rp-process and stellar weak interaction rates of waiting point nuclei

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Outline

- *complex* **EXCITED VAMPIR beyond-mean-field model**

- **shape-coexistence effects on terrestrial and stellar weak interaction rates of**

  - ***^{68}Se and ^{72}Kr - rp-process waiting points in type-I x-ray bursts***

- **impact *of ^{68}Se and ^{72}Kr stellar weak interaction rates* on rp-process nucleosynthesis and energetics**

A~70 waiting points play a critical role in rp-process nucleosynthesis

A~70 proton-rich nuclei manifest exotic structure and dynamics *generated by*

- ***shape coexistence and shape mixing***
- ***competing T=0 and T=1 pairing correlations***
- ***isospin-symmetry-breaking interactions***

responsible for

drastic changes in structure with number of nucleons, spin, and excitation energy

Challenges for nuclear many-body theory

- ***realistic effective Hamiltonians in adequate model spaces, beyond-mean-field methods***
- ***comprehensive understanding of structure phenomena and β-decay properties***
- ***robust predictions on stellar weak interaction rates***

based on

self-consistent description of experimentally accessible properties

complex VAMPIR model family

- **the model space is defined by a finite dimensional set of spherical single particle states**

- **the effective many-body Hamiltonian is represented as a sum of one- and two-body terms**

- **the basic building blocks are Hartree-Fock-Bogoliubov (HFB) vacua**

- **the HFB transformations are essentially *complex* and allow for proton-neutron, parity and angular momentum mixing being restricted by time-reversal and axial symmetry**

(T=1 and T=0 neutron-proton pairing correlations already included at the mean-field level)

- **the broken symmetries (s=N, Z, I, p) are restored by projection before variation**

**** The models allow to use rather large model spaces and realistic effective interactions***

Beyond-mean-field variational procedure: complex EXCITED VAMPIR model

Vampir

$$E^s[F_1^s] = \frac{\langle F_1^s|\hat{H}\hat{\Theta}_{00}^s|F_1^s\rangle}{\langle F_1^s|\hat{\Theta}_{00}^s|F_1^s\rangle}$$

Θ^s_{00} - symmetry projector

$|F^s_1>$ - HFB vacuum

$$|\psi(F_1^s); sM\rangle = \frac{\hat{\Theta}_{M0}^s|F_1^s\rangle}{\sqrt{\langle F_1^s|\hat{\Theta}_{00}^s|F_1^s\rangle}}$$

Excited Vampir

$$|\psi(F_2^s); sM\rangle = \hat{\Theta}_{M0}^s\left\{|F_1^s\rangle\alpha_1^2 + |F_2^s\rangle\alpha_2^2\right\}$$

$$|\psi(F_i^s); sM\rangle = \Sigma_{j=1}^{i}\,|\phi(F_j^s)\rangle\,\alpha_j^i \qquad \text{for} \quad i = 1, ..., n-1$$

$$|\phi(F_i^s); sM\rangle = \Theta_{M0}^s|F_i^s\rangle$$

$$|\psi(F_n^s); sM\rangle = \Sigma_{j=1}^{n-1}\,|\phi(F_j^s)\rangle\,\alpha_j^n + |\phi(F_n^s)\rangle\,\alpha_n^n$$

$$(H - E^{(n)}N)f^n = 0$$

$$(f^{(n)})^+ N f^{(n)} = 1$$

$$|\Psi_\alpha^{(n)}; sM> = \sum_{i=1}^{n}|\psi_i; sM> f_{i\alpha}^{(n)}, \qquad \alpha = 1, \ldots, n$$

A ~ 70 mass region

^{40}Ca - core

model space for protons and neutrons

$1p_{1/2}$ $1p_{3/2}$ $0f_{5/2}$ $0f_{7/2}$ $1d_{5/2}$ $0g_{9/2}$

(charge-symmetric basis + Coulomb contributions to the π-spe from the core)

$1p_{1/2}$ $1p_{3/2}$ $0f_{5/2}$ $0f_{7/2}$ $2s_{1/2}$ $1d_{3/2}$ $1d_{5/2}$ $0g_{7/2}$ $0g_{9/2}$ $0h_{11/2}$ (ext-model space)

renormalized G-matrix (OBEP- Bonn A/ CD)

- ***pairing properties enhanced by short range Gaussians for:***

  T = 1 : pp (*-35 MeV*), np (*-20 MeV*), nn (*-35 MeV*)

  T = 0: np (*-35 MeV*)

- ***onset of deformation influenced by monopole shifts:***

  $<0g_{9/2}\ 0f;\ T=0\ |G|\ 0g_{9/2}\ 0f;T=0>$ $(0f_{5/2}, 0f_{7/2})$

  $<1d_{5/2}\ 1p;\ T=0\ |G|\ 1d_{5/2}\ 1p;T=0>$ $(1p_{1/2}, 1p_{3/2})$

- ***Coulomb interaction between valence protons added***

Self-consistent terrestrial and stellar weak interaction rates

Gamow-Teller transition probabilities

$$B_{if}(GT) = \frac{1}{2J_i + 1} \frac{g_A^2}{4\pi} |M_{GT}|^2$$

$$\begin{aligned} M_{GT} &\equiv (\xi_f J_f || \hat{\sigma} || \xi_i J_i) \\ &= \sum_{ab} M_{GT}(ab) (\xi_f J_f || [c_a^\dagger \tilde{c}_b]_1 || \xi_i J_i) \end{aligned}$$

$$M_{GT}(ab) = 1/\sqrt{3} (a || \hat{\sigma} || b)$$

Independent chains of variational calculations for all parent and daughter states

Weak interaction rates in X-ray burst astrophysical environment

A. Petrovici and O. Andrei, Eur. Phys. J. A51, 133 (2015)
Phys. Rev. C92, 064305 (2015)

In the X-ray burst stellar environment at densities (~10^6 mol/cm^3) and temperatures (~10^9K) typical for the rp-process the contribution of thermally populated low-lying 0^+ and 2^+ states may be relevant.

$$\lambda^{\alpha} = \frac{ln2}{K} \sum_i \frac{(2J_i+1)e^{-E_i/(kT)}}{G(Z,A,T)} \sum_j B_{ij}\phi_{ij}^{\alpha}$$

$$G(Z,A,T) = \sum_i (2J_i+1)exp(-E_i/(kT))$$

$$B_{ij} = B_{ij}(F) + B_{ij}(GT)$$

$$\phi_{ij}^{ec} = \int_{w_l}^{\infty} wp(Q_{ij}+w)^2 F(Z,w) S_e(w)(1-S_{\nu}(Q_{ij}+w))dw$$

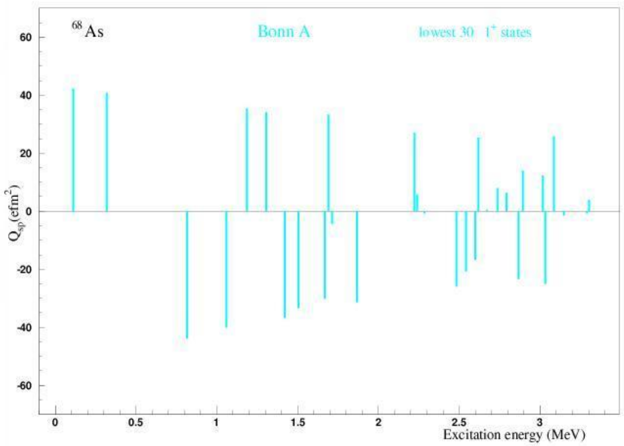
$$\phi_{ij}^{\beta^+} = \int_{1}^{Q_{ij}} wp(Q_{ij}-w)^2 F(-Z+1,w)(1-S_p(w))(1-S_{\nu}(Q_{ij}-w))dw$$

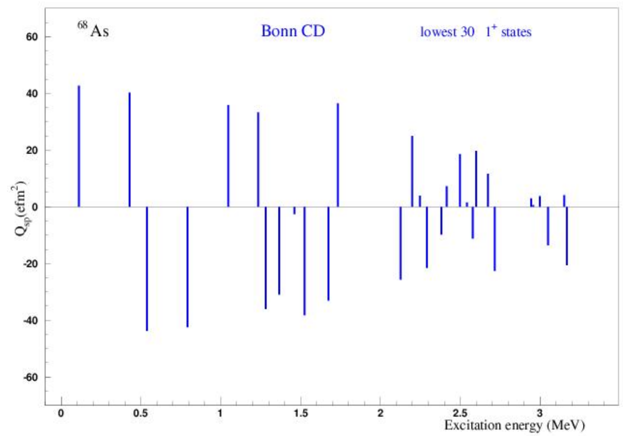
Shape coexistence and weak interaction rates for ^{68}Se rp-process waiting point

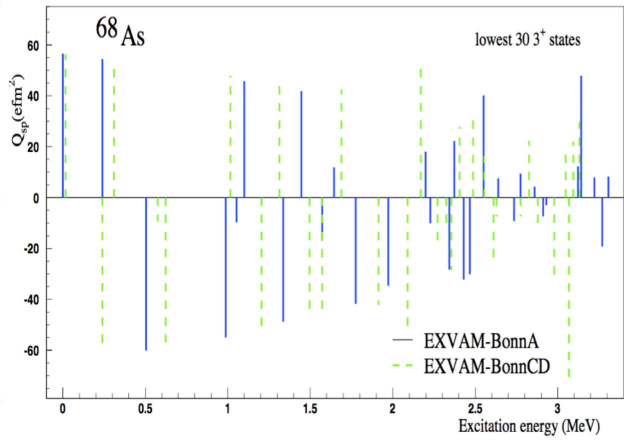
A. Petrovici and O. Andrei, Eur. Phys. J. A51, 133 (2015)

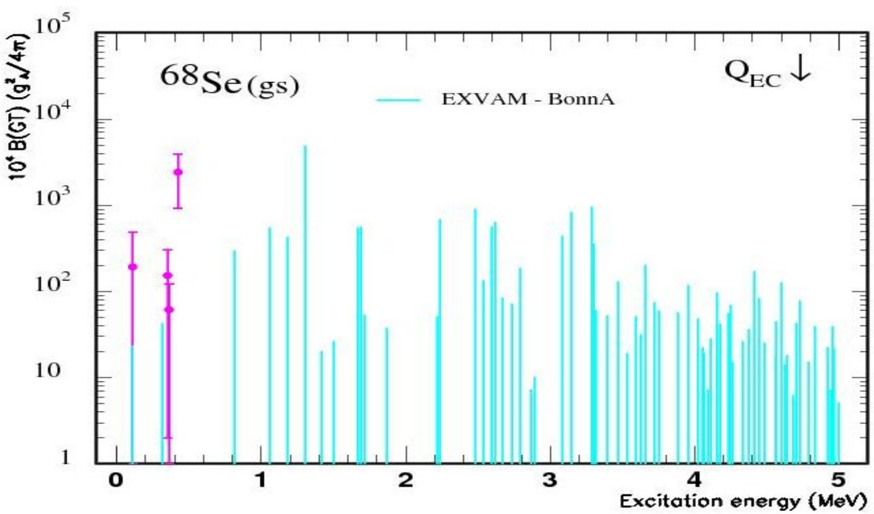
$E_{0^+_{gs}}$ = 0.0 MeV [*62/55(%) – oblate (*BonnA/BonnCD)] **$E_{2^+_{yr}}$ = 0.854 MeV** [*60/41(%) – oblate (*BonnA/BonnCD)]

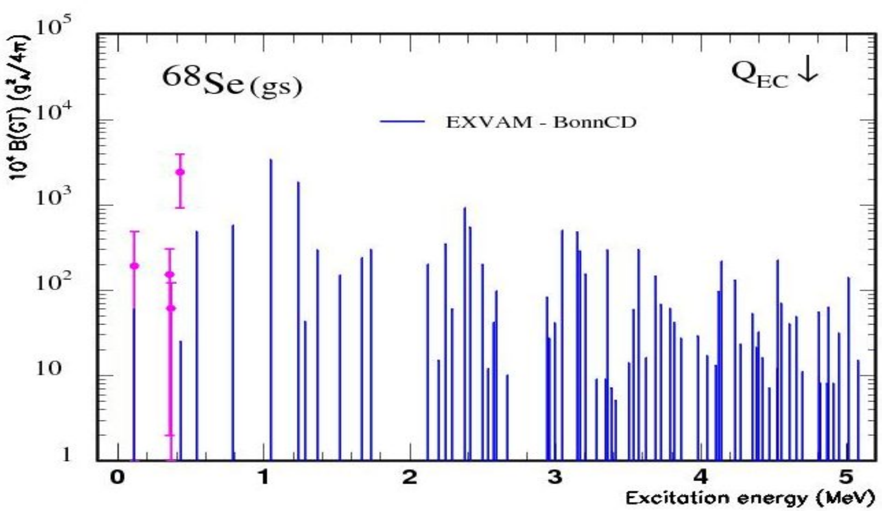
$Q^{sp}_{2^+_{yr}}$ = 3.5 efm^2(A) / -7.1 efm^2 (CD) **B(E2;2^+-> 0^+) =521/503** e^{2}fm^4 *(*BonnA/BonnCD) **Exp.: 430(60) e^{2}fm^4**

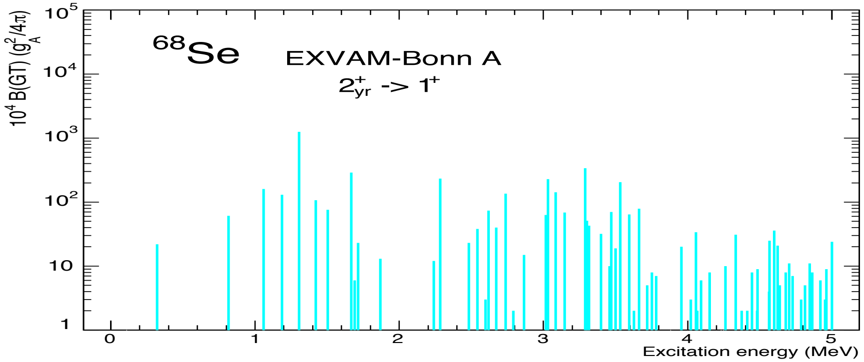


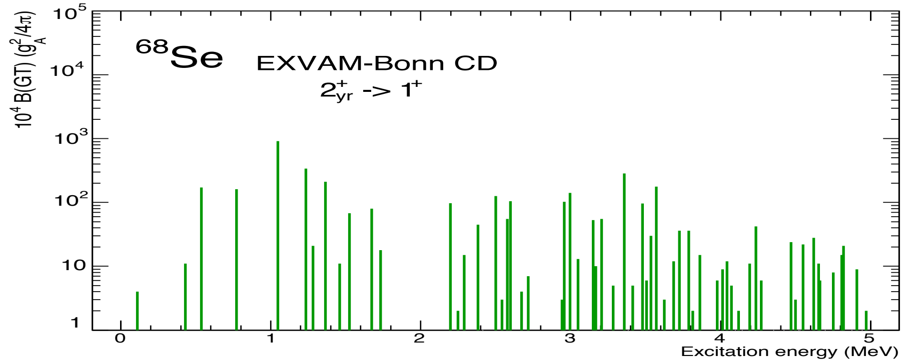


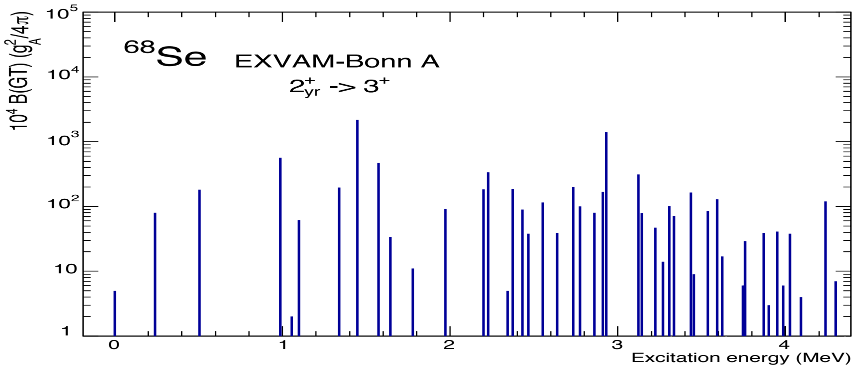


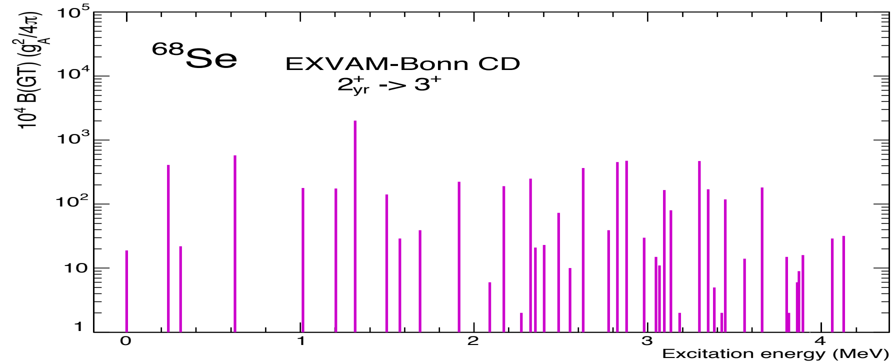






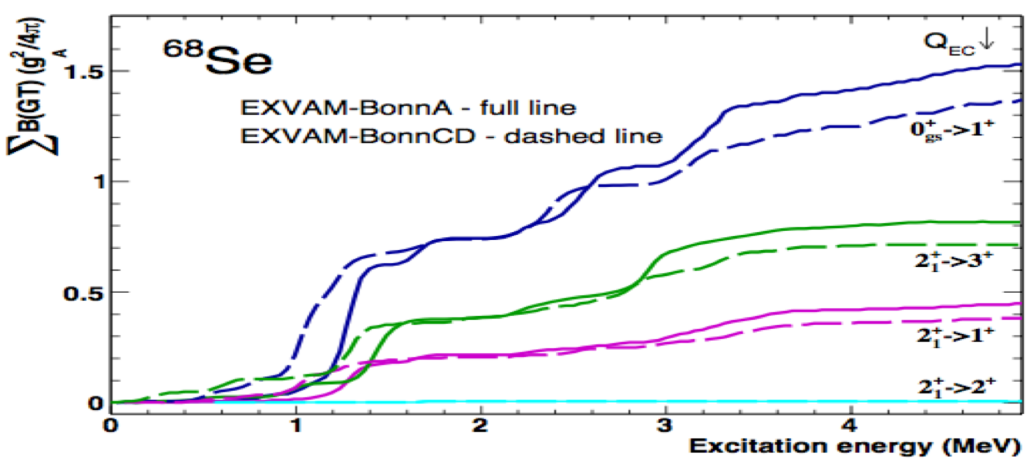






Contributions: - $p^{\nu(\pi)}_{1/2} p^{\pi(\nu)}_{3/2}$, $p^{\nu}_{3/2} p^{\pi}_{3/2}$, $f^{\nu}_{5/2} f^{\pi}_{5/2}$, $f^{\nu(\pi)}_{5/2} f^{\pi(\nu)}_{7/2}$, $g^{\nu}_{9/2} g^{\pi}_{9/2}$ matrix elements (decay to 1^+ states)

- $p^{\nu}_{3/2} p^{\pi}_{1/2}$, $p^{\nu}_{3/2} p^{\pi}_{3/2}$, $f^{\nu}_{5/2} f^{\pi}_{7/2}$ matrix elements (decay to 3^+ states)



$T_{1/2}^{exp} = 35.5(7)$ s

$T_{1/2}^{EXVAM} = 48.9 / 34.9$ s (BonnA/BonnCD)

Shape coexistence and weak interaction rates for ^{72}Kr rp-process waiting point

A. Petrovici and O. Andrei, Eur. Phys. J. A51, 133 (2015)

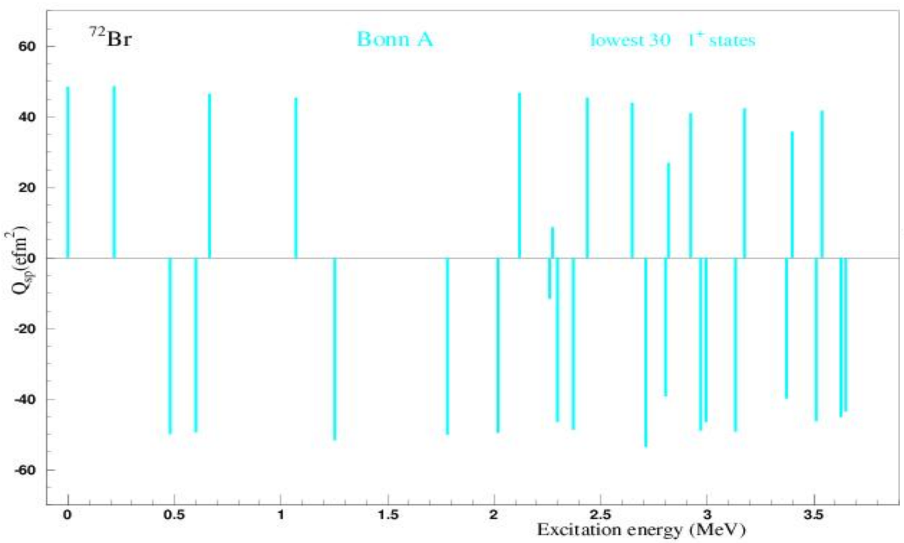
$1p_{1/2}$ $1p_{3/2}$ $0f_{5/2}$ $0f_{7/2}$ $1d_{5/2}$ $0g_{9/2}$ (standard-model space)

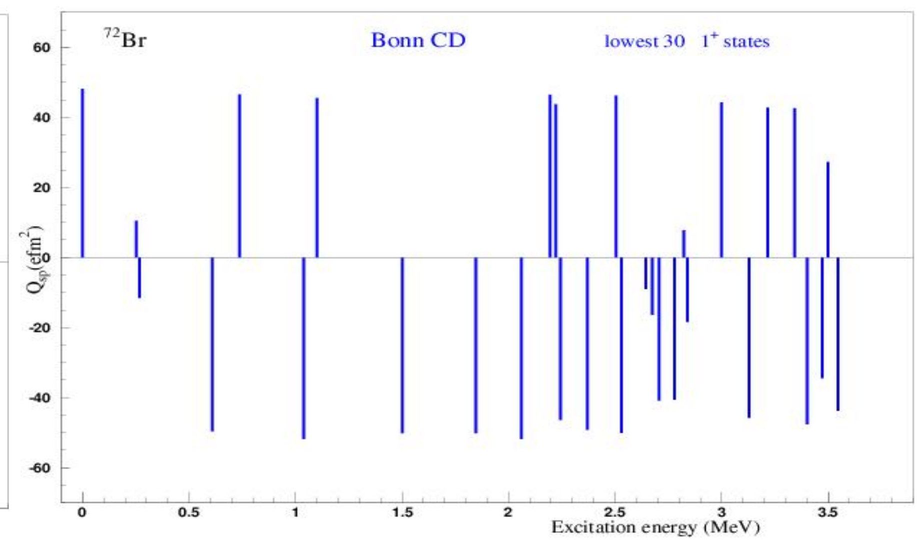
$1p_{1/2}$ $1p_{3/2}$ $0f_{5/2}$ $0f_{7/2}$ $2s_{1/2}$ $1d_{3/2}$ $1d_{5/2}$ $0g_{7/2}$ $0g_{9/2}$ $0h_{11/2}$ (ext-model space)

$E_{0^+_{gs}}$ = 0.0 MeV p/o mixing *60/40%* (BonnA-ext-space) *34/66%* (BonnA-standard space)
$E_{0^+_{exc}}$ = 0.671 MeV p/o mixing *38/62%* (BonnA-ext-space) *63/37%* (BonnA-standard space)
$E_{2^+_{yrast}}$ = 0.710 MeV p/o mixing *41/59%* (BonnA-ext-space)) *7/93%* (BonnA-standard space)

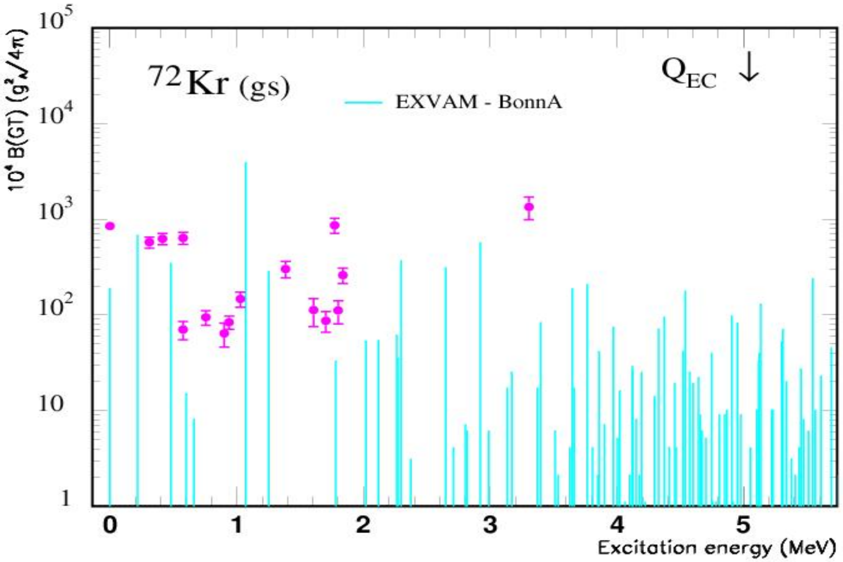
$B(E2;2^+ \to 0^+)$ = **853/670** e^2fm^4 (BonnA-extended space/BonnA-standard space) Exp.: **810 (150)** e^2fm^4

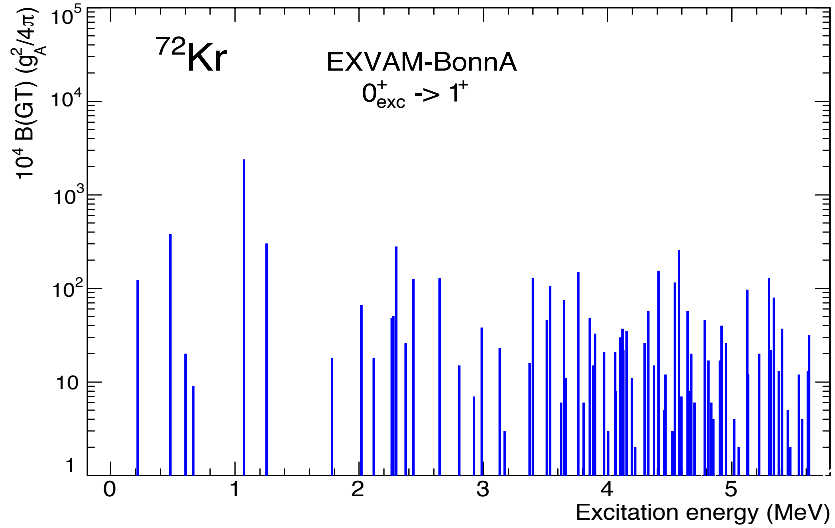
Shape coexistence and mixing in parent and daughter nucleus

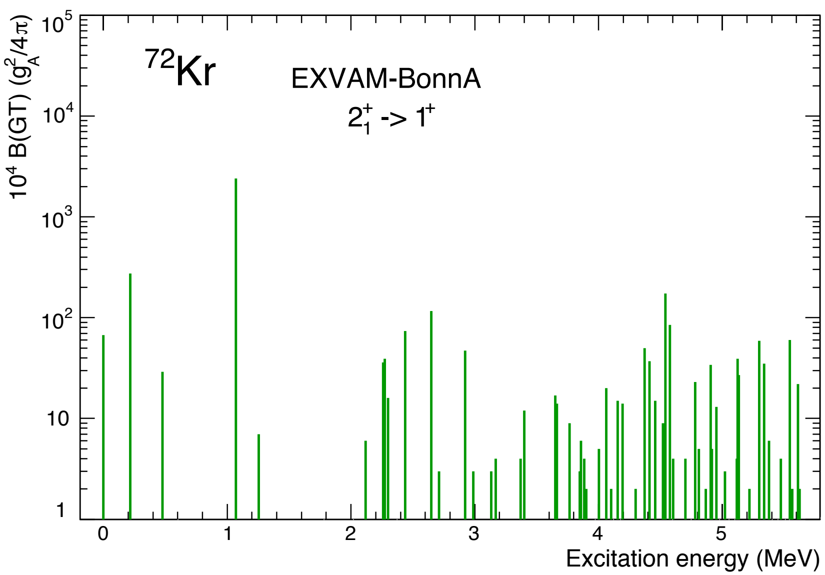


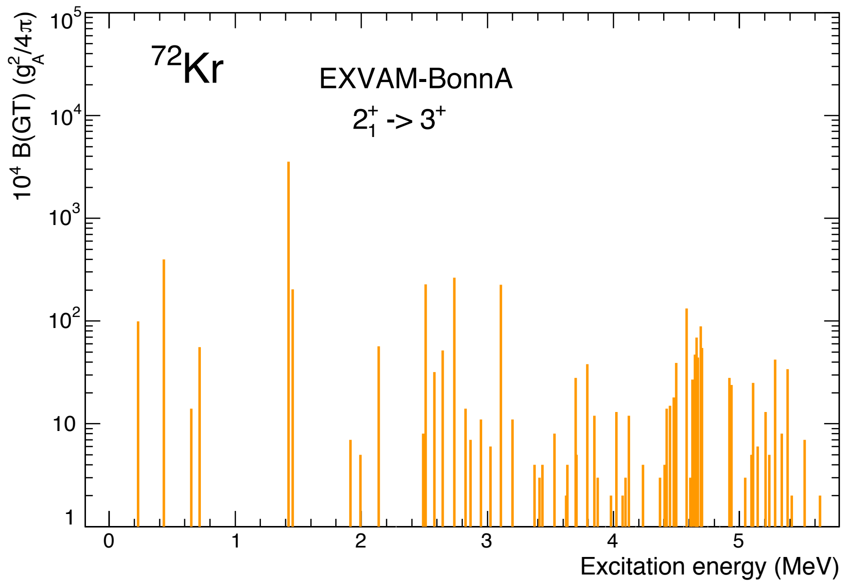


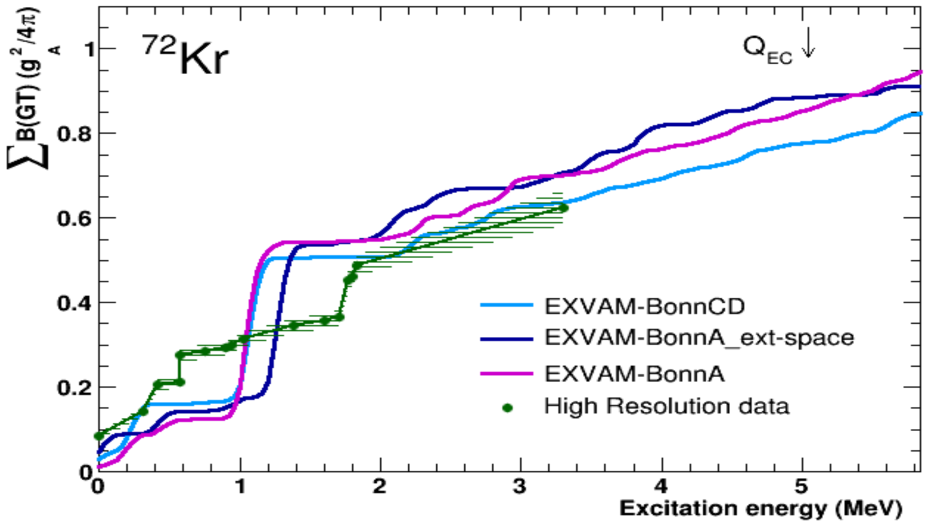
Gamow-Teller strength distributions depend strongly on parent and daughter structure











$T_{1/2}^{EXVAM}$ = 18.9 s (BonnCD)

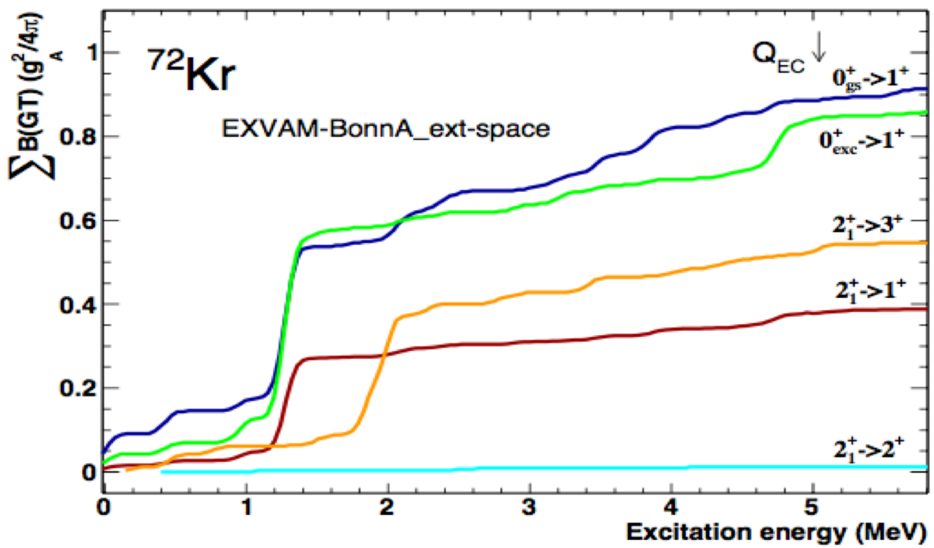
$T_{1/2}^{EXVAM}$ = 18.6 s (BonnA)

$T_{1/2}^{EXVAM}$ = 18.5 s (BonnA-ext-space)

$T_{1/2}^{exp}$ = 17.1(2) s

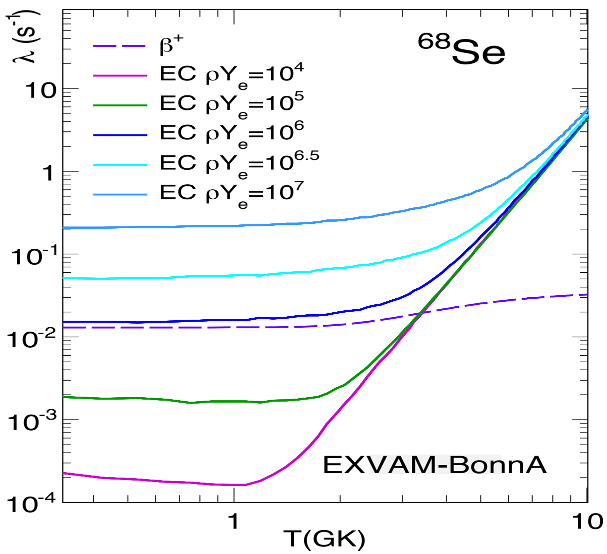
Contributions: - $p^{\nu(\pi)}_{1/2}p^{\pi(\nu)}_{3/2}$, $p^{\nu}_{3/2}p^{\pi}_{3/2}$, $f^{\nu}_{5/2}f^{\pi}_{5/2}$, $f^{\nu(\pi)}_{5/2}f^{\pi(\nu)}_{7/2}$, $g^{\nu}_{9/2}g^{\pi}_{9/2}$ matrix elements (decay to 1^+ states)

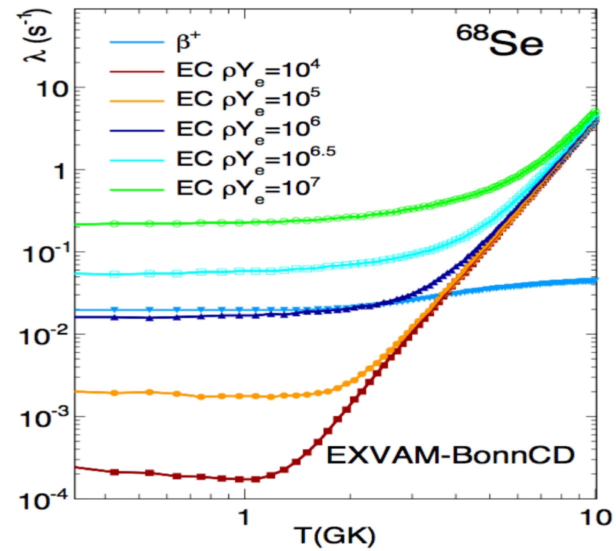
- $p^{\nu}_{3/2}p^{\pi}_{1/2}$, $p^{\nu}_{3/2}p^{\pi}_{3/2}$, $f^{\nu}_{5/2}f^{\pi}_{7/2}$ matrix elements (decay to 3^+ states)

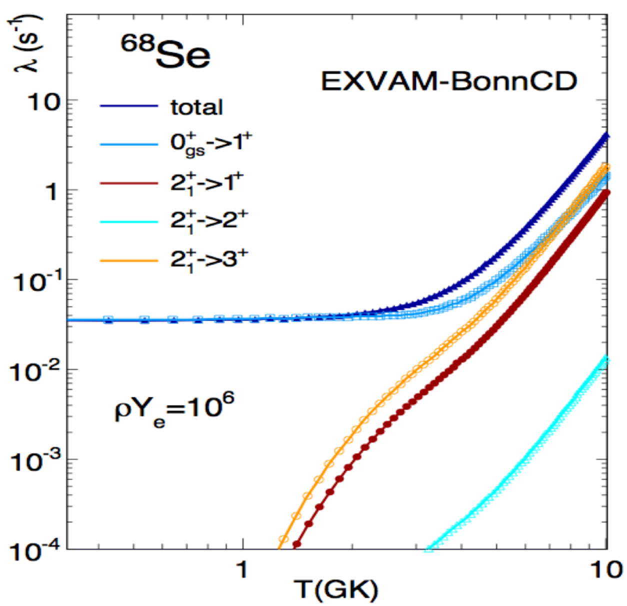


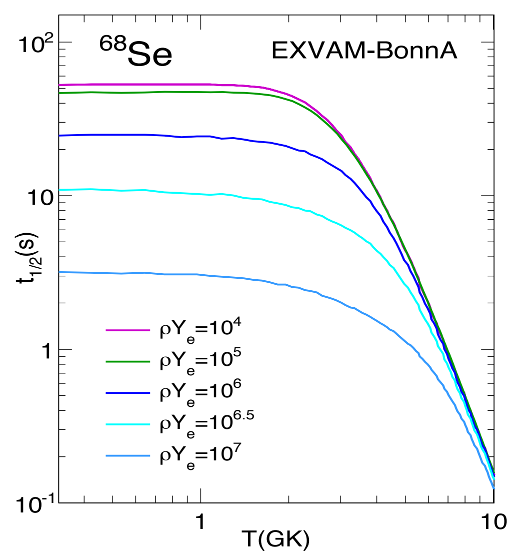
Stellar rates for ^{68}Se : β^+ and continuum electron capture

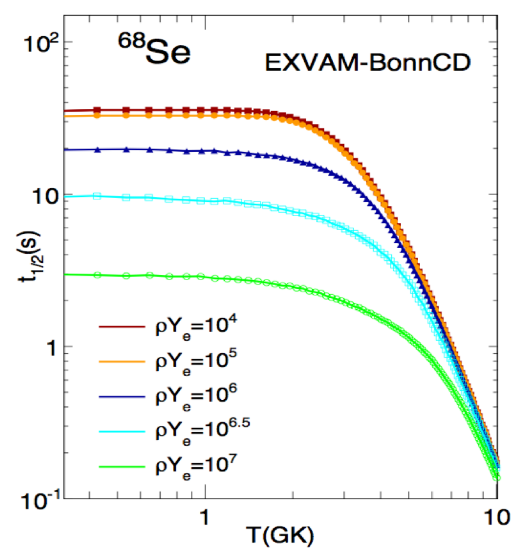
Significant continuum electron capture contribution





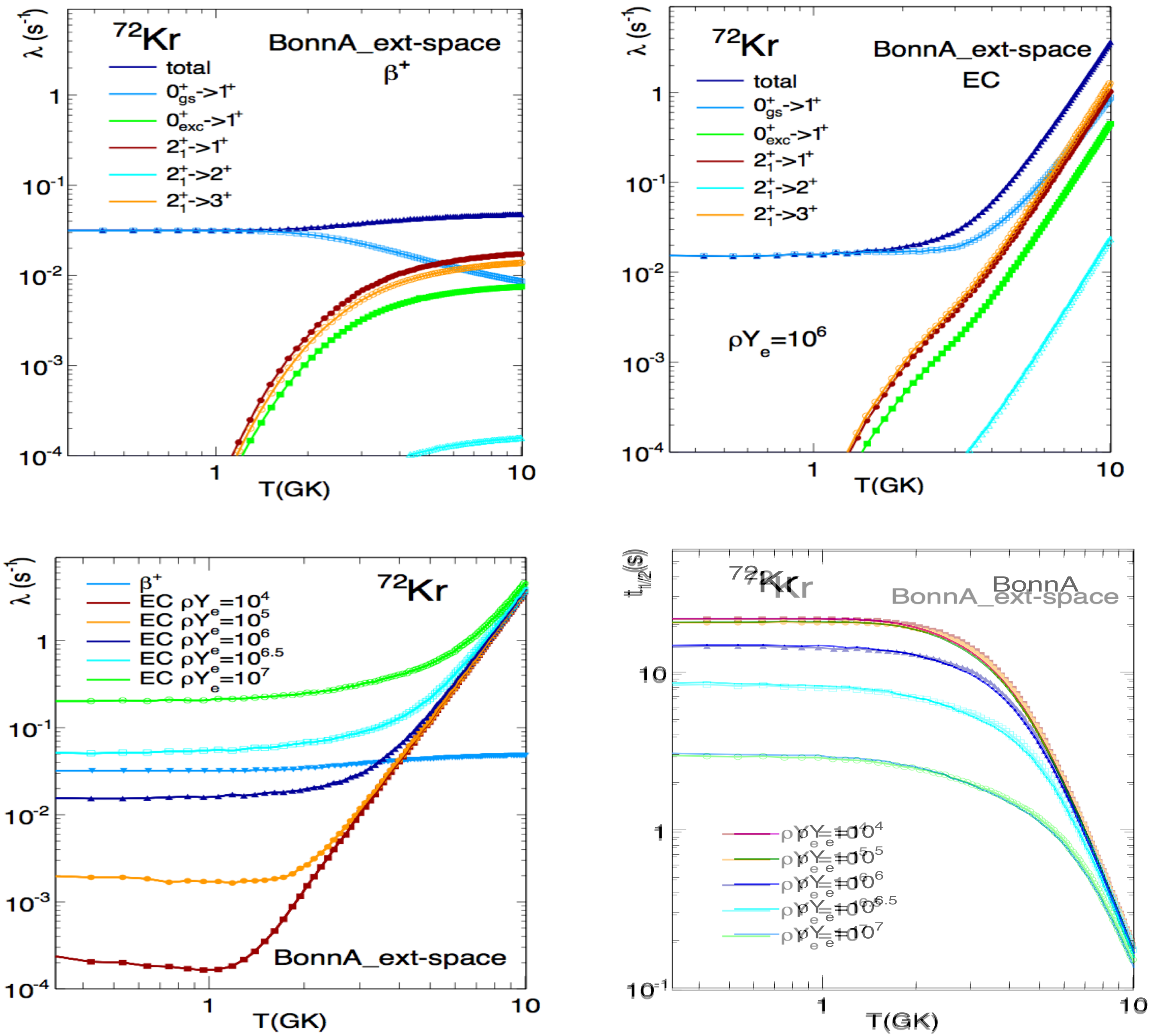






Stellar rates for ^{72}Kr : β^{+} and continuum electron capture

Significant continuum electron capture contribution



Impact of ^{68}Se and ^{72}Kr stellar weak interaction rates on rp-process nucleosynthesis and energetics

Post-processing approach *based on a* ***one-zone model*** *- H. Schatz et al, PRL 86, 3471 (2001)*

- *temperature and density profile with time*
- *nuclear reaction network includes proton-rich nuclei from H to Xe*
- *x-ray burst - ignition conditions: density 1.1×10^6 g/cm^3; T_{peak}=1.9 GK*
  - rise time ~ 4 s; cooling phase ~ 200 s
- *initial H(X) / He(Y) mixing and metallicity :*

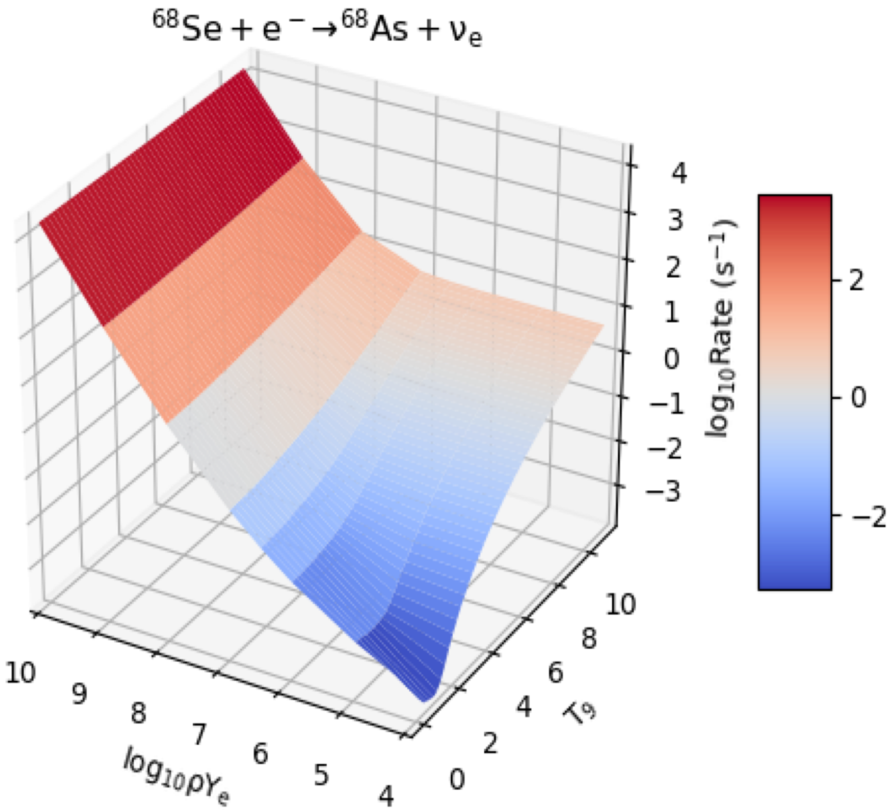
X=0.66, Y=0.339, Z=0.001 (hhez1 - Schatz)

X=0.64, Y=0.359, Z=0.001 (hhez2)

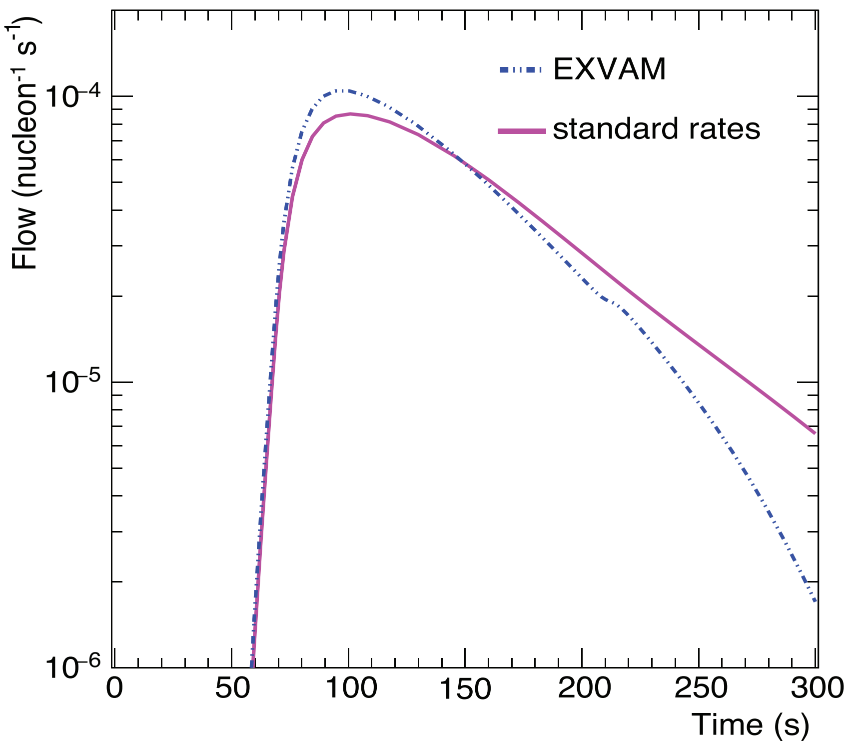
X=0.7048, Y=0.2752, Z=0.02 (^{14}N) (hhez3 - solar)

X=0.759, Y=0.24, Z=0.001 (hhez4)

2D-evolution of ^{68}Se continuum electron capture rates

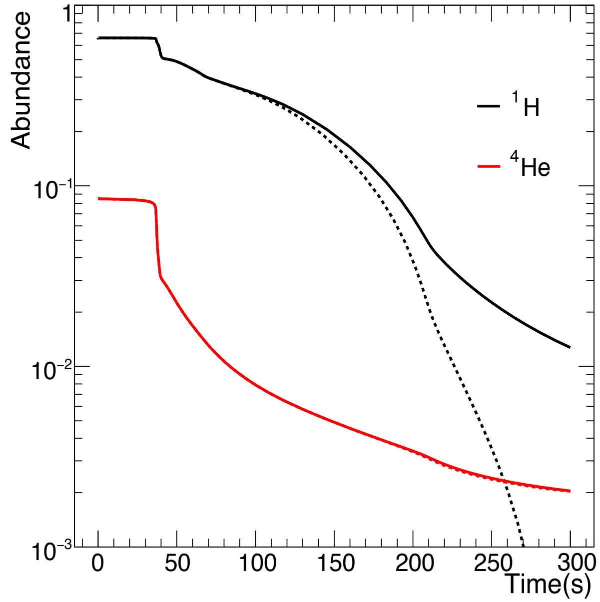


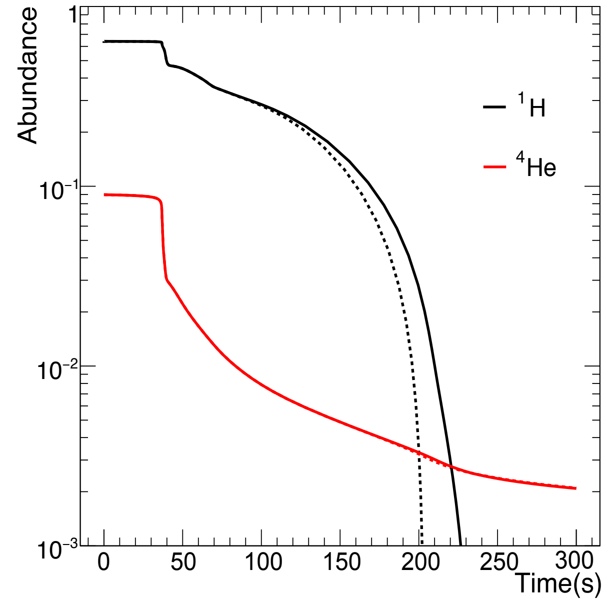
^{68}Se weak decay flow (hhez1)



H/He abundances: EXVAM** (dotted lines) / **standard weak rates** (full lines) for **^{68}Se and ^{72}Kr

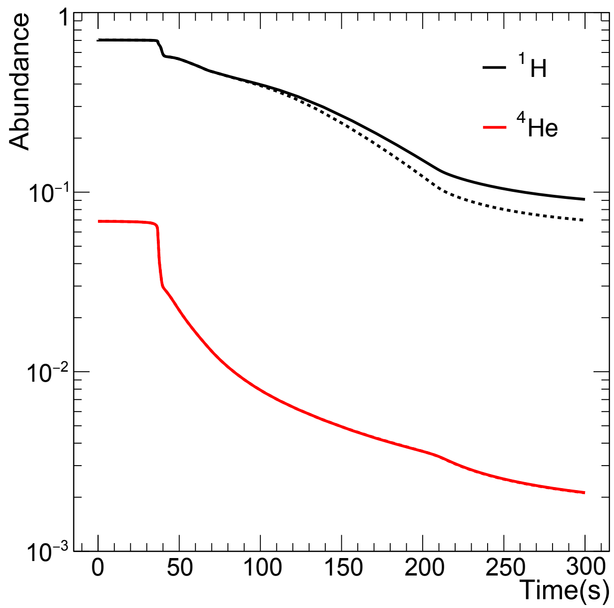
hhez1

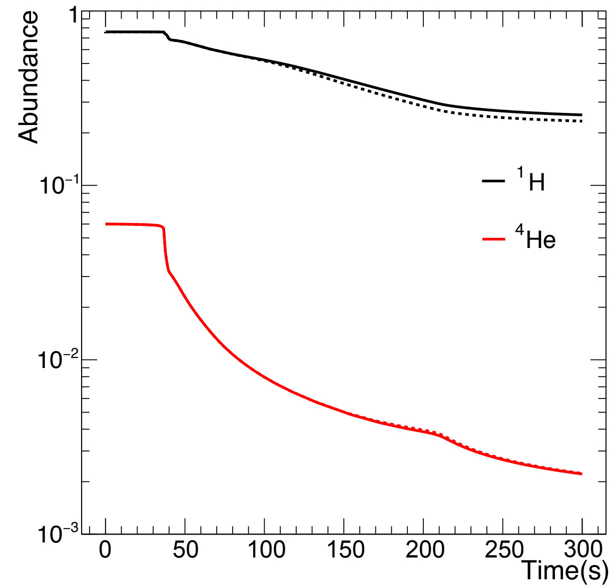




hhez2

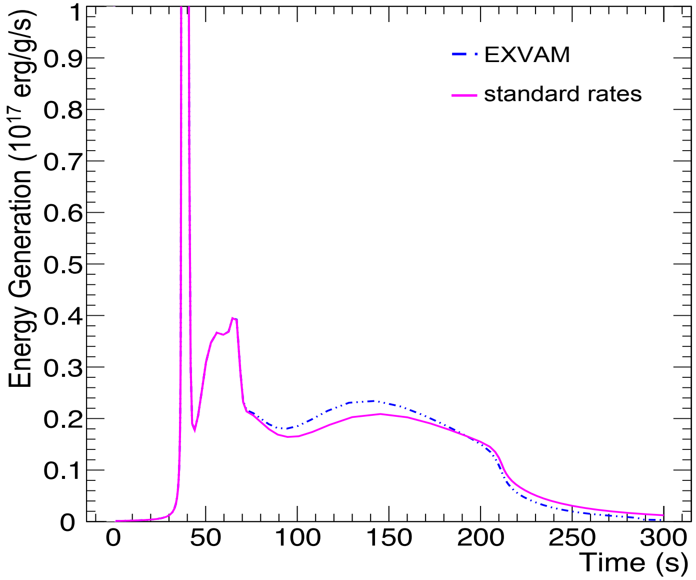
hhez3



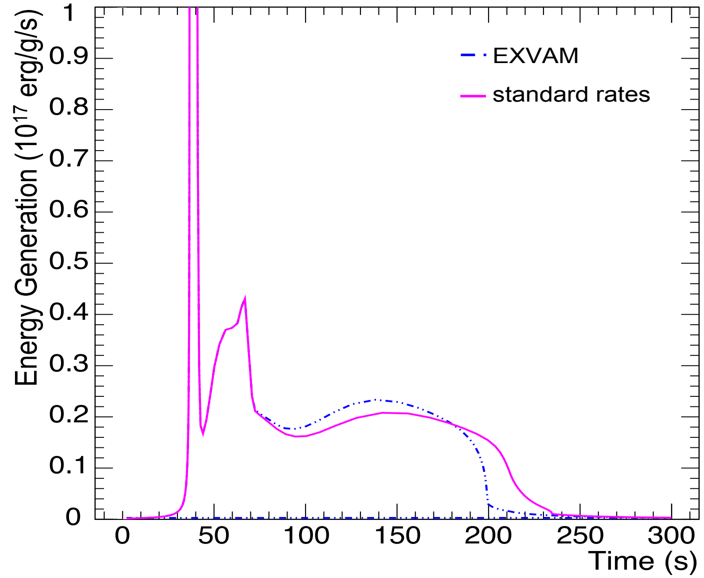


hhez4

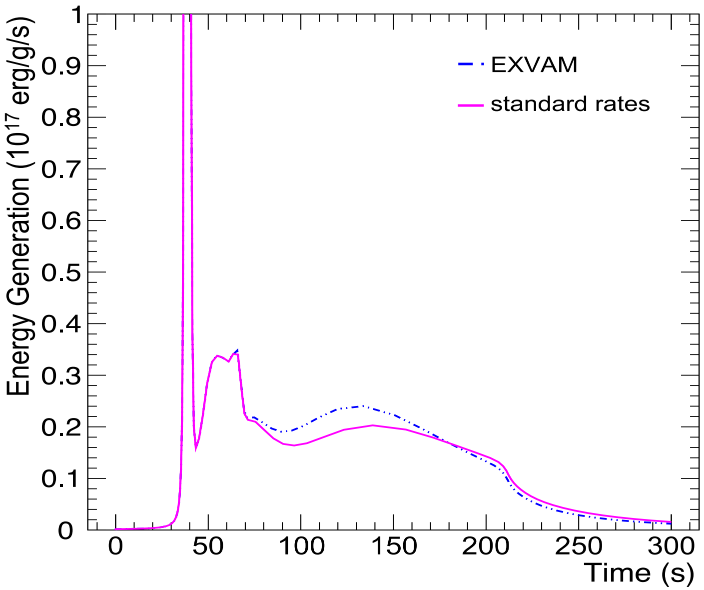
Energy generation rate



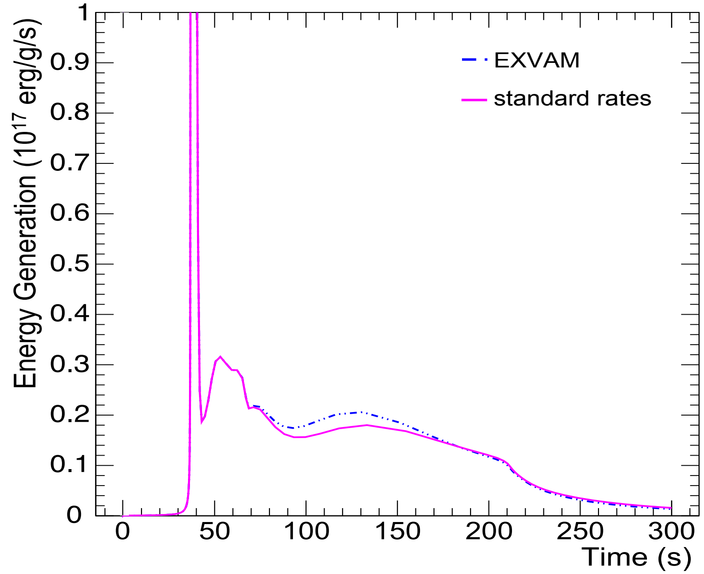
hhez1



hhez2



hhez3

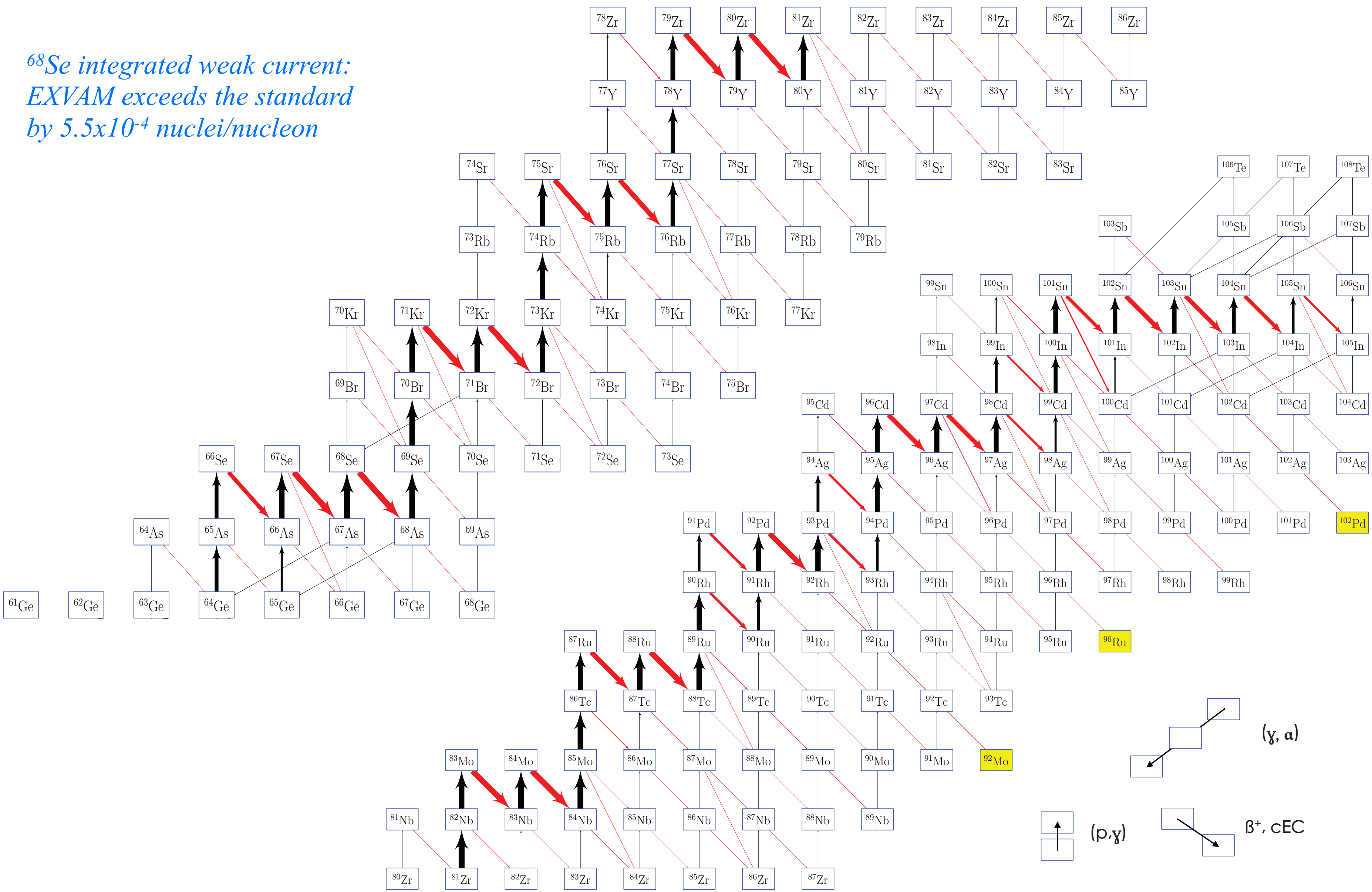


hhez4

Integrated reaction currents during an x-ray burst

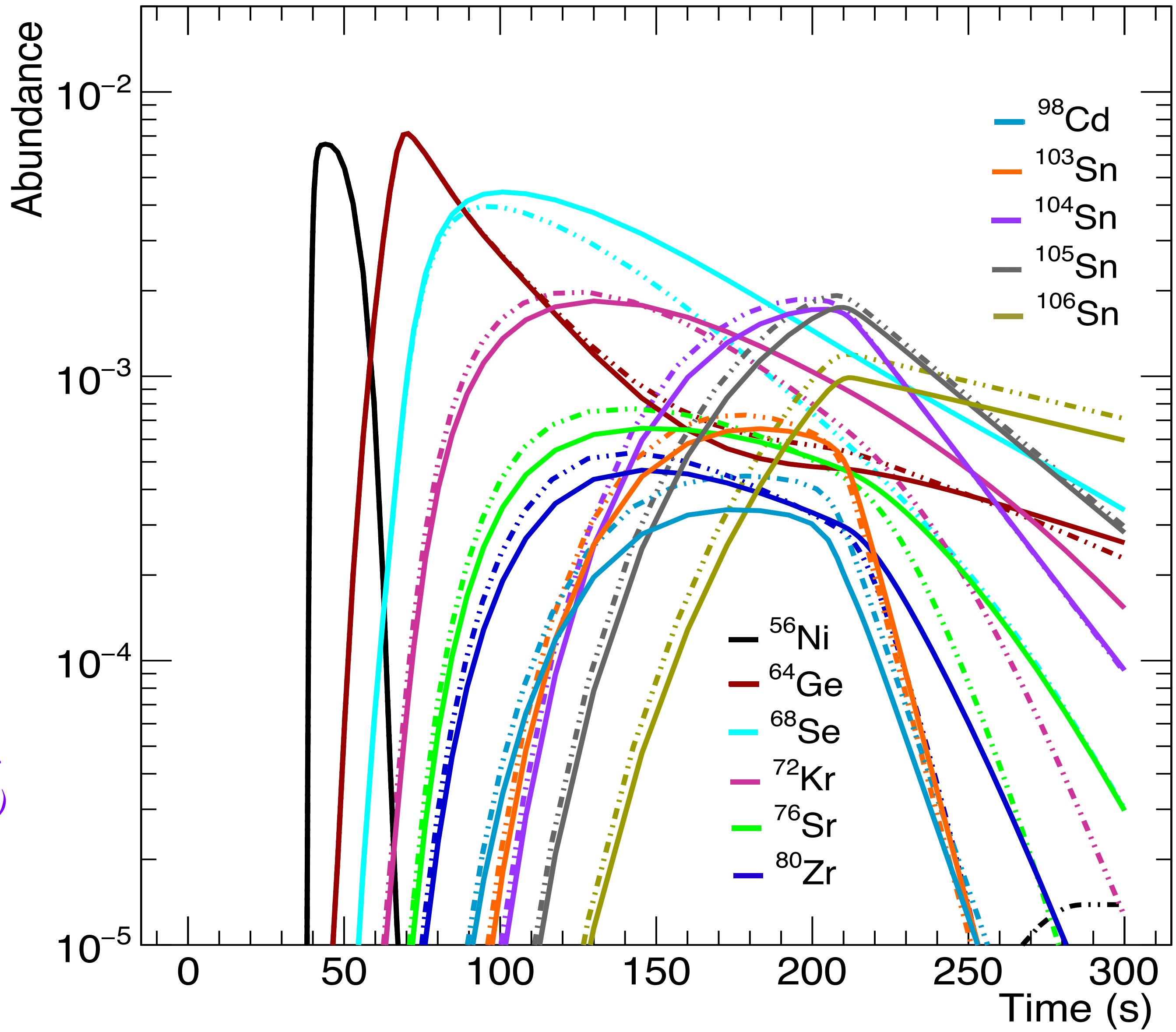
^{68}Se integrated weak current: EXVAM exceeds the standard by 5.5x10^{-4} nuclei/nucleon

hhez1



Abundances of waiting point nuclei & Sn isotopes

EXVAM (ddl) / standard (fl) - hhez1



Final abundances:
(standard/EXVAM)

^{68}Se	*3.8*
^{72}Kr	*3.3*

Summary

- ***complex*** **EXCITED VAMPIR beyond-mean-field model self-consistently describes**

shape-coexistence effects on

terrestrial and stellar weak interaction rates for A~70 proton-rich nuclei

rp-process waiting points: ^{68}Se and ^{72}Kr

- **impact of *^{68}Se and ^{72}Kr* EXVAM stellar weak interaction rates on rp-process nucleosynthesis and energetics:** ***significantly affect the energy production, burst duration, and final abundances***

In collaboration with:

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