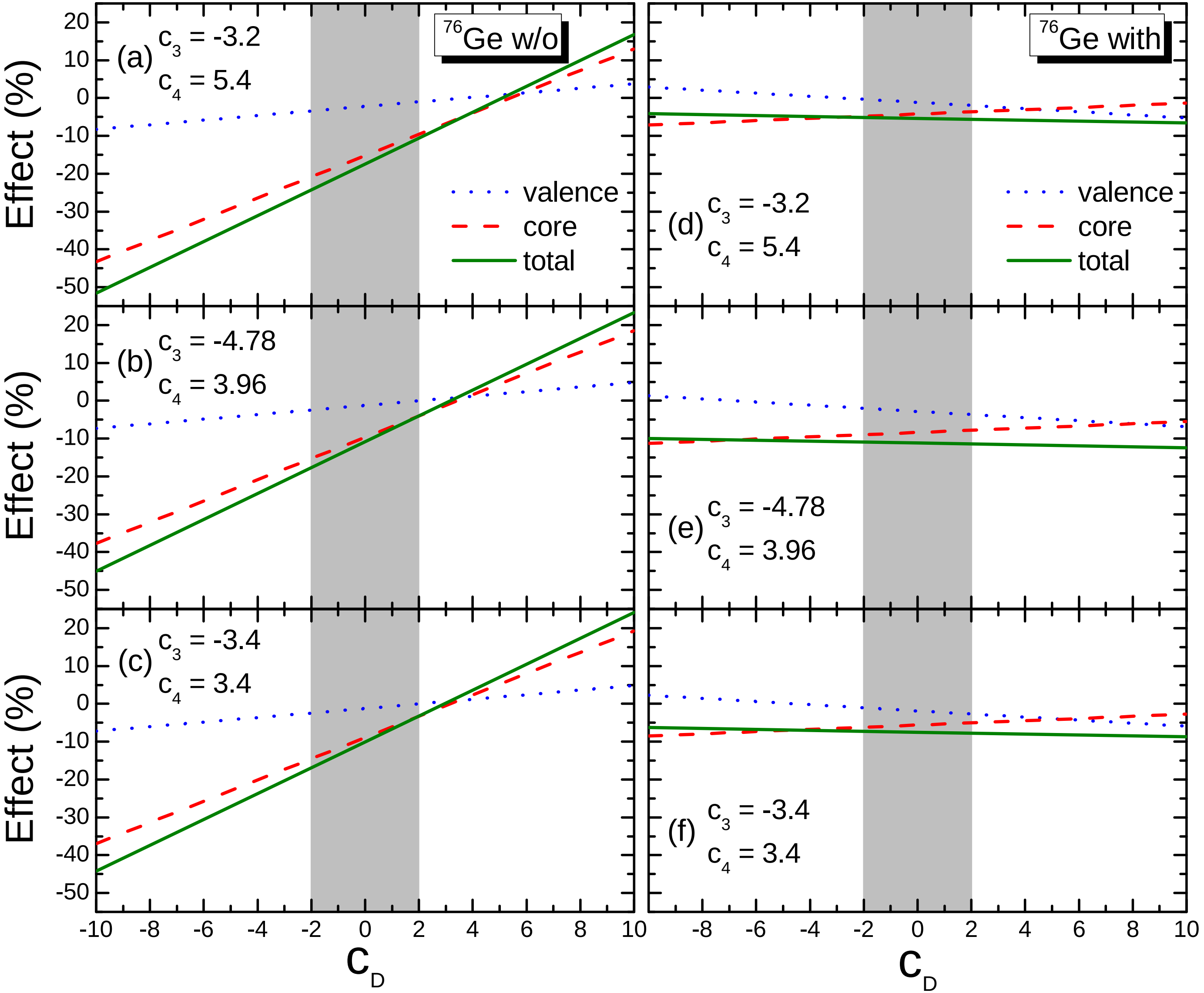
$$\rho^{T}_{3b} = \left\langle 0^+_F \right| \left[\left[\left[\hat{c}^\dagger_{\bar{a}} \hat{c}^\dagger_{\bar{b}} \right]^{J_{ab}} \hat{c}^\dagger_{\bar{c}} \right]^{J} \left[\left[\hat{c}_{\tilde{\bar{d}}} \hat{c}_{\tilde{\bar{e}}} \right]^{J_{de}} \hat{c}_{\tilde{\bar{f}}} \right]^{J} \right]^{00} \left| 0^+_I \right\rangle. \quad (4)$$

Wave functions by GCM with isoscalar pairing.

L.-J. Wang, J. Engel and J.-M. Yao: PRC (2018R)

J.-M. Yao, J. Engel, L.-J. Wang, C. Jiao and H. Hergert: PRC (2018)

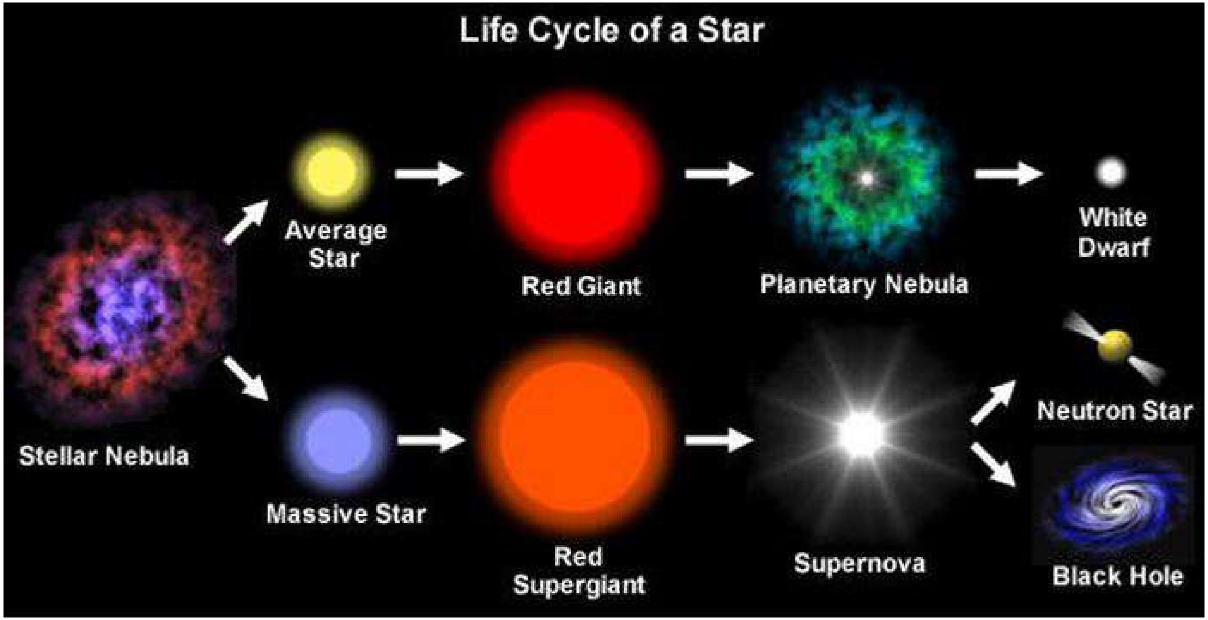
3-body parts: ^{76}Ge



L.-J. Wang, J. Engel and J. M. Yao: PRC (2018R)

Outline

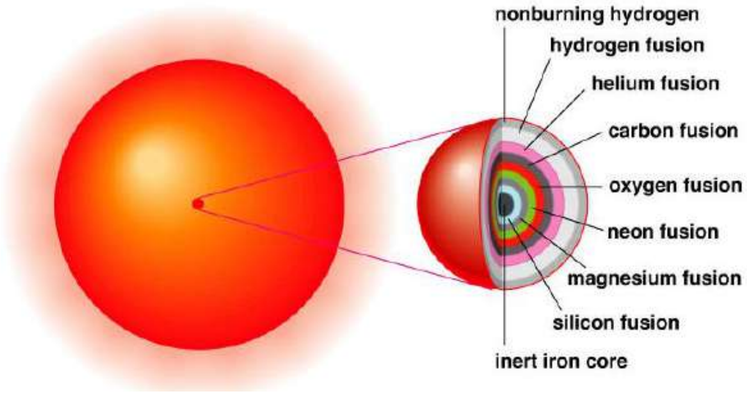
Why we care about electron capture?



$$^{A}_{Z}\mathsf{X} + e^{-} \rightarrow {}^{\;\;A}_{Z-1}\mathsf{Y} + \nu_e$$

- In stellar evolution

- Reduce pressure from degenerate relativistic electron gas
- cooling environment by neutrinos
- drive the composition to be more neutron-rich



Electron-capture rates in astrophysics

$$ {}^{A}_{Z}\mathsf{X} + e^- \rightarrow {}^{A}_{Z-1}\mathsf{Y} + \nu_e $$

$$ \lambda^{\mathsf{EC}} = \frac{\ln 2}{K} \sum_i \frac{(2J_i+1)e^{-E_i/(k_B T)}}{G(Z,A,T)} \sum_j B_{ij} \Phi_{ij}^{\mathsf{EC}}, \quad (5) $$

$$ \Phi_{ij}^{\mathsf{EC}} = \int_{\omega_l}^{\infty} \omega p (Q_{ij}+\omega)^2 F(Z,\omega) S_e(\omega) d\omega, \quad (6) $$

$$ S_e(\omega) = \frac{1}{\exp\left[(\omega-\mu_e)/k_B T)\right]+1}, \quad (7) $$

$$ \rho Y_e = \frac{1}{\pi^2 N_A} \left(\frac{m_e c}{\hbar}\right)^3 \int_0^{\infty} (S_e - S_p) p^2 dp, \quad (8) $$

Fuller, Fowler and Newman (FFN): ApJSS (1980), ApJ (1982), ApJSS (1982), ApJ (1985).

Nuclear uncertainties

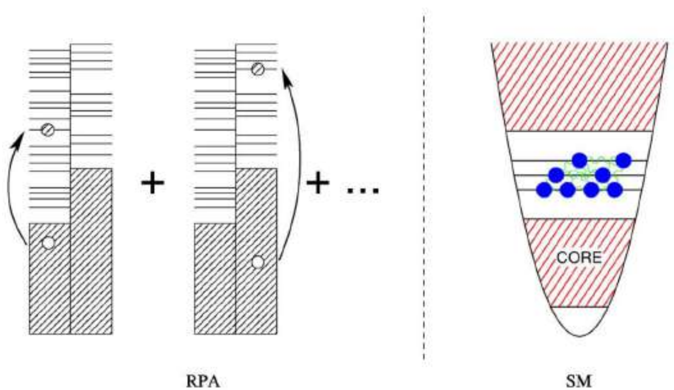
- Reduced nuclear transition M.E.

$$B_{ij} = B_{ij}(\mathsf{GT}^+) = \left(\frac{g_A}{g_V}\right)^2_{\text{eff}} \frac{\left\langle \Psi^{n_j}_{J_j} \| \sum_k \hat{\sigma}^k \hat{\tau}^k_+ \| \Psi^{n_i}_{J_i} \right\rangle^2}{2J_i + 1} \tag{9}$$

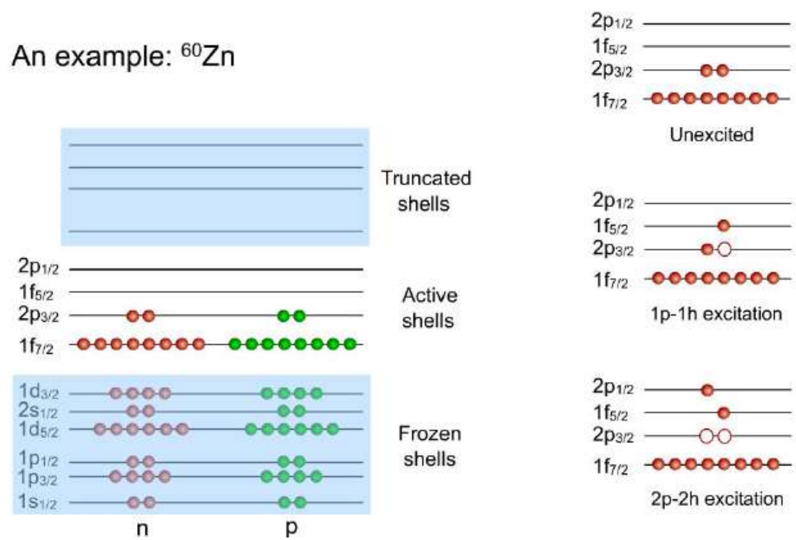
- Transition operator:

$$\left(\frac{g_A}{g_V}\right)_{\text{eff}} = f_{\text{quench}} \left(\frac{g_A}{g_V}\right)_{\text{bare}} \tag{10}$$

- Nuclear wave functions:



Langanke & Martínez-Pinedo: RMP (2003)



https://www.physics.sjtu.edu.cn/ ysun/

Our model with projections

- Description in intrinsic system

$$\Big\{\hat{a}^\dagger_{\nu_i}|\Phi\rangle(\varepsilon),\ \hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}|\Phi\rangle(\varepsilon),$$
$$\hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}\hat{a}^\dagger_{\pi_l}\hat{a}^\dagger_{\pi_m}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}\hat{a}^\dagger_{\nu_l}\hat{a}^\dagger_{\nu_m}\hat{a}^\dagger_{\pi_n}\hat{a}^\dagger_{\pi_o}|\Phi(\varepsilon)\rangle,$$
$$\hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}\hat{a}^\dagger_{\pi_l}\hat{a}^\dagger_{\pi_m}\hat{a}^\dagger_{\pi_n}\hat{a}^\dagger_{\pi_o}|\Phi(\varepsilon)\rangle.\Big\} \tag{11}$$

$$\Big\{\hat{a}^\dagger_{\pi_i}|\Phi\rangle(\varepsilon),\ \hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}|\Phi(\varepsilon)\rangle,$$
$$\hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}\hat{a}^\dagger_{\nu_l}\hat{a}^\dagger_{\nu_m}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}\hat{a}^\dagger_{\pi_l}\hat{a}^\dagger_{\pi_m}\hat{a}^\dagger_{\nu_n}\hat{a}^\dagger_{\nu_o}|\Phi(\varepsilon)\rangle,$$
$$\hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}\hat{a}^\dagger_{\nu_l}\hat{a}^\dagger_{\nu_m}\hat{a}^\dagger_{\nu_n}\hat{a}^\dagger_{\nu_o}|\Phi(\varepsilon)\rangle.\Big\} \tag{12}$$

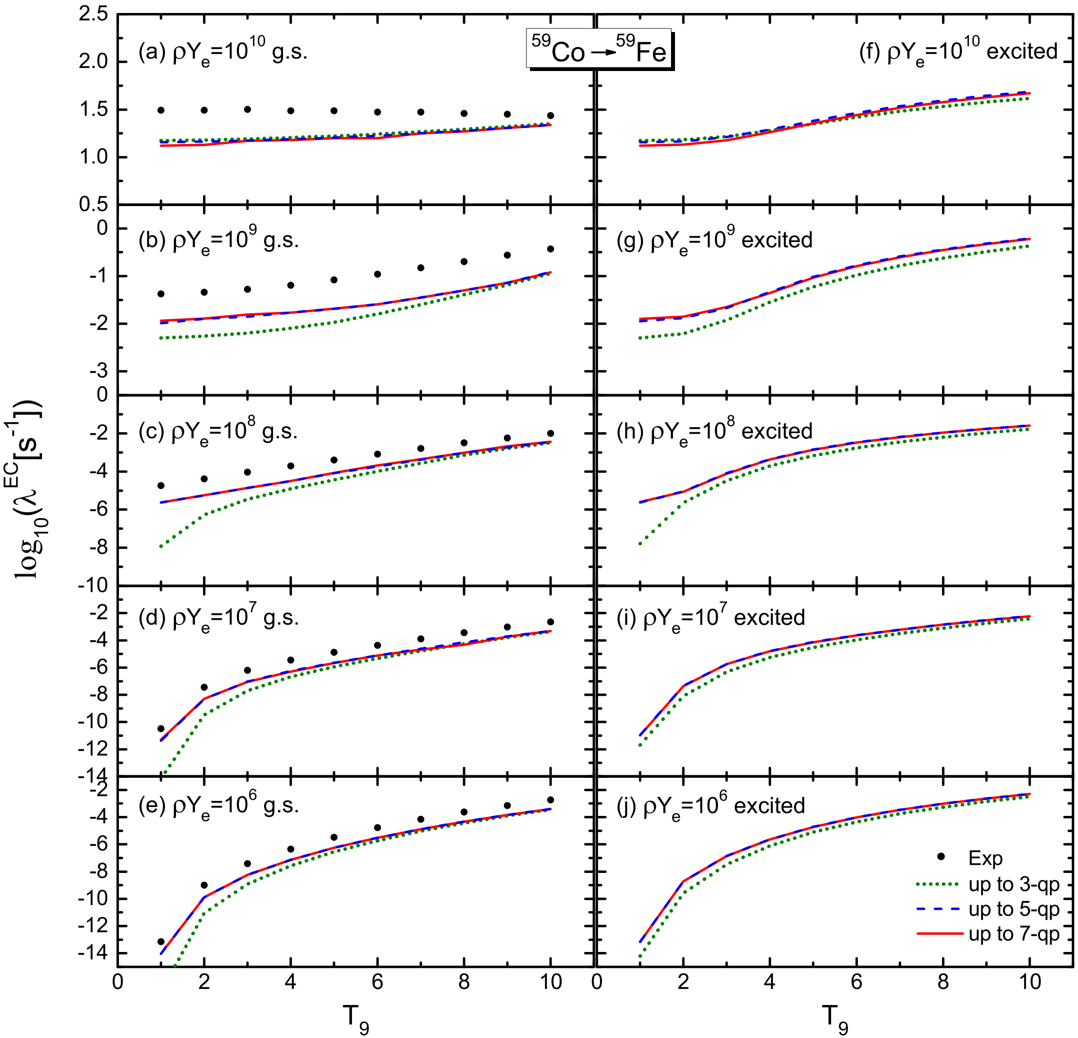
- Transform to laboratory frame

$$|\Psi^n_{JM}\rangle = \sum_{K\kappa} F^n_{JK\kappa}\hat{P}^J_{MK}|\Phi_\kappa\rangle, \tag{13}$$

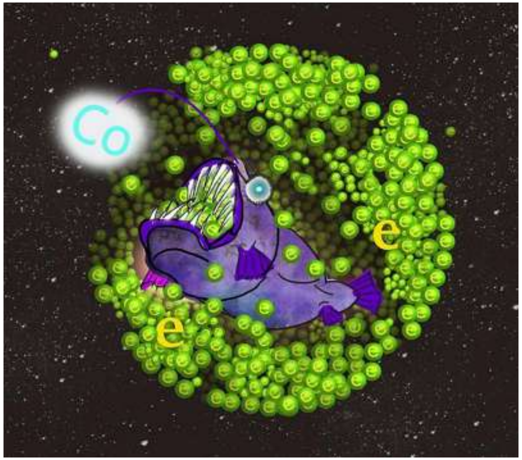
$$\hat{P}^J_{MK} = \frac{2J+1}{8\pi^2}\int d\Omega D^J_{MK}(\Omega)\hat{R}(\Omega), \tag{14}$$

L.-J. Wang, Y. Sun & S.K. Ghorui: PRC (2018)*; *L. Tan, Y.X. Liu, L.-J. Wang* et al.,: PLB (2020)*

EC rates: qp excitations



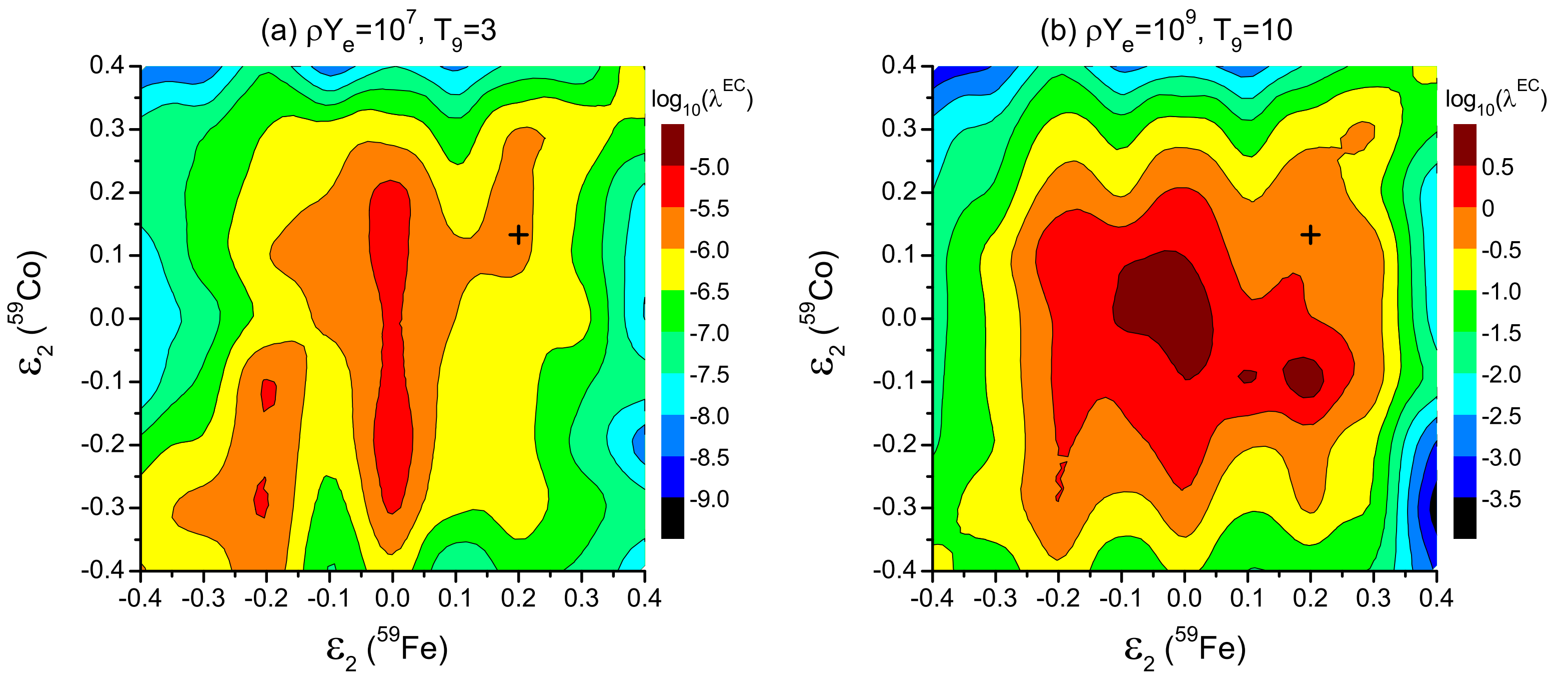
$$^{59}_{27}\text{Co} + e^- \rightarrow {}^{59}_{26}\text{Fe} + \nu_e$$



https://www.ipmu.jp/en/20200330-ElectronCapture

L. Tan, Y.-X. Liu, L.-J. Wang, Z. Li, and Y. Sun: Phys. Lett. B (2020)*

EC rates: collective excitations



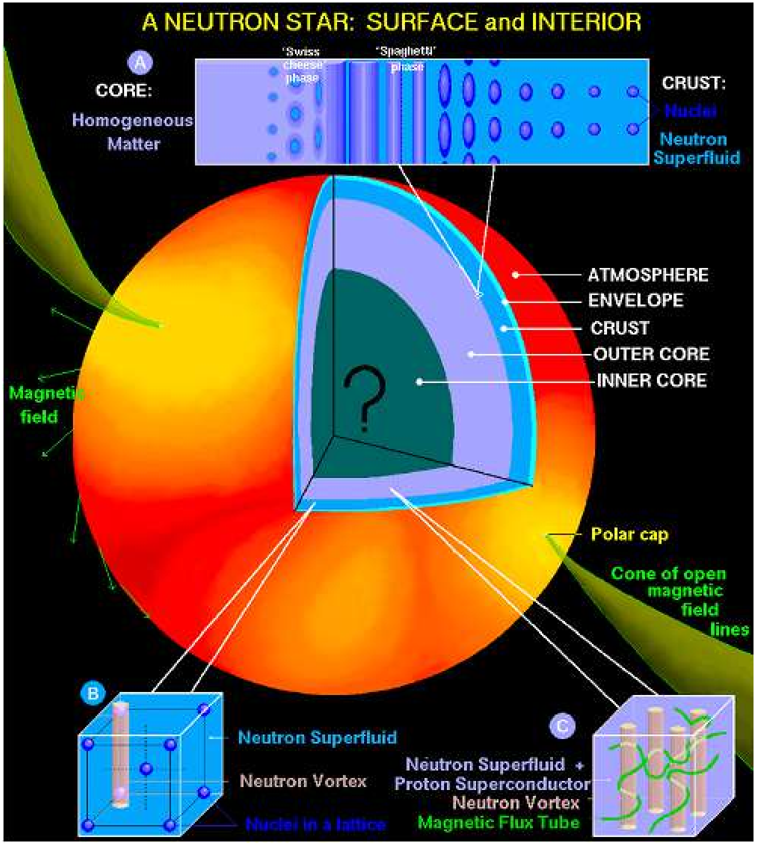
L. Tan, Y.-X. Liu, L.-J. Wang, Z. Li, and Y. Sun: Phys. Lett. B (2020)*

L.-J. Wang, F. Q. Chen, and Y. Sun: Phys. Lett. B (2020)*

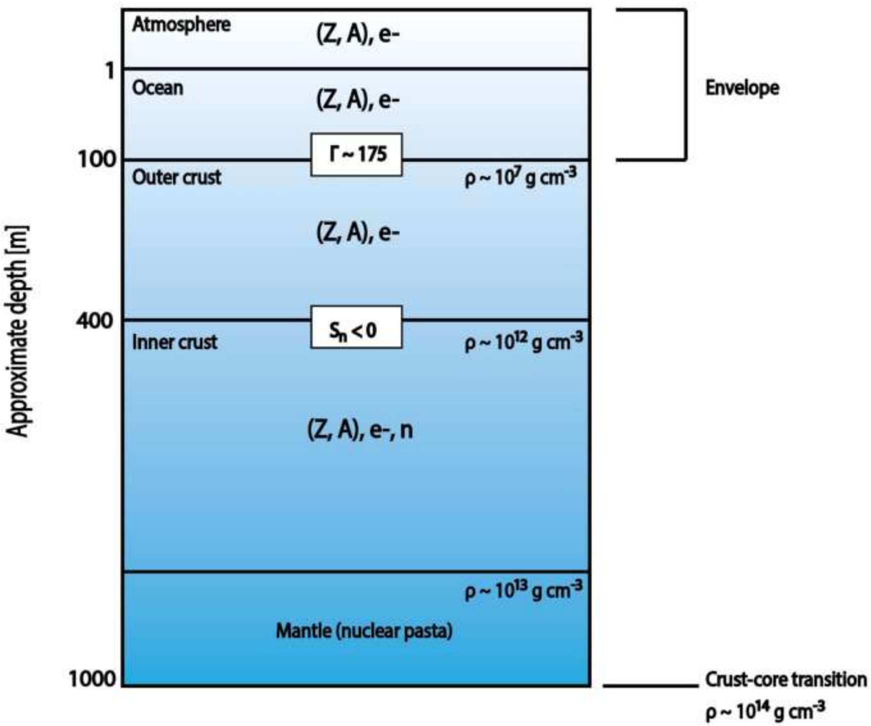
L.-J. Wang, L. Tan, Z. Li, B. Gao and Y. Sun: submitted (2021)*

Outline

Neutron-star structure

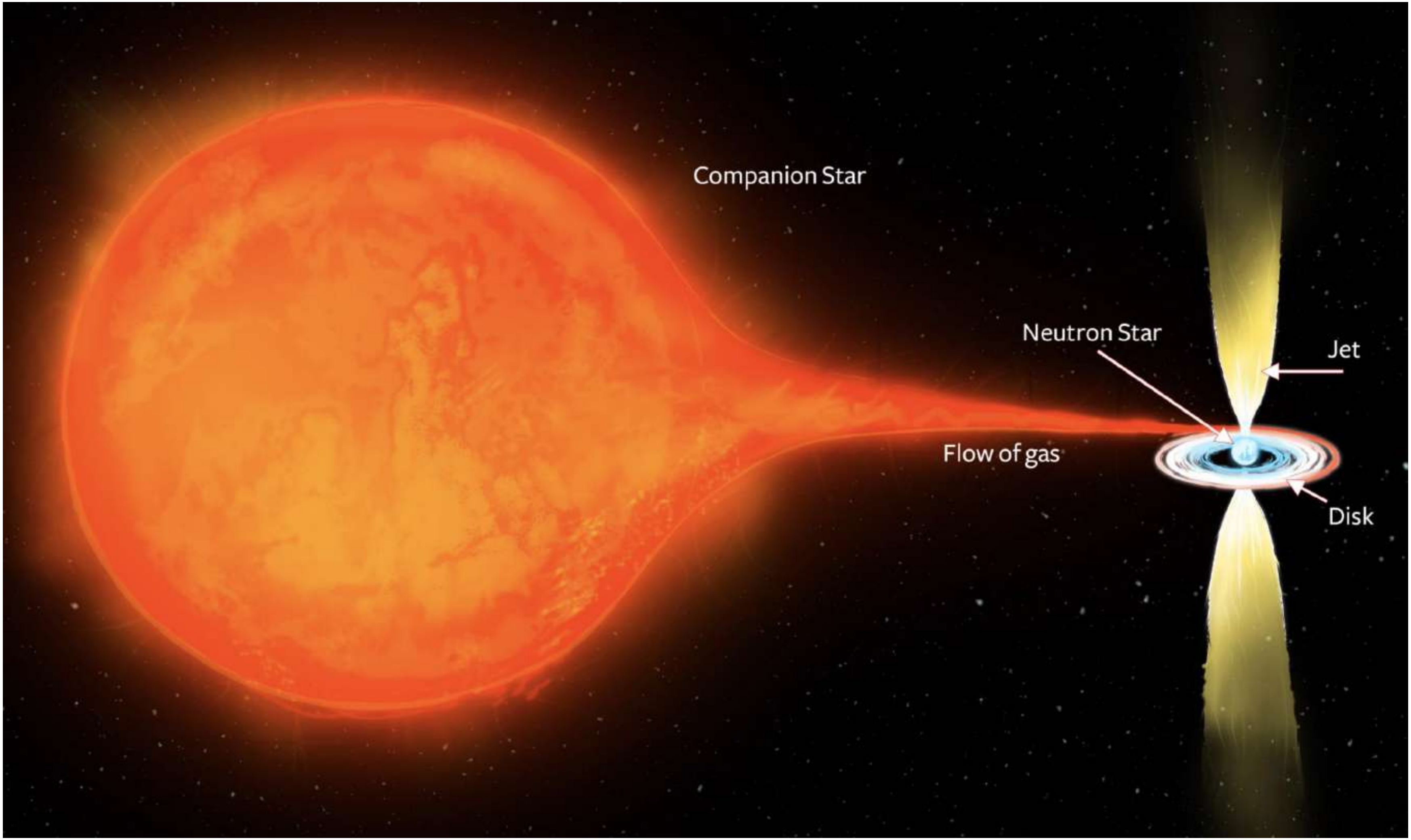


Lattimer and Prakash: Science (2004)

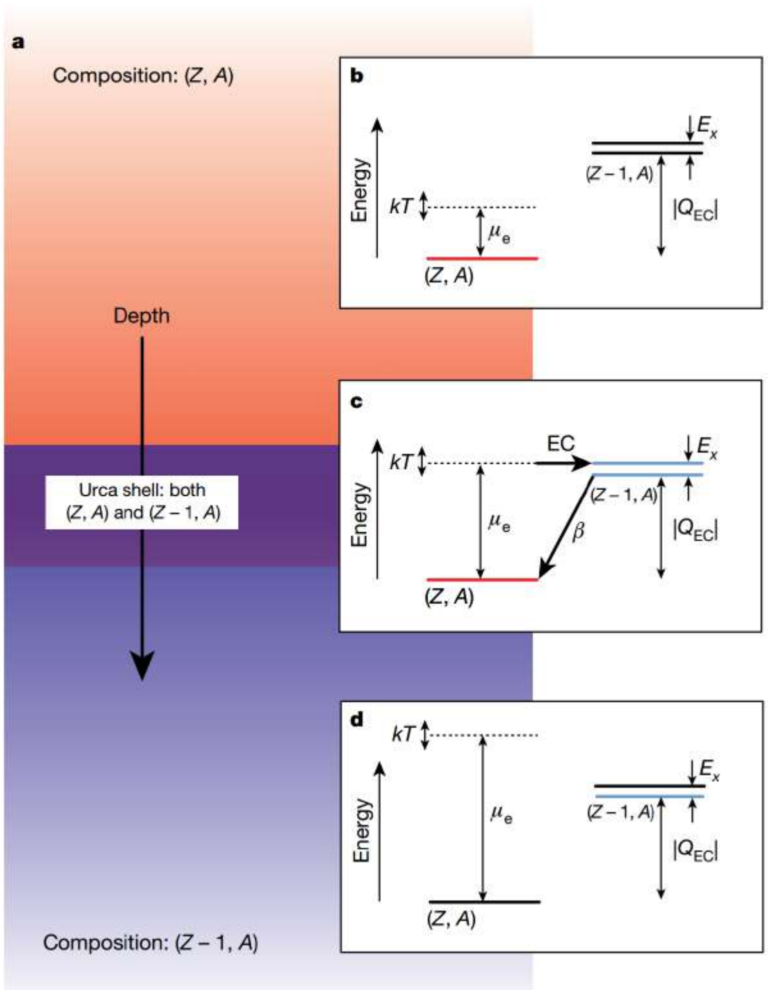


Meisel et al: JPG (2018)

Neutron-star structure

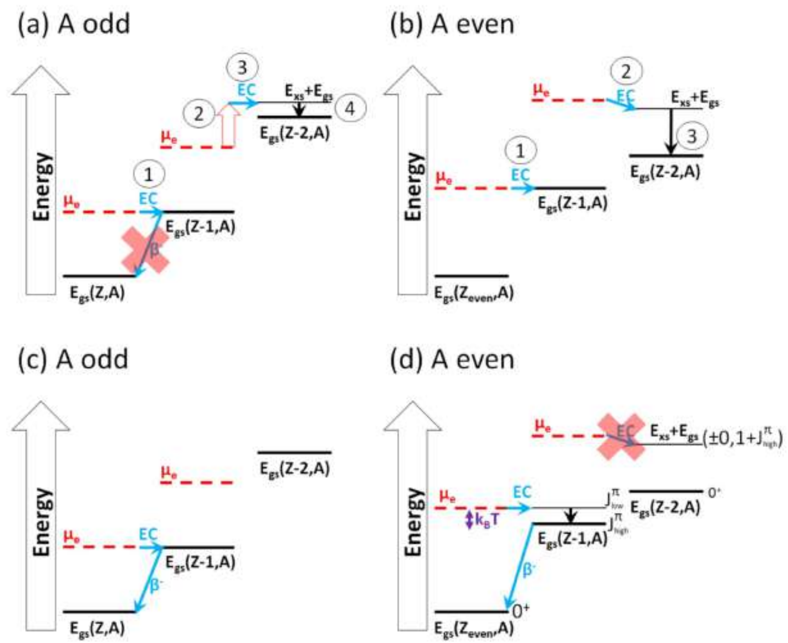


Urca cooling



H. Schatz: Nature (2014)

$$\text{EC}: \quad {}^{A}_{Z}\text{X} + e^- \rightarrow {}^{A}_{Z-1}\text{Y} + \nu_e$$
$$\beta^-: \quad {}^{A}_{Z-1}\text{Y} \rightarrow {}^{A}_{Z}\text{X} + e^- + \bar{\nu}_e$$



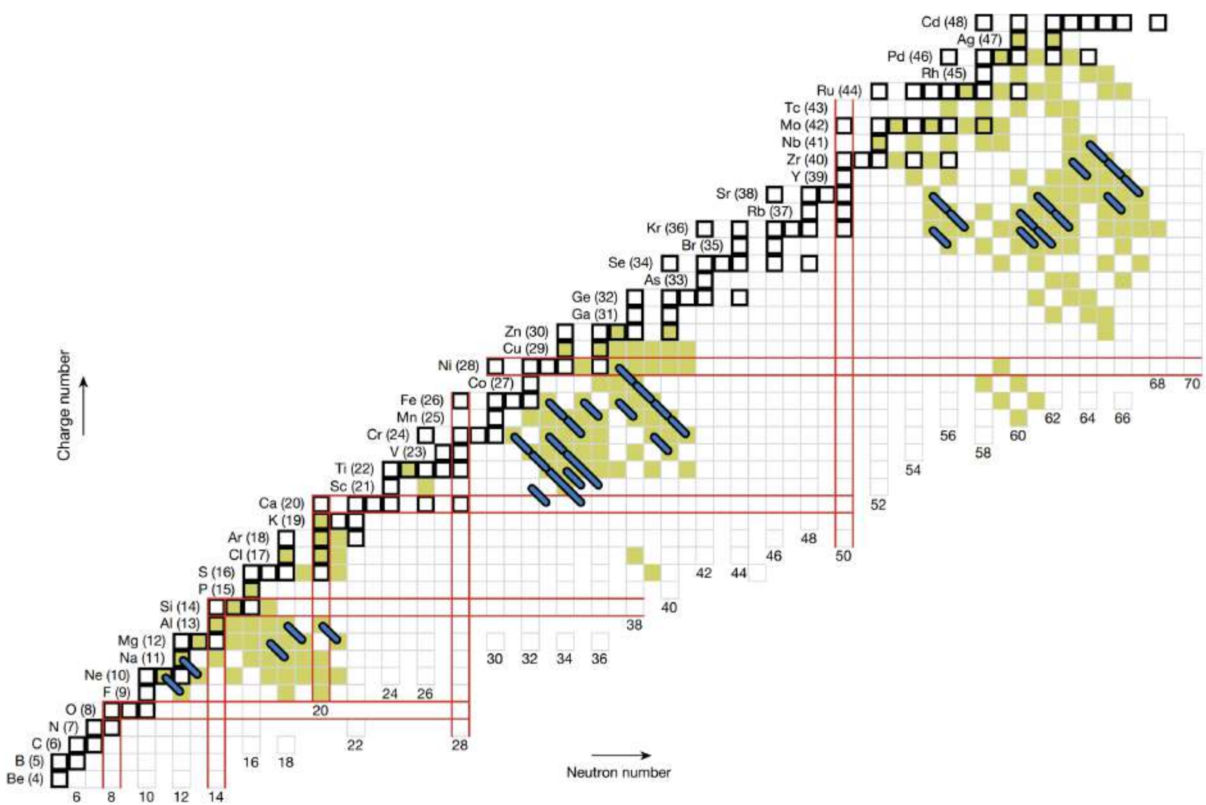
Meisel et al: JPG (2018)

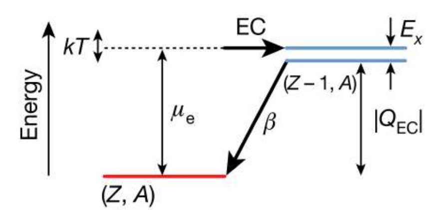
Neutrino luminosity: Previous expression

$$L_\nu(Z,A,T) \approx L_{34}(Z,A,T) \times 10^{34}\,\mathrm{erg\ s^{-1}}\,X(A)\,T_9^5\left(\frac{g_{14}}{2}\right)^{-1} R_{10}^2,$$

$$L_{34}(Z,A) = 0.87\left(\frac{10^6\ \mathrm{s}}{ft}\right)\left(\frac{56}{A}\right)\left(\frac{|Q_{\mathrm{EC}}|}{4\ \mathrm{MeV}}\right)^5\left(\frac{\langle F\rangle^*}{0.5}\right).$$

Deibel, Meisel, Schatz, Brown & Cumming: ApJ (2016)

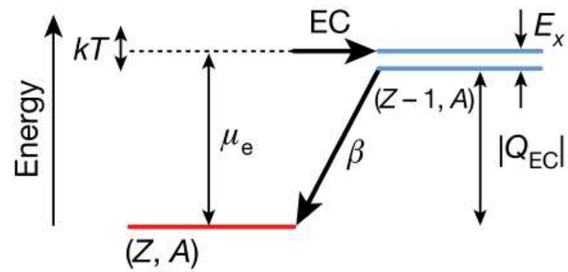


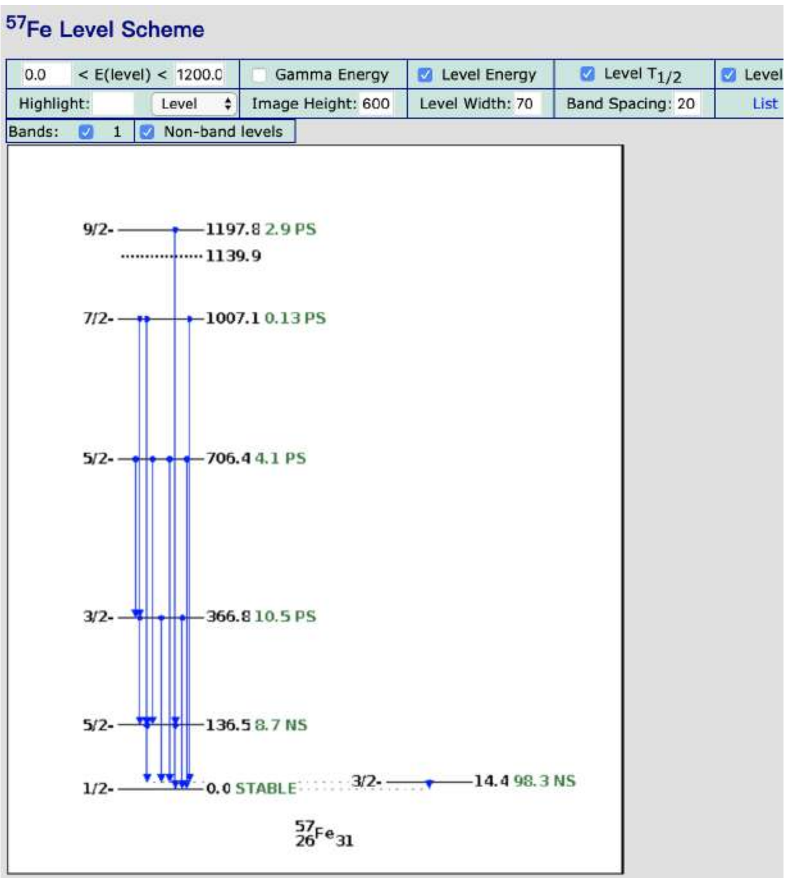


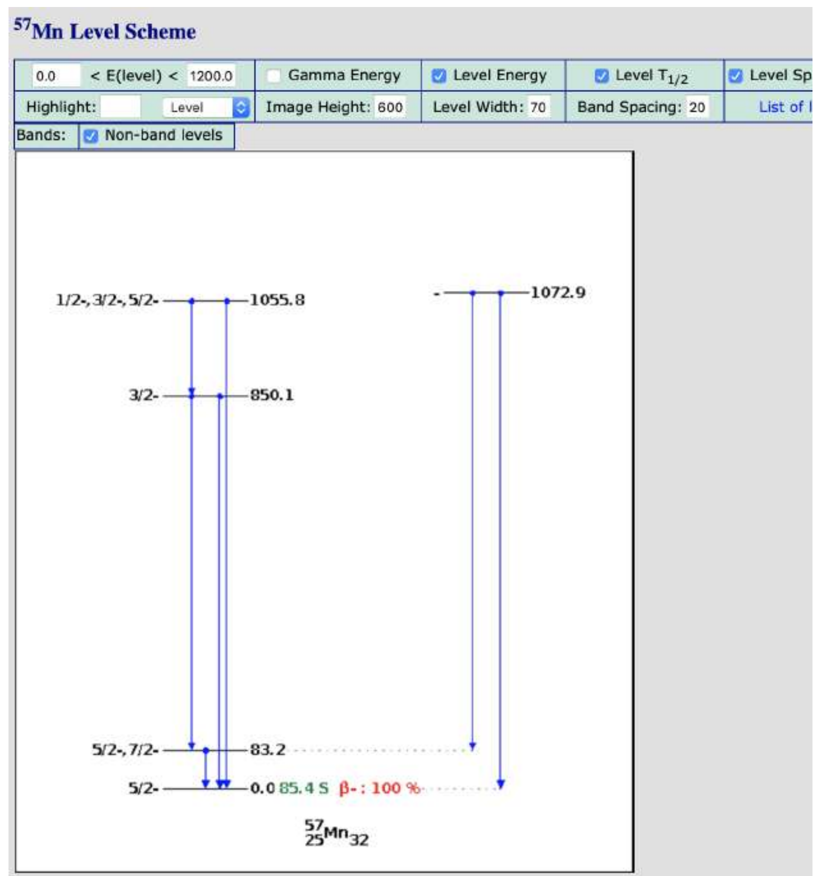
Schatz et al: Nature (2014)

Meisel et al: ApJ (2017)

Nuclear excitations: odd-A







Neutrino luminosity: modified expression

$$L_\nu(Z,A,T) \approx L_{34}(Z,A,T) \times 10^{34} \text{erg s}^{-1} X(A)\, T_9^5 \left(\frac{g_{14}}{2}\right)^{-1} R_{10}^2 \quad (15)$$

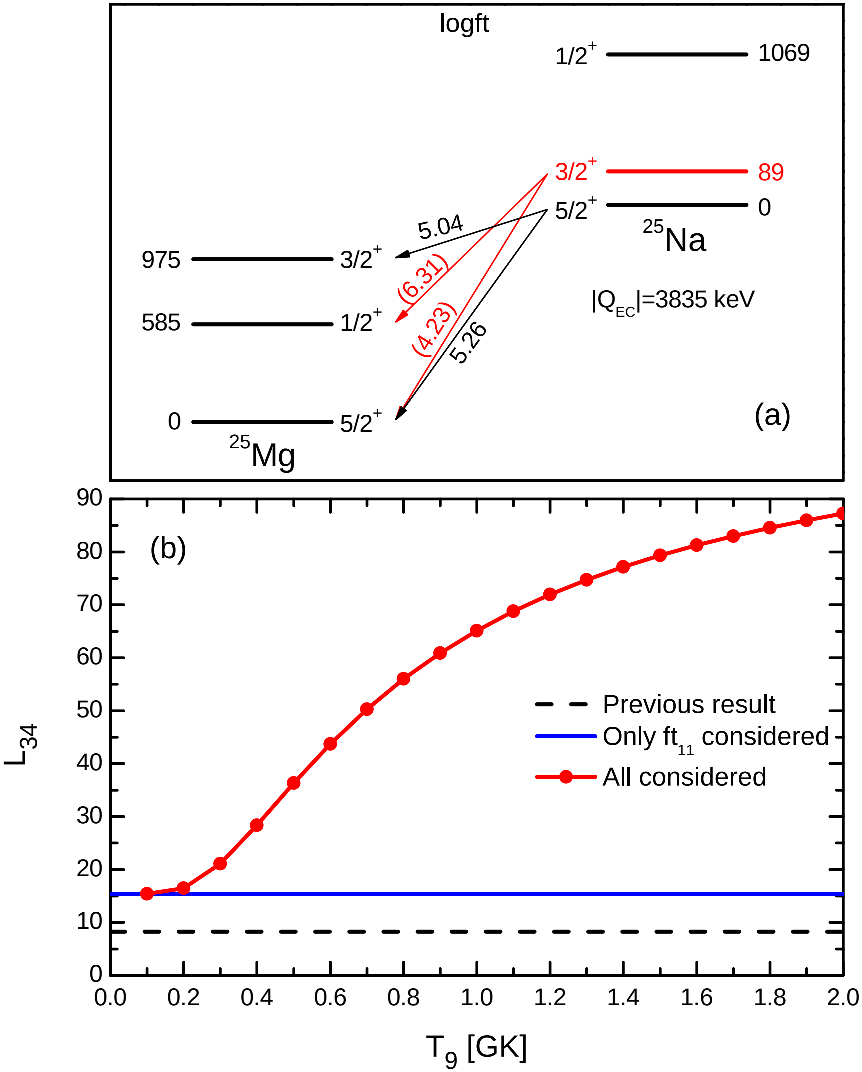
Previous: $$L_{34}(Z,A) = 0.87 \left(\frac{10^6 \text{ s}}{ft}\right)\left(\frac{56}{A}\right)\left(\frac{|Q_{\text{EC}}|}{4 \text{ MeV}}\right)^5 \left(\frac{\langle F\rangle^*}{0.5}\right) \quad (16)$$

Ours: $$L_{34}(Z,A,T) = \sum_{if} 0.87 \left(\frac{10^6 \text{ s}}{\langle ft\rangle_{if}}\right)\left(\frac{56}{A}\right)\left[\frac{|Q_{(if)}(Z,A)|}{4 \text{ MeV}}\right]^5 \left(\frac{\langle F\rangle^*}{0.5}\right) \quad (17)$$

$$\begin{aligned}
\langle ft\rangle_{if} &\equiv \frac{\langle F\rangle^+ \widetilde{ft}_{if}^- + \langle F\rangle^- \widetilde{ft}_{if}^+}{\langle F\rangle^+ + \langle F\rangle^-} \\
\langle F\rangle^* &\equiv \frac{\langle F\rangle^+ \langle F\rangle^-}{\langle F\rangle^+ + \langle F\rangle^-} \\
\langle F\rangle^\pm &\approx \frac{2\pi\alpha Z}{\left|1 - e^{(\mp 2\pi\alpha Z)}\right|} \\
\widetilde{ft}_{if}^+ &\equiv \frac{G^+(Z,A,T)}{(2J_i+1)e^{-E_i/(kT)}} ft_{if}^+ \\
\widetilde{ft}_{if}^- &\equiv \frac{G^-(Z,A,T)}{(2J_f+1)e^{-E_f/(kT)}} ft_{if}^- \\
Q_{(if)}(Z,A) &= M_p c^2 - M_d c^2 + E_i - E_f
\end{aligned}$$

L.-J. Wang, L. Tan, Z. Li, G. W. Misch and Y. Sun: Arguing for *** (2021)*

Effects of nuclear excitations



*L.-J. Wang**, *L. Tan, Z. Li, G. W. Misch and Y. Sun: Arguing for *** (2021)*

L. Tan, *L.-J. Wang**, *Z. Li, G. W. Misch and Y. Sun: submitted (2021)*

Outline

Summary

- Chiral two-body currents for $0\nu\beta\beta$-decay operator.
- A projected method for stellar electron-capture rates with nuclear excitations.
- A modified expression for neutrino luminosity in Urca processes of neutron star crust and ocean: nuclear excitations.

Outlook

- a lot of works ... ...
- Nuclear excitations for stellar β-decays,
- Chiral two-body currents for stellar weak-interaction processes,
- Role of isomers in stellar β-decay and Urca cooling processes etc.
- new database for stellar weak-interaction rates,
- new list for candidate Urca pairs in neutron star crust,
- calculate neutrino (electron) spectrum for experimentalists,
- ... ... let me stop here ... ...

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G. Wendell Misch	Los Alamos National Lab
Zhipan Li	SWU
Jianmin Dong	IMP
Liang Tan	SWU
Yi-Xiu Liu	SWU

Thank you for your attention!