Electron-Capture Rates for Exotic Nuclei at Stellar Environments

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• GT strengths in Ni and Fe isotopes by new shell model Hamiltonians, GXPF1J
• Electron capture rates for Ni, Fe, (Co, Mn) isotopes at stellar environments
• Type-Ia supernova explosions and nucleosynthesis
  \[ ^{56}\text{Ni}(e^{-}, \nu)^{56}\text{Co} \]
• rp-process and XRB (X-ray burst)
  \[ ^{55}\text{Ni}(e^{-}, \nu)^{55}\text{Co} \]
• Type-II core-collapse supernova explosions
  e-capture rates on Fe isotopes
○ New shell-model Hamiltonians in fp-shell:

**GXPF1**: Honma et al., PR C65 (2002); C69 (2004)

**KB3**: Caurier et al., Rev. Mod. Phys. 77, 427 (2005)

○ KB3G  $A = 47$-$52$   KB + monopole corrections

○ GXPF1  $A = 47$-$66$

• Spin properties of fp-shell nuclei are well described

$B(GT)$ for $^{58}$Ni  $g_A^{\text{eff}}/g_A^{\text{free}}=0.74$

M1 strength ($GXPF1J$)

$g_S^{\text{eff}}/g_S=0.75 \pm 0.2$

![Graphs and data points](image)

- Fujita et al.
- Comparison between theoretical predictions and experimental data.
Electron-capture rate in stellar environment

\[ \epsilon^- + Z\, A \rightarrow \nu + (Z-1)\, A \]

\[ T = 0: \mu + M(Z\, A) \geq M((Z-1)\, A) \]

\[ \mu \geq M(Z-1\, A) - M(Z\, A) \]

\[ \rho Y_e = 10^7 - 10^{10} \, \text{g/cm}^3 \]

\[ T = T_9 \times 10^9 \, \text{K} \]

Chemical potential of \( \epsilon^- (\mu) \) increases at high density.

\[ \lambda = \frac{\ln 2}{6146(s)} \sum_j B_j(GT) \int_0^\infty \omega p(Q_j + \omega)^2 F(Z, \omega) S_e(\omega) d\omega \]

\[ Q_j = (M_p c^2 - M_d c^2 - E_j)/m_e c^2 \]

\[ T = T_9 \times 10^9 \, \text{K}, \quad S_e(E_e) = \frac{1}{\exp[(E_e - \mu_e)/kT] + 1} \]

\[ \rho Y_e = \frac{1}{\pi^2 N_A} \left( \frac{m_e c}{\hbar} \right)^3 \int_0^\infty (S_e - S_p) p^2 dp \quad \mu_p = -\mu_e \]
Sasano et al.  
PRL 107, 202501 (2011)

\[ f_7/2 \rightarrow f_5/2 \]

**e-capture rates in stellar environments**

\[ \rho Y_e = 10^7 - 10^{10} \text{ g/cm}^3 \]

\[ T = T_9 \times 10^9 \text{ K} \]
**Type-Ia supernova explosion**

Accretion of matter to white-dwarf from binary star → supernova explosion when white-dwarf mass > Chandrasekhar limit → $^{56}\text{Ni}$ (N=Z) → $^{56}\text{Ni}$ (e$^-$, ν) $^{56}\text{Co}$ $Y_e=0.5 \rightarrow Y_e < 0.5$ (neutron-rich) → production of neutron-rich isotopes; more $^{58}\text{Ni}$

Decrease of e-capture rate on $^{56}\text{Ni}$ → less production of $^{58}\text{Ni}$.

*e-capture rates: GXPF1J < KB3G* $\leftarrow \rightarrow Y_e \text{(GXPF1J)} > Y_e \text{(KB3G)}$
Problem of over-production of $^{58}\text{Ni}$

and ignition densities to put new constraints on the above key quantities. The abundance of the Fe group, in particular of neutron-rich species like $^{48}\text{Ca}$, $^{50}\text{Ti}$, $^{54}\text{Cr}$, $^{54,58}\text{Fe}$, and $^{58}\text{Ni}$, is highly sensitive to the electron captures taking place in the central layers. The yields obtained from such a slow central NSE calculation by Famiano and Ye show decreasing trends for $^{58}\text{Ni}/^{56}\text{Ni}$.

Ratio between $^{58}\text{Ni}/^{56}\text{Ni}$

Graphs showing the decrease in $^{58}\text{Ni}/^{56}\text{Ni}$ for different models and densities.
rp-process and X-ray burst

\((p, \gamma) \; \& \; \beta^+\text{-decay/e-capture}\)

\[\rightarrow ^{50}\text{Fe}(e^+,\nu)^{50}\text{Mn} \quad ^{50}\text{Fe}(e^-,\nu)^{50}\text{Mn}\]

\[\rightarrow ^{55}\text{Ni}(e^-,\nu)^{55}\text{Co}\]

Parikh et al., PPNP 69, 225 (2013)
X-ray burst

\[ ^{56}\text{Ni} \rightarrow ^{56}\text{Cu} \]

- e-capture and beta-decay rates with KBF:
  Langanke and Martinez-Pinedo, Atomic Data and Nuclear Data Tables 79, 1 (2001)

Sn-Sb-Te cycle

\[ ^{60}\text{Zn}, ^{64}\text{Ge}, ^{68}\text{Se} \]
Type-II Core-Collapse SNe

Rates for $^{54}\text{Fe}$, $^{55}\text{Fe}$, $^{56}\text{Fe}$, $^{57}\text{Fe}$

GXPF1J vs. KBF

Langanke and Martinez-Pinedo, RMP 75 (2003)
Rates for $^{54}\text{Fe}$, $^{56}\text{Fe}$

**GXPF1J vs. KBF**

- **$^{54}\text{Fe}(e^-, \nu)^{54}\text{Mn}$**
  - $\rho_{Y_e}=10^7$
  - $\rho_{Y_e}=10^8$
  - $\rho_{Y_e}=10^9$

- **$^{56}\text{Fe}(e^-, \nu)^{56}\text{Mn}$**
  - $\rho_{Y_e}=10^7$
  - $\rho_{Y_e}=10^8$
  - $\rho_{Y_e}=10^9$

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**e-capture rates**

- **GXP > KBF** for $^{54,55,56}\text{Fe}$
  - $Y_e \downarrow$ for GXP

- **GXP < KBF** for $^{57}\text{Fe}$
  - $Y_e \uparrow$ for GXP
$^{60}\text{Co} \rightarrow ^{60}\text{Fe}$

$\rho Y_e = 10^7 \sim 10^{10}$

- Langanke and Martinez-Pinedo, Atomic and Nucl. Data Tables (2001)
Summary

• A new shell model Hamiltonian GXPF1J well describes the spin responses in fp-shell niclei
  → new GT strengths in Ni and Fe isotopes

• GT strengths and electron capture rates in $^{56}\text{Ni}$, $^{55}\text{Co}$, $^{58}\text{Ni}$, $^{60}\text{Ni}$ are well described by GXPF1J.
  Suzuki, Honma, Mao, Otsuka, Kajino, PR C83, 044619 (2011)

• Effects on Type Ia SNe nucleosynthesis, rp-process and XRB, Type-II core-collapse SNe are discussed

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