e^{-}-capture on nuclei in the hot & dense stellar environment

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Ioannina: The Ancient Theater DODONI (18,000 spectators, built 4th-3rd century B.C.)

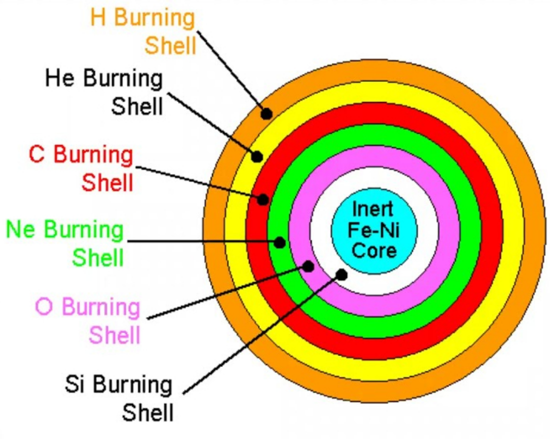
Overview

[1]P.G. Giannaka and T.S. Kosmas, Adv. High En. Phys. 2015 (2015) 398796.
[2] P.G. Giannaka and T.S. Kosmas, Particles 5 (2022) 377–389
[3] P.G. Giannaka, T.S. Kosmas, and H. Ejiri, Particles 5 (2022) 390–406
[4] K. Langanke, G. Martínez-Pinedo, and R.G.T. Zegers, Rep. Prog. Phys. 84 (2021) 066301

Brief description of

Massive Star's Evolution

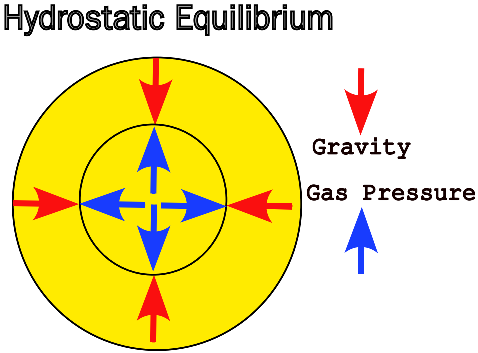
Massive star's evolution: Onion-like structure in main-sequence Phase



Picture of burning shells in the main sequence star

- Massive star's: $12M_\odot \leq M_{star} \leq 20 - 25M_\odot$
- Onion-like structure

Massive star's evolution: Hydrostatic Equilibrium



- Thermonuclear pressure
- Gravitational Force

- During the main sequence stages of stars' life, a hydrostatic equilibrium between the gravitational force and the thermonuclear pressure is prevailing.
- The central burning shell (iron-core) gets out of fuel.
- Then the Hydrostatic equilibrium is destroyed in the pre-supernova and SN-phases and the star collapses due to its own gravity (gravitational collapse).

Star's evolution. Motivation of present studies

$$(A, Z) + e^- \to \nu_e + (A, Z-1), \quad \textit{for any nucleus } (A, Z)$$

- In the evolution of massive stars ($12M_\odot \leq M_{star} \leq 20M_\odot$) at the late stages of their life e^--capture plays crucial role. Specifically, during core-collapse leading to SN explosion (core–collapse SN type II).
- The recent prediction **"the e^--capture on nuclei dominates over e^--capture on free protons"**, motivated detailed investigations.
- Up to now, available e^--capture rates (under collapse conditions) are limited even though rate-tabulations exist for a great number of nuclear isotopes.
- Most of the studied nuclei dominate in the early stage of the collapse or dominate at high stellar densities.
- Also, rates of e^--capture on nuclei with $A \sim 80$ and $N \sim 50$ are required to clarify open questions related to core–collapse dependence of e^--capture process.

The lack of detailed cross sections predictions throughout the chart of nuclides motivates the present and future studies

Weak-interaction rate collections for supernova simulations

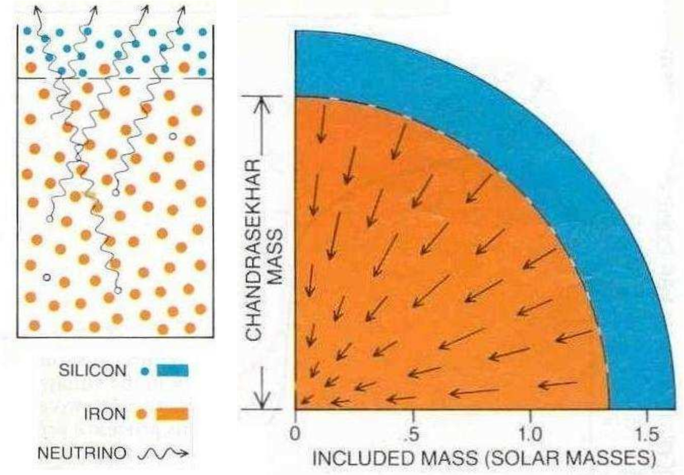
The existed rate-tabulations, in general, refer to weak-interaction rates for SN conditions as:

- e^--capture and e^+-capture by (A,Z)
- Nuclear $\beta^\pm$-decay
- Charged-current ν $(\tilde{\nu})$ - nucleus reactions

Weak-interaction rate tabulations for SN simulations

- Oda, T.; Hino, M.; Muto, K.; Takahara, M.; Sato, K. Rate Tables for the weak processes of sd-shell nuclei in stellar matter. At. Data Nucl. Data Tables 1994, 56, 231.
- Nabi, J.U.; Klapdor-Kleingrothaus, H.V. Weak interaction rates of sd-shell nuclei in stellar environments calculated in the the proton-neutron quasi-particle random-phase approximation. At. Data Nucl. Data Tables 1999, 71, 149.
- Langanke, K.; Martinez-Pinedo, G. Rate Tables for the weak processes of p f -shell nuclei in stellar environments. At. Data Nucl. Data Tables 2001, 79, 1.
- Nabi, J.U.; Rahman, M.U.; Sajjad, M. Electron and positron capture rates on 55 Co in stellar matter. Braz. J. Phys. 2007, 37, 4.

The e^- capture in the Pre-supernova evolution phase

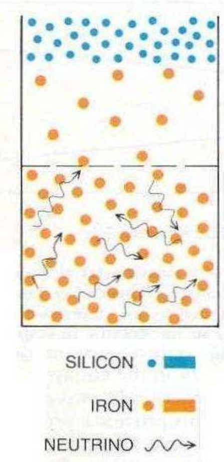


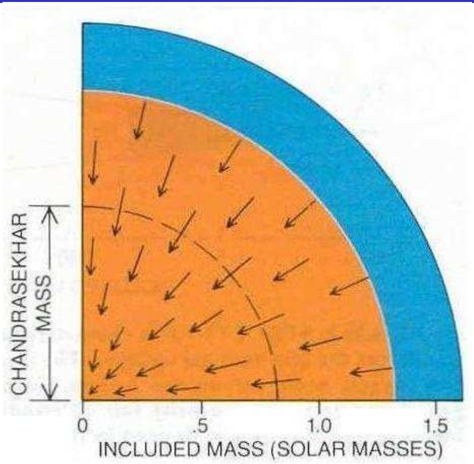
Pre-supernova phase conditions:

- **Matter density:**
  $\rho \leq 10^{10}\ g\ cm^{-3}$
- **Temperature:**
  $300\ keV \leq T \leq 800 keV$
- e^-**-capture on** $A < 65$ **nuclei**
- ν**-cooling (**ν**-escaping)**
- **Chandrashekar limit:**
  $M_{core} \leq 1.4 M_\odot$

- **Capture-rates on individual nuclei with** $A < 65$ **are needed to be computed.**

The e^- capture in the collapse-phase of Core-Collapse Supernova





SN

collapse-phase conditions
ν-trapping
ν-blocking

- **Detailed Capture-rates on nuclei with $A > 65$ are needed to be computed.**
- **Due to missing of such rates, relevant SN-codes DO NOT EXPLODE !**

Stellar e^--capture on nuclei: $E_e \leq 30$

Electron Capture on nuclei in pre-supernova conditions

$$(A, Z) + e^- \rightarrow \nu_e + (A, Z-1), \quad for\ A < 65$$

- T $= 0.1 - 1.0$ MeV, $\rho = 10^7 - 10^{10} g\ cm^{-3}$
- Core Composition A=45 - 65 (iron group nuclei)
- The evolution decreases the number of e^-: Ratio $Y_e = \frac{n_e^- - n_e^+}{n_b}$

Electron Capture on nuclei in core-collapse supernova conditions

$$(A, Z) + e^- \rightarrow \nu_e + (A, Z-1), \quad for\ A > 65$$

- $T > 1.0$ MeV, $\rho > 10^{10} gcm^{-3}$
- Other important processes

$$e^- + p \rightarrow n + \nu_e \quad (e^- - capture\ on\ protons)$$

$$\nu + (A, Z) \rightleftarrows \nu + (A, Z) \quad (neutrino\ trapping)$$

K. Langanke, G. Martinez-Pinedo, Rev. Mod. Phys. 75 (2003) 819, P.G. Giannaka, T.S. Kosmas, Adv.HEP 398796 (2015) 1-11.

Objective of studying stellar e^--Capture on Nuclei

- Our main objective is: First, to perform original e^--capture cross-sections for nuclei in both classes: $A < 65$ and $A > 65$ cases
- Using the original e^--capture cross-sections (computed with QRPA), we may evaluate folded (with e^- spectra) e^--capture rates for stellar environment.
- We assume that parent nuclei (A,Z) and e^- interact inside the deep stellar interior during the late stages of evolution of massive stars.
- We choose two categories of nuclei (for detailed e^--capture cross sections calculations):
  - Isotopes with $A < 65$ (^{48}Ti and ^{56}Fe) that belong to Fe-group nuclei (e^--capture occurs mostly during the pre-SN stage)
  - Heavier and more neutron-rich isotopes with $A > 65$ (^{66}Zn and ^{90}Zr) (e^--capture occurs during CC-SN phase).
- A comparison with previous calculations, obtained with various nuclear models is included.
- Make available for use in stellar simulations

Stellar simulations for core-collapse supernova

The reaction rates and energetics for e^--capture on nuclei λ_j and on free protons λ_p enter the stellar simulations as:

$$R_N = \sum_j Y_j \lambda_j \equiv Y \cdot \lambda \,, \qquad R_p = Y_p \lambda_p \,,$$

- The sum runs over all nuclear isotopes within the stellar core environment.
- Y_p = abundances for free protons
- Y_j = abundances for the stellar core nuclei
- the e^--capture rates $\lambda_{ec}(T)$ for all nuclear isotopes of the star's core are given by

$$\lambda_{ec}(T) = \frac{c}{\pi^2 \hbar^3} \int_{E_e^0}^{\infty} \sigma(E_e, T) S_e(E_e, \mu_e, T)\, E_e p_e \, dE_e$$

Knowledge of nuclear composition of the stellar core mass and the rates entering this equation must be known for a wide range of:

(i) nuclear matter density, ϱ (ii) the temperature, T

Fermi-Dirac distributions and chemical potentials of $e^{\pm}$

In the central core stellar environment, the e^- (or e^+) spectrum is well described by a Fermi-Dirac distribution S_e (S_p) parametrized with T and μ_e (or μ_p) as

$$S_e = \frac{1}{1 + exp[(E_e - \mu_e)/(k_B T)]}, \qquad S_p = \frac{1}{1 + exp[(E_e + \mu_p)/(k_B T)]}.$$

k_B = Boltzman's constant

- **The chemical potential of e^+ is equal to: $\mu_p = -\mu_e$**
- **At pre-SN the ν's released through weak interaction processes on nuclei with $45 \leq A \leq 65$ (β-decays, $e^{\pm}$-capture) can escape, i.e. $S_\nu \approx 0$.**
- **ν-blocking effect occurs for $A > 65$ ($S_\nu \neq 0$)**

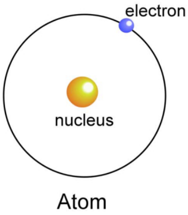
Connection of matter density ϱ with Y_e and μ_e (μ_p)

The relation connecting the key-role quantities: matter density ϱ, Y_e (the electron-to-baryon ratio) and the chemical potentials μ_e and μ_p is:

$$\varrho Y_e = \frac{1}{\pi^2 N_A}\left(\frac{m_e c}{\hbar}\right)^3 \int_0^\infty (S_e - S_p) p_e^2 dp_e$$

- **S_e (S_p) is the e^- (e^+) Fermi distribution function**
- **N_A = Avogadro's number**
- **p_e = the e^- (or e^+) momentum**

e^--capture under laboratory conditions



Differential e^--capture cross section within Donnelly-Walecka method

First step of Calculations: The original e^--capture differential cross section $d\sigma/d\omega$ is written as

$$\frac{d\sigma}{d\omega} \equiv \Big[\frac{d\sigma}{d\omega}\Big]_{excl} = \frac{G_F^2 cos^2\theta_c}{2\pi}\frac{F(Z,E_e)}{(2J_i+1)} \cdot \Big\{ \int d\Omega \mathcal{W}(E_\nu)\,\{[1-\alpha cos\Phi + bsin^2\Phi]\big[|\langle J_f\|\widehat{\mathcal{T}}_J^{mag}\|J_i\rangle|^2$$

$$+|\langle J_f\|\widehat{\mathcal{T}}_J^{el}\|J_i\rangle|^2\big] - \big[\frac{(\varepsilon_i+\varepsilon_f)}{q}(1-\alpha cos\Phi)-d\big]2Re\langle J_f\|\widehat{\mathcal{T}}_J^{mag}\|J_i\rangle\langle J_f\|\widehat{\mathcal{T}}_J^{el}\|J_i\rangle^*(1+\alpha cos\Phi)|\langle J_f\|\widehat{\mathcal{M}}_J\|J_i\rangle|^2$$

$$+(1+\alpha cos\Phi - 2bsin^2\Phi)|\langle J_f\|\widehat{\mathcal{L}}_J\|J_i\rangle|^2 - \big[\frac{\omega}{q}(1+\alpha cos\Phi)+d\big]2Re\langle J_f\|\widehat{\mathcal{L}}_J\|J_i\rangle\langle J_f\|\widehat{\mathcal{M}}_J\|J_i\rangle^*\}\Big\}$$

$F(Z,E_e)$=Fermi function, $\mathcal{W}(E_\nu)$=recoil factor

The kinematical parameters α, b, d are given by

$$\alpha = \frac{k_e}{E_e} = \Big[1-\Big(\frac{m_e c^2}{E_e}\Big)^2\Big]^{1/2}, \qquad b = \frac{E_e E_{\nu_e}\alpha^2}{\mathbf{q^2}}, \qquad d = \frac{(m_e c^2)^2}{qE_e}.$$

The 3-momentum transfer $\mathbf{q}$ is defined by $\mathbf{q} = \nu - \mathbf{k}$, where ν, $\mathbf{k}$ the 3-momenta of ν and e^-

Ordinary (orbital) electron capture on nuclei

An atomic e^- of energy E_e may be captured by the nucleus (A,Z) due to mutual electroweak interaction mediated by $W^\pm$ bosons (within the SM) as

$$(A, Z) + e^- \to \nu_e + (A, Z-1), \quad \textit{for any nucleus}\,(A, Z)$$

The produced ν_e carries away energy E_ν
The daughter nucleus absorbs energy $E_x = E_f - E_i$
E_i=energy of initial state, E_f=energy of final nuclear state

The e^--capture@lab:

- When the e^- is bound in a K, L, M, ... energy-state (ordinary nuclear electron capture, $E_e \precsim 2.0$ MeV.
- The e^--capture in lab conditions is a conventional, well-studied process within the SM
- The beam e^--capture energy range is: $E_e \leq 30 - 50$ MeV

Energetics of Charged-Current processes

Nuclear beta-decay modes energetics

- β^--decay, $A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \nu_e$
- β^+ decay, $A(Z,N) \rightarrow A(Z-1,N+1) + e^+ + \nu_e$
- Electron capture, $A(Z,N) + e^- \rightarrow \nu_e + A(Z-1,N+1)$

Q-value, the total kinetic energy released in a reaction, is

- $Q_{\beta^-} = M_i - M_f + E_i - E_f$
- $Q_{\beta^+} = M_i - M_f + E_i - E_f - 2m_e$
- $Q_{EC} = M_i - M_f + E_i - E_f$

P.G. Giannaka, T.S. Kosmas, PRC C 92 (2015) 014606.

The general Formalism for Single-Charge-Exchange processes

Weak interaction Hamiltonian (current-current interaction)-Transition matrix elements

- Weak Interaction Hamiltonian: $\hat{\mathcal{H}}_w = \frac{G}{\sqrt{2}} j_\mu^{lept} \hat{\mathcal{J}}^\mu$
- Transition matrix elements: $\langle f, \nu_e | \hat{\mathcal{H}}_w | i, e \rangle = \frac{G}{\sqrt{2}} \ell^\mu \int d^3\mathbf{x} e^{i\mathbf{q}\cdot\mathbf{x}} \langle f | \hat{\mathcal{H}}_w | i \rangle$

- **The Hamiltonian $\hat{\mathcal{H}}_w$ includes Polar-Vector and Axial-Vector components**
- **The quenching of the Axial-Vector coupling constant g_A must be considered**

From kinematics, the 3-momentum transfer **q** is written as

- e^--capture gives: $q = [\omega^2 + 2\varepsilon_i \varepsilon_f (1 - \alpha cos\Phi) - (m_e c^2)]^{1/2}$
- μ^--capture gives: $q = m_\mu - \epsilon_b + E_i - E_f$

The pn-QRPA (Nuclear Method)

Derivation of ground state (Solving the BCS Equations)

- Renormalization of pairing interaction via the pairing parameters: g_p^{pair}, g_n^{pair} (IOWA group parametrization for Woods-Saxon potential)

Employment of realistic Nucleon-Nucleon interaction

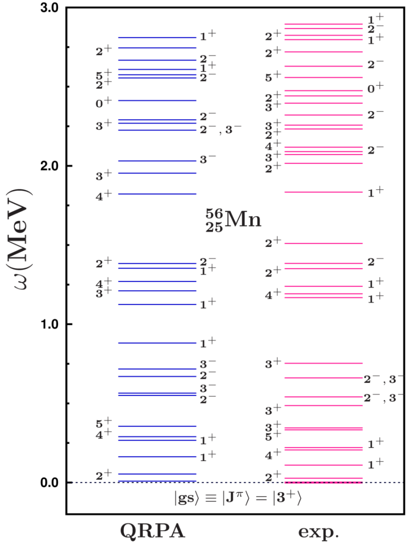
- The Bonn-C two-body potential
- The Bonn C-D two-body potential

Derivation of excited states (Solving the QRPA Equations)

- Renormalization of the residual interaction is done (Bonn C-D) via the parameters: g_{pp} (particle-particle strength), g_{ph} (particle-hole strength)
- Shifting of the spectrum (of the daughter nucleus) is necessary whenever in the pn-QRPA a BCS is used

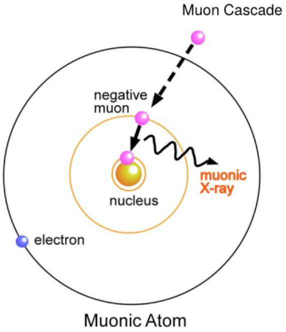
Testing QRPA on the nuclear excitation spectrum

Low-lying QRPA Excitation Spectrum



The first step of our tests is the reproducibility of the excitation spectrum. Our QRPA spectra fit well the experimental data for low lying excitations ($E_x \leq 3 - 5 MeV$).

Testing pn-QRPA on the total μ^--capture rates



Testing of pn-QRPA on the ordinary Muon capture

The μ^--capture, though not significant for stellar nucleosynthesis, is a useful reaction for:

The ordinary μ^--capture rates in testing nuclear methods

- Testing the nuclear models employed in nuclear applications and astrophysics.
- Testing the accuracy of several properties in semi-leptonic weak interaction processes.

In our method, we test the pn-QRPA, in addition to nuclear spectra, also in the "Total muon-capture rates" (due to rich availability of accurate and data/measurements)

The exclusive μ^--capture transition rates

The computation of exclusive μ^--capture rates (between $|J_i\rangle$ and $|J_f\rangle$ nuclear states) is written as (Donnelly-Walecka decomposition method)

$$\Lambda_{i\rightarrow f} = \frac{2G^2 q_f^2}{2J_i+1} R_f \left[\left| \langle J_f \| \Phi_{1s}(\widehat{\mathcal{M}}_J - \widehat{\mathcal{L}}_J) \| J_i \rangle \right|^2 + \left| \langle J_f \| \Phi_{1s}(\widehat{\mathcal{T}}_J^{el} - \widehat{\mathcal{T}}_J^{magn}) \| J_i \rangle \right|^2 \right]$$

- Φ_{1s} = the muon w-f (in the 1s μ^--orbit).
- R_f = recoil factor.
- The multipole operators $\widehat{\mathcal{M}}_J$ (Coulomb), $\widehat{\mathcal{L}}_J$ (longitudinal), $\widehat{\mathcal{T}}_J^{el}$ (transverse electric) and $\widehat{\mathcal{T}}_J^{magn}$ (transverse magnetic) contain polar-vector and axial-vector parts.

For the muon-wave function Φ_{1s} we developed advanced code. In this work we used a mean muon-wave function $\langle\Phi_{1s}\rangle$ (see below).

State-by-state calculations of exclusive μ^--capture rates

Exclusive rates

$$\Lambda_{gs\rightarrow J_f^\pi} \equiv \Lambda_{J_f^\pi} = 2G^2 \langle \Phi_{1s} \rangle^2 R_f q_f^2 \Big[\Big| \langle J_f^\pi \| (\widehat{\mathcal{M}}_J - \widehat{\mathcal{L}}_J) \| 0^+_{gs} \rangle \Big|^2 + \Big| \langle J_f^\pi \| (\widehat{\mathcal{T}}_J^{el} - \widehat{\mathcal{T}}_J^{magn}) \| 0^+_{gs} \rangle \Big|^2 \Big]$$

Quenching effect

$\underline{^{28}Si} \Longrightarrow g_A = 1.262$ **free nucleon coupling constant**
$\underline{^{56}Fe} \Longrightarrow g_A = 1.135$ **takes into account the small quenching effect** ($g_A^{eff} = 0.90 g_A$) **indicated for medium-weight nuclei.**

Code possibilities

Our code provides: Separate contributions induced by the components of muon capture operators

- polar vector operator
- axial vector operator
- overlap Vector-Axial terms

State-by-state calculations of exclusive μ^--capture transition rates

Contribution of each multipolarity J^π

Then, we focused on the separate contributions of each multipolarity (for $J^\pi \leq 5^\pm$). In the model space chosen, we have:

$\underline{^{28}Si} \Longrightarrow$ **286 states** , $\underline{^{56}Fe} \Longrightarrow$ **488 states**

We found that the most important contributions are these of $J^\pi = 1^-$ multipolarity.

Comparison of 1^- peaks with the empirical peak of Giant Dipole Resonance

For medium-weight and heavy isotopes the <u>empirical</u> giant dipole resonance peak is located at energy

$$E_{IVD} = 31.2A^{-1/3} + 20.6A^{-1/6}$$

This empirical peak is in good agreement with the 1^- pronounced peak of our results.

Total μ^--capture Results

The Λ_{tot} rates result by summing over all partial multipole transition rates as

$$\Lambda_{tot} = \sum_{J^\pi} \Lambda_{J^\pi} = \sum_{J^\pi} \sum_{f} \Lambda_{J_f^\pi}$$

Total Muon-capture rates $\Lambda_{tot}(\times 10^6)s^{-1}$							
	pn-QRPA Calculations [3]				Exper.	Other Methods	
(A,Z)	Λ_{tot}^{V}	Λ_{tot}^{A}	Λ_{tot}^{VA}	Λ_{tot}	Λ_{tot}^{exp}	Λ_{tot}^{th} [1]	Λ_{tot}^{th} [2]
^{28}Si	0.150	0.751	-0.009	0.892	0.871	0.823	0.789
^{32}S	0.204	1.078	-0.017	1.265	1.352	1.269	1.485
^{48}Ti	0.628	1.902	-0.081	2.447	2.590	2.214	2.544
^{56}Fe	1.075	3.179	-0.129	4.125	4.411	4.457	4.723
^{66}Zn	1.651	4.487	-0.204	5.934	5.809	4.976	5.809
^{90}Zr	2.679	7.310	-0.357	9.631	9.350	8.974	9.874

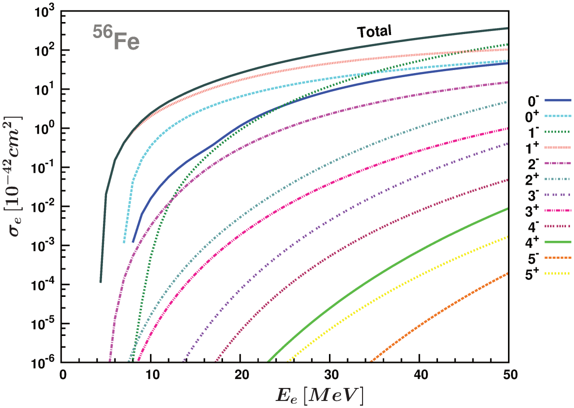
[1] Zinner, Langanke, Vogel, PRC 74(2006)024326, [2] T. Marketin, et al, PRC 79(2009)054323, [3] P. Giannaka, T.S.K, PRC 92(2015)014606

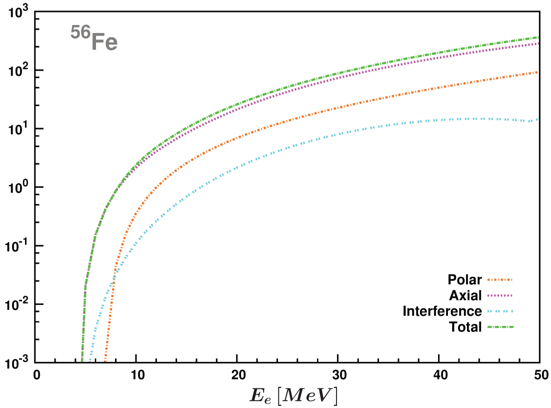
Original e^--capture cross sections for exclusive processes

- Our exclusive e^--capture cross sections refer to a set of isotopes that cover the light-and medium-weight region of the periodic table.
- This set includes
  - the light nuclei ^{28}Si and ^{32}S,
  - the medium weight isotopes ^{48}Ti, ^{56}Fe, that belong to the iron group nuclei and
  - the heavier (more neutron rich) ^{66}Zn and ^{90}Zr isotopes.
- The initial $|J_i\rangle$ and the final $|J_f\rangle$ states are determined by solving the pn-QRPA equations, for the ground state and the excited states.

The realistic two body interactions of Bonn C-D potential was employed for the studied isotopes

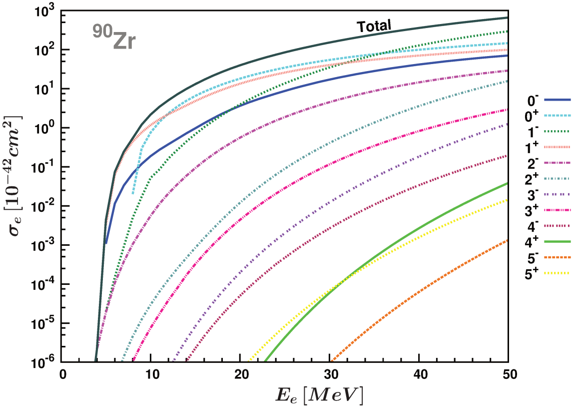
The $^{56}Fe(e^-, \nu_e)^{56}Mn$ reaction

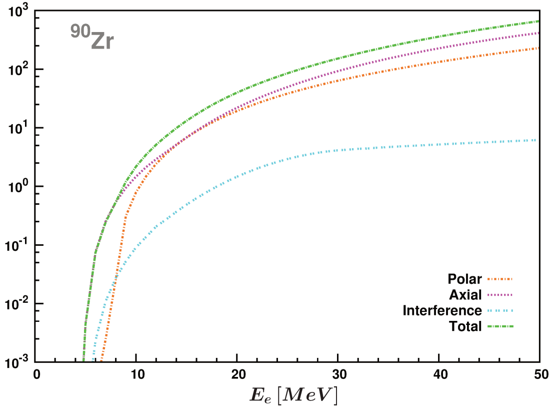




The e^--capture reaction: $^{56}Fe(e^-, \nu_e)^{56}Mn$. The individual contribution to the total e^--capture cross sections (bold, full line) of various channels ($J^\pi \leq 5^\pm$) are demonstrated

The $^{90}Zr(e^-, \nu_e)^{90}Y$ reaction





The $^{90}Zr(e^-, \nu_e)^{90}Y$ reaction.

Percentages of low-spin multipolarities to the total e^--capture rates

Table: The percentages of low-spin multipolarities (up to $J^\pi \leq 3^\pm$) into the total e^--capture cross sections, evaluated with our pn-QRPA method.

	^{28}Si	^{32}S	^{48}Ti	^{56}Fe	^{66}Zn	^{90}Zr
0^-	5.45	8.74	9.16	7.63	5.54	10.30
0^+	24.47	5.23	37.37	23.51	32.82	40.73
1^-	3.19	8.23	6.75	7.83	12.07	16.14
1^+	65.86	75.97	44.33	59.04	47.68	30.48
2^-	0.98	1.73	2.33	1.91	1.78	2.21
2^+	0.04	0.09	0.05	0.06	0.09	0.10
3^-	~ 0.00	~ 0.00	~ 0.00	~ 0.00	~ 0.00	~ 0.00
3^+	0.01	0.01	0.01	0.02	0.01	0.03

- Our pn-QRPA gives higher 0^+ contributions compared to other methods. However, recent 0^+ contributions of other pn-QRPA versions are much smaller than the experimental data.

Jokiniemi, Suhonen, PRC 100(2019)014619

Our method gives 0^+ results towards the correct direction.

Stellar (Temperature dependent)

e^--**capture cross sections** $\sigma_{tot}^{stel}(E_e, T)$

Finite temperature and matter density (T & ϱ) effects

In astrophysical environment (finite temperature T and matter density ϱ, effects cannot be ignored). As initial nuclear state a weighted sum over all populated states must be taken Assuming Maxwell–Boltzmann distribution for the $|i\rangle$ states, the total e^{-}-capture $\sigma(E_e, T)$ is

$$\sigma(E_e, T) = \frac{G_F^2 cos^2\theta_c}{2\pi} \sum_i F(Z, E_e) \frac{(2J_i + 1)e^{-E_i/(kT)}}{G(Z, A, T)} \sum_{f,J} (E_e - Q + E_i - E_f)^2 \frac{|\langle i|\widehat{O}_J|f\rangle|^2}{(2J_i + 1)}$$

The sum over "i" denotes thermal average of energy levels with partition function G(Z,A,T). It is worth noting that in calculating the original total e^{-}-capture cross-sections, a quenched value for the static axial-vector coupling constant g_A is necessary.

Total stellar cross-sections for a given isotope

Practically the total stellar cross-sections for a given isotope are obtained by summing over the contribution of only the low-spin multipolaries of the daughter nucleus

Under stellar interior conditions (high ϱ and T), we assumed that:

- the initial state of the parent nucleus may be either its ground state or any excited state with $E_x \leq 3.0$ MeV (contributions of states of the parent nucleus, with $E_x > 2.5 - 3.0$ MeV, are negligible due to low population)
- all leptons (e^-, e^+, ν, etc.) under stellar conditions follow Fermi–Dirac energy distributions

Stellar e-Capture Rates in Nuclei with $A \leq 65$

In computing e^--capture cross-sections for ^{48}Ti, as parent nucleus, initial states we considered the

- the two lowest 0^+ states,
- the two lowest 2^+ states,
- the lowest 4^+ state

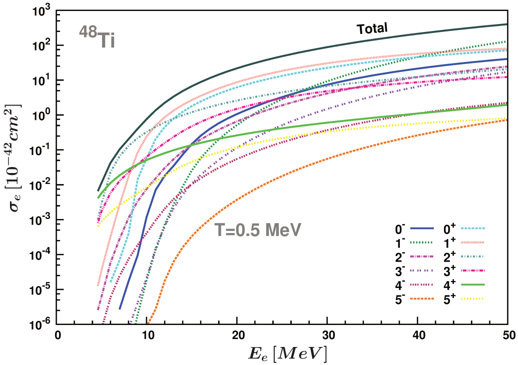
Correspondingly, in the model space chosen, we had 338 accessible final states for the daughter nucleus ^{48}Sc.

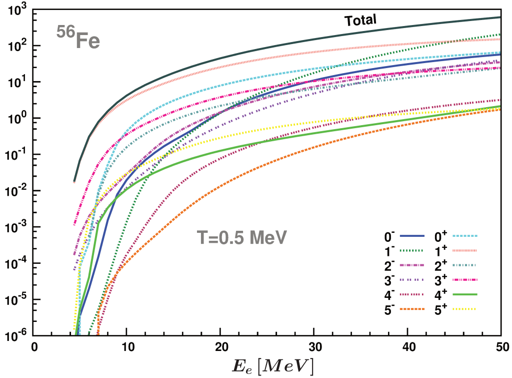
Similarly, for the parent nucleus ^{56}Fe, we assumed that the initial state could be any of

- the three lowest 2^+ states,
- the two lowest 0^+,
- the lowest 4^+ state,

These correspond to 488 excited states of the ^{56}Mn daughter nucleus. All of them were involved in the state-by-state calculations performed within our pn-QRPA method.

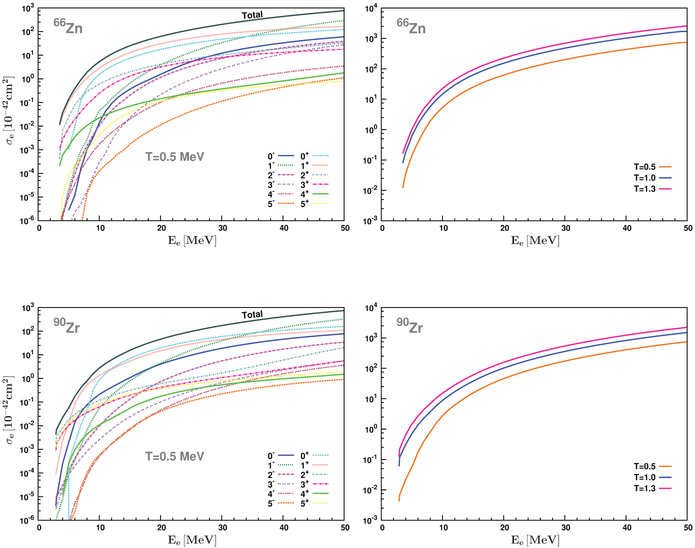
Total e^--capture cross sections in ^{48}Ti and ^{56}Fe





Electron-capture cross sections for the parent nuclei ^{48}Ti and ^{56}Fe at temperature T=0.5 MeV (stellar environment). Total cross sections and the pronounced individual multipole channels for $J^{\pi} \leq 5^{\pm}$ are demonstrated as functions of the incident electron energy $E_e leq MeV$.

Temperature dependence of e^--capture cross sections for $A > 65$ Nuclei



As T increases the total cross-section $\sigma(E_e, T)$ reaches saturation. This behaviour agrees with previous findings

Comparison of GT contributions
coming out of various methods

The important Gamow-Teller transitions

Many authors estimate the total e^--capture cross sections starting from

$$\sigma_{fi}(E_e) = \frac{6(E_e - E)^2 G_F^2 \cos^2\theta_c}{\pi(2J_i+1)} |\langle J_f \| \widehat{\mathcal{L}}_1 \| J_i \rangle|^2$$

where the operator $\widehat{\mathcal{L}}_{1M}$ (assuming low momentum transfer, $q \to 0$), is written as

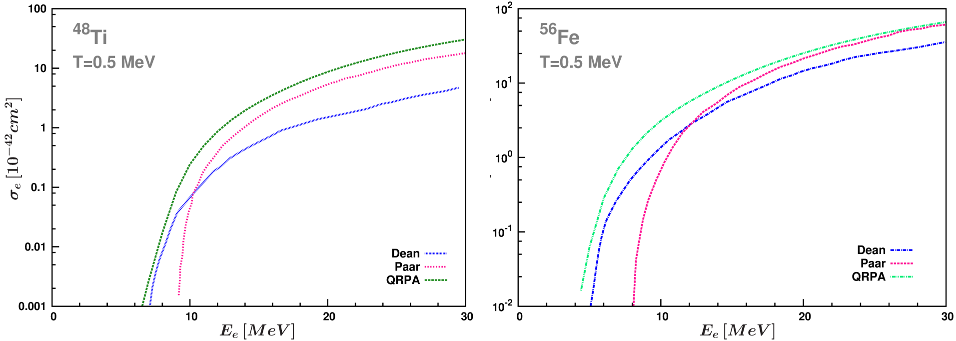
$$\widehat{\mathcal{L}}_{1M} = \frac{i}{\sqrt{12\pi}} G_A \sum_{i=1}^{A} \tau^+(i)\sigma_{1M}(i)$$

Then, the transitions of Gamow-Teller operator

$$GT_+ = \sum_i \tau_i^+ \sigma_i$$

provides the dominant contribution to the total cross section

Comparison of our GT rates with other models for ^{48}Ti and ^{56}Fe



- In Dean et al.[1] the total e^--capture rates were calculated with shell model and considering only the GT contributions.
- In Paar et al. [2] the relativistic RPA was used with schematic N-N interaction for both Fermi and Gammow-Teller contributions.

[1]Paar, N.; Colo, G.; Khan, E.; Vretenar, D. Calculation of stellar electron-capture cross sections on nuclei based on microscopic Skyrme functionals. Phys. Rev. C 2009, 80, 055801.

[2]Dean, D.J.;Langanke, K.; Chatterjee, L.; Radha, P.B.; Strayer, M.R. Electron capture on iron group nuclei. Phys. Rev. C 1998, 58, 536.

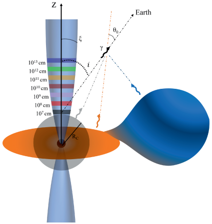
Comparison of GT contributions coming out of various methods

- It is very interesting the fact that the comparison of our result for 1^+ (GT transitions) with those of the aforementioned works (stellar temperature T $=$ 0.5 MeV), is good.
- Our results agree rather well with those of both previous findings. Throughout the energy range $0 \leq Ee \leq 30$, our results are a bit higher.
- It should be noted that, for the axial vector coupling constant $g_A^{eff} \approx 1.135$ employed in this work (the same for all studied isotopes).
- Better agreement could be achieved for all E_e if we choose a smaller value for g_A^{eff}.
- The fine structure of the comparison shows that our results are in better agreement with those of Dean et al. for energies $E_e \lesssim 8$ MeV (region of particle-bound states), while for $E_e \gtrsim 10$ MeV, our results are in better agreement with those of Paar et al.
- From the two isotopes ^{48}Ti (left) and ^{56}Fe (right), the adopted parametrizations in the three methods, favours the global picture of ^{56}Fe isotope.

Ongoing and Future investigations

Neutrino and γ-ray calculations for the deep space

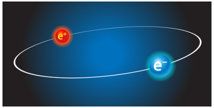
- The extension of our research to Astrophysics includes evolution of systems like the Stellar Black Hole Binary Stars.
- We simulate high energy neutrino and γ-ray productions.
- In the figure, the Compact Object is shown at the center (black spot), the accretion disc (in red) at its equatorial region, and the donor star (blue) at the r.h.s.
- The emission of high energy ν's, γ-rays, X-rays, etc., is ejected (like jet) vertically to the accretion disc.

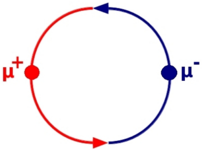


Ongoing and Future investigations

Calculations for the world of leptonic atoms ("microcosm")

- These days we are going to start dealing (Ioannina - UCL collaboration) with purely leptonic atoms based on the derivation of advanced codes for leptons ($e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$). We will solve the Dirac Equation (involving the Dirac Hamiltonia plus relativistic corrections).
- The applications will refer to systems as: the true muonium atom (a bound state of a muon (μ^{+}) and an antimuon(μ^{-}), the Positronium (e^{+}, e^{-})).
- A relevant research proposal (Scientific Coordonator T.S.K) has benn recently aproved (more details in a future talk).





Summary, Conclusions and Outlook

- The theoretical method and calculations I presented have developed and established during the last decades. They belong to the interplay between Astro-nuclear Physics, Muon and Atomic Physics as well as the exotic particle physics (beyond the SM physics).
- We used a numerical approach describing several semi leptonic weak interaction processes (a version of the pn-QRPA) tested on 1) on the nuclear spectrum 2) the study of orbital muon capture process.
- The agreement with experimental and other theoretical results of partial and total μ-capture rates and portions of various low-lying excitations is very good which provides us with high confidence level of our method.
- Next we applied this method to e^- capture process and calculated 1) original as well as 2) stellar e^--capture cross sections and studied their temperature dependence.
- Such results may be added to rate-tabulation which are employed for pre-SN and core-collapse SN phase description (simulations) as well stellar nucleosynthesis

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Thank you for your attention

Ioannina, the city of silver and gold!

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