Electron-Capture Rates for Exotic Nuclei at Stellar Environments

Toshio Suzuki
Nihon University

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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

  $^{56}\mathrm{Ni}(\mathrm{e}^-,\nu)^{56}\mathrm{Co}$

- rp-process and XRB (X-ray burst)

  $^{55}\mathrm{Ni}(\mathrm{e}^-,\nu)^{55}\mathrm{Co}$

- 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

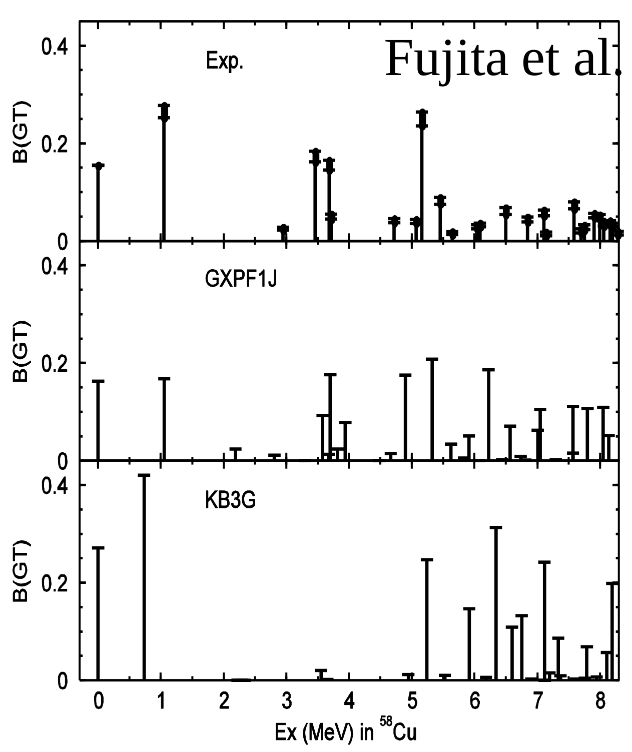
- **Spin properties of fp-shell nuclei are well described**

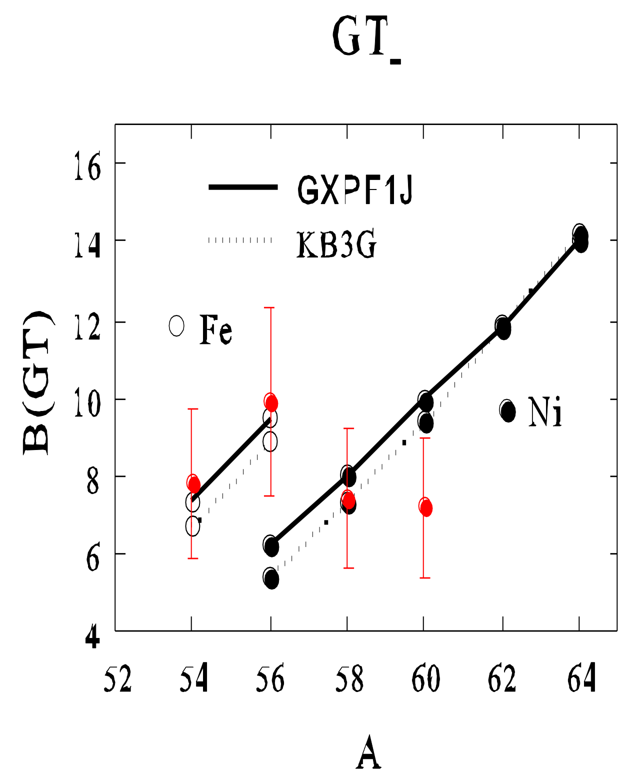
B(GT$_-$) for ^{58}Ni

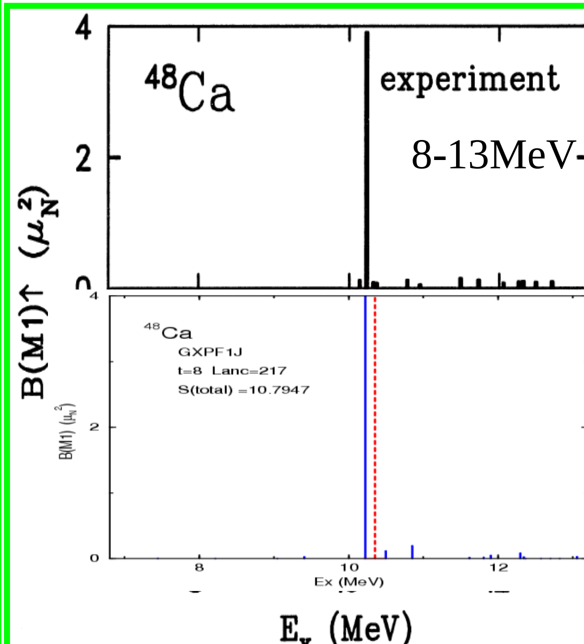
$g_A^{eff}/g_A^{free}=0.74$

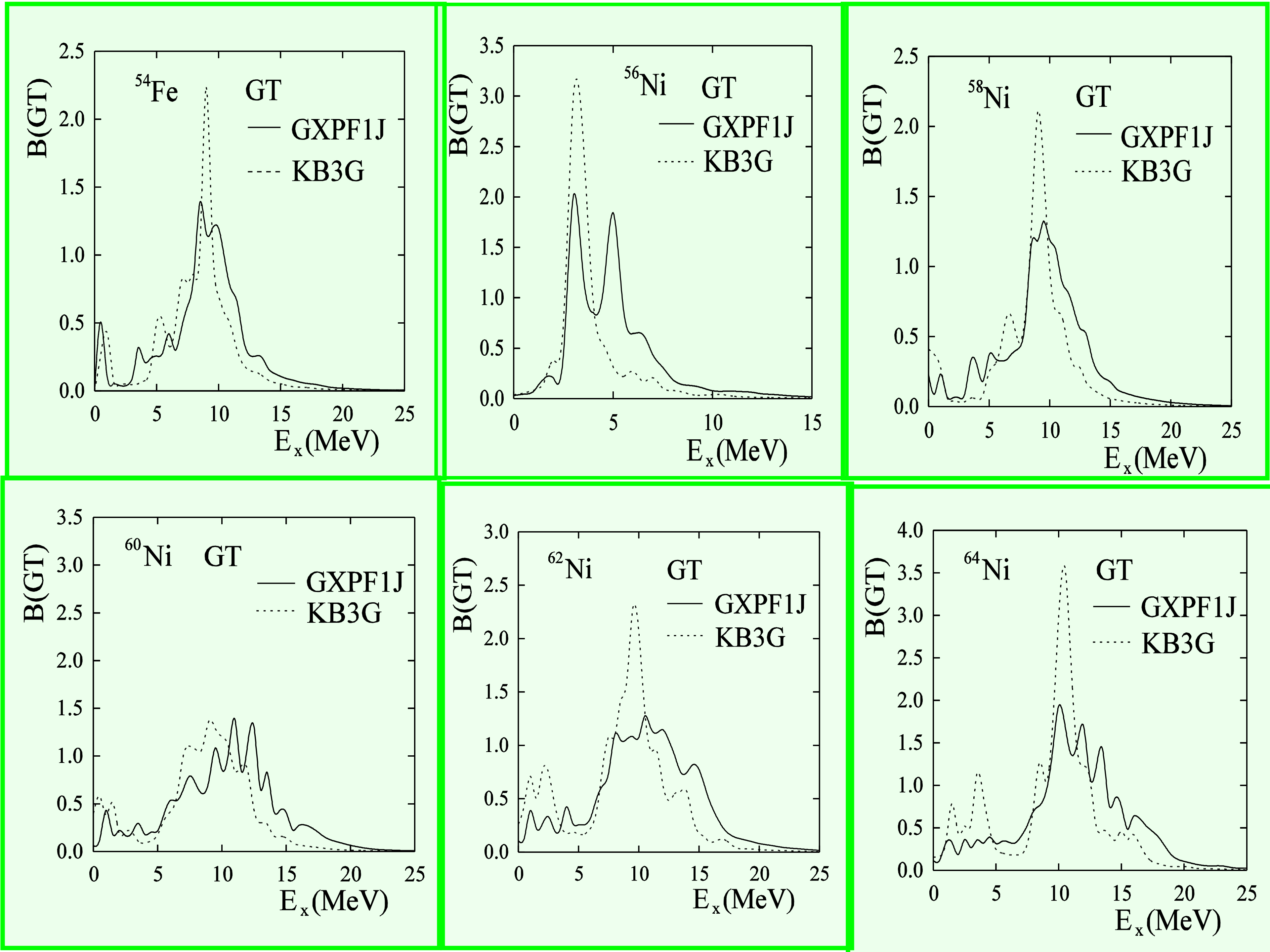
M1 strength (GXPF1J)

$g_S^{eff}/g_S=0.75\pm0.2$



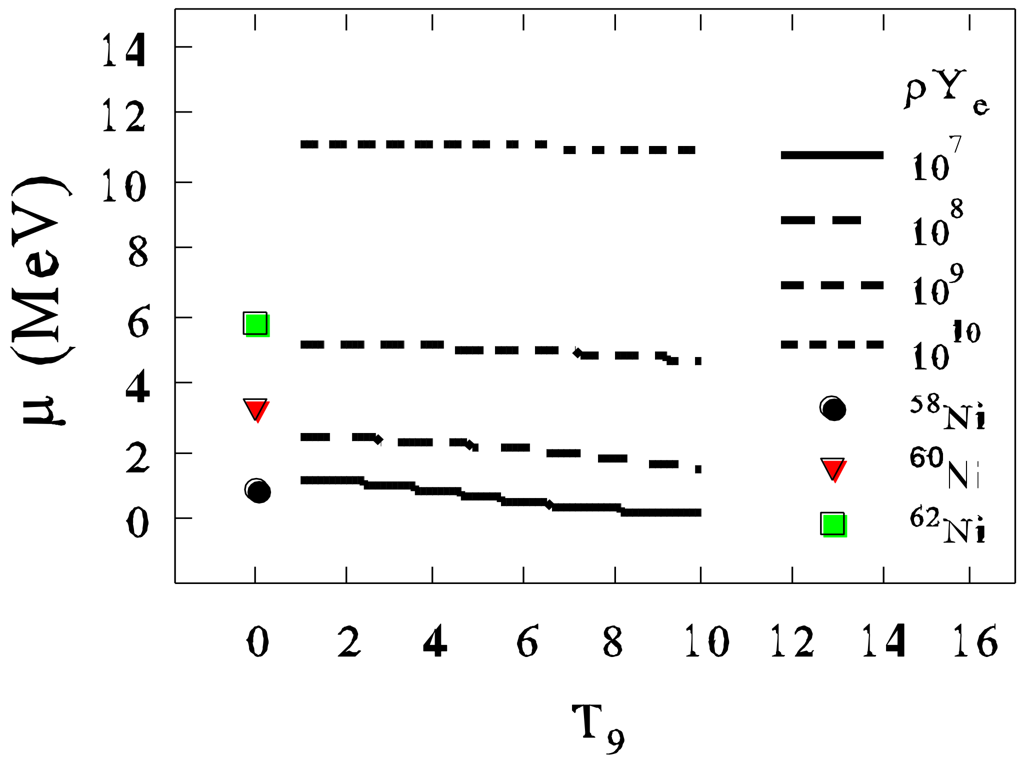






54Fe GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
56Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
58Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
60Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
62Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
64Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)

●Electron-capture rate in stellar environment



$$\mathbf{e^- + {}_Z A \rightarrow \nu + {}_{Z-1}A}$$

$$\mathbf{T = 0: \quad \mu + M({}_Z A) \geq M({}_{Z-1}A)}$$

$$\mathbf{\mu \geq M({}_{Z-1}A) - M({}_Z A)}$$

$$\rho Y_e = 10^7 - 10^{10} \ \ g/cm^3$$

$$T = T_9 \times 10^9 K$$

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

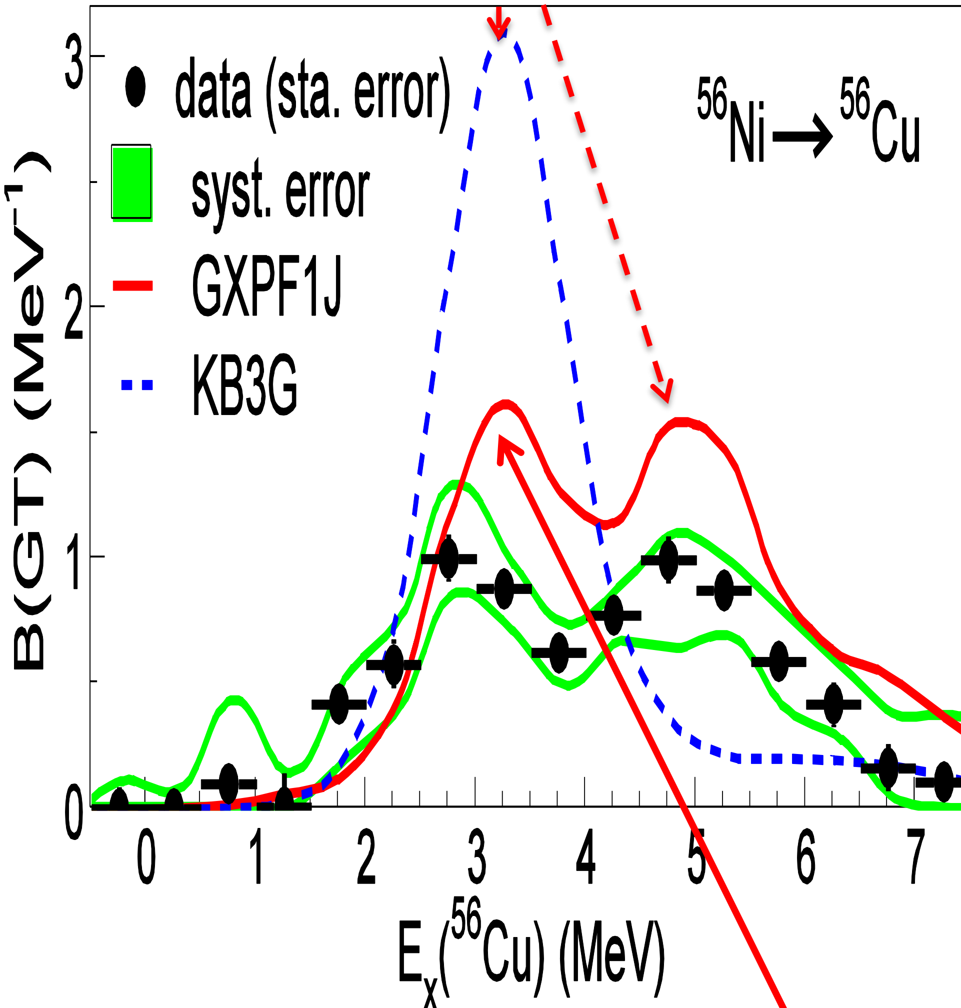
$$Q_j = (M_p c^2 - M_d c^2 - E_j)/m_e c^2$$

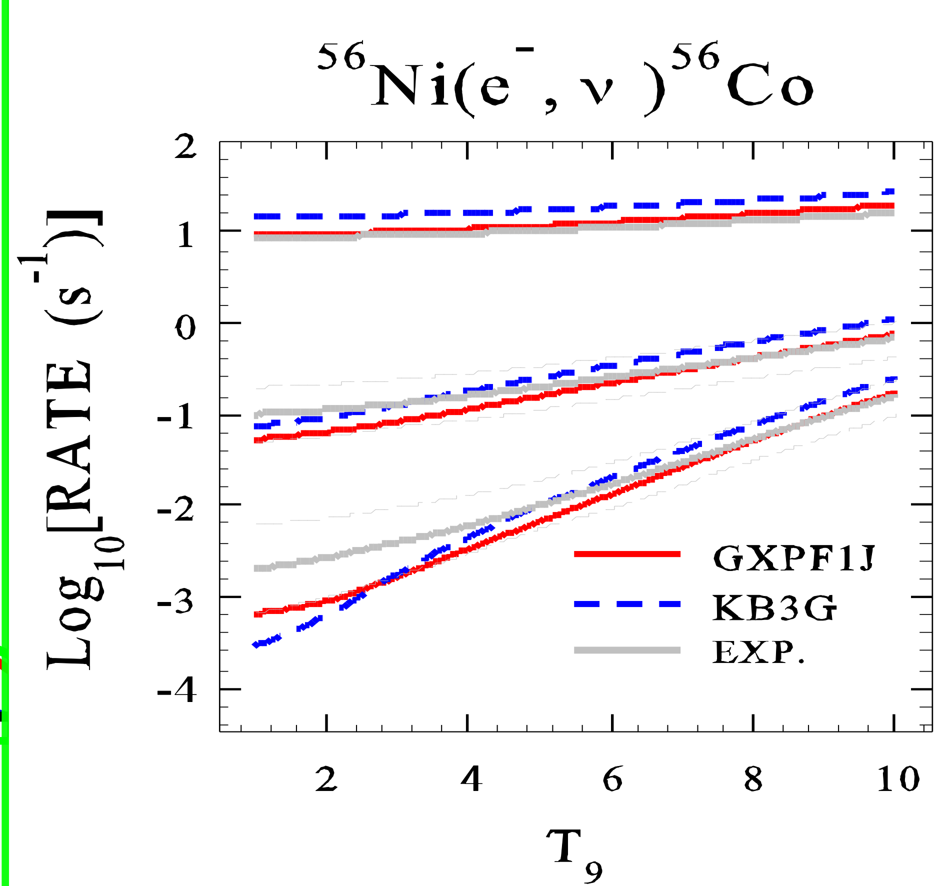
$$T = T_9 \times 10^9 K, \qquad S_e(E_e) = \frac{1}{\exp[(E_e - \mu_e)/kT] + 1}$$

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

Chemical potential of e⁻ (μ) increases at high density f7/2 -> f5/2

e-capture rates in stellar environments





f7/2 -> f7/2

f7/2 -> f5/2

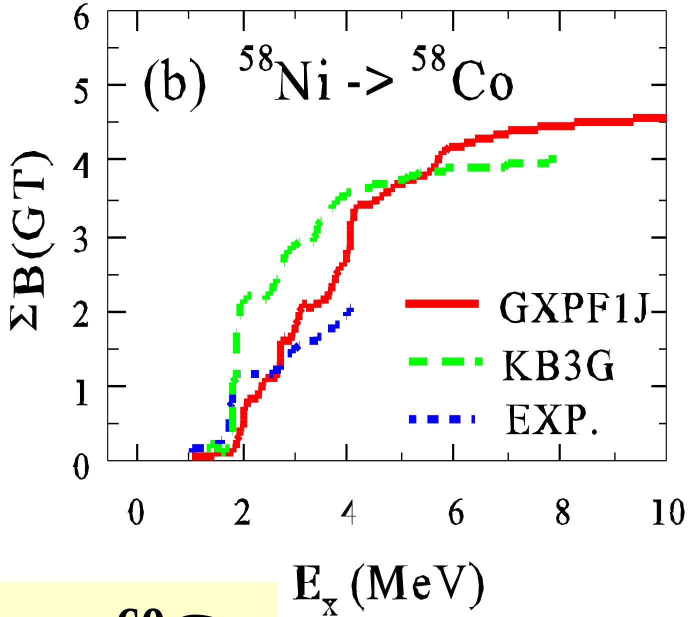
Sasano et al.

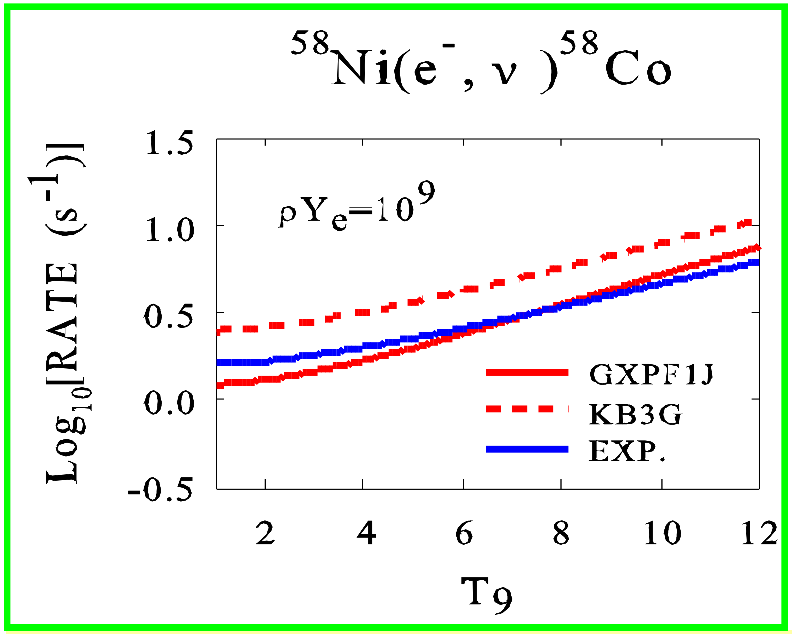
PRL 107, 202501 (2011)

$$\rho Y_e = 10^7 - 10^{10}\ g/cm^3$$

$$T = T_9 \times 10^9 K$$

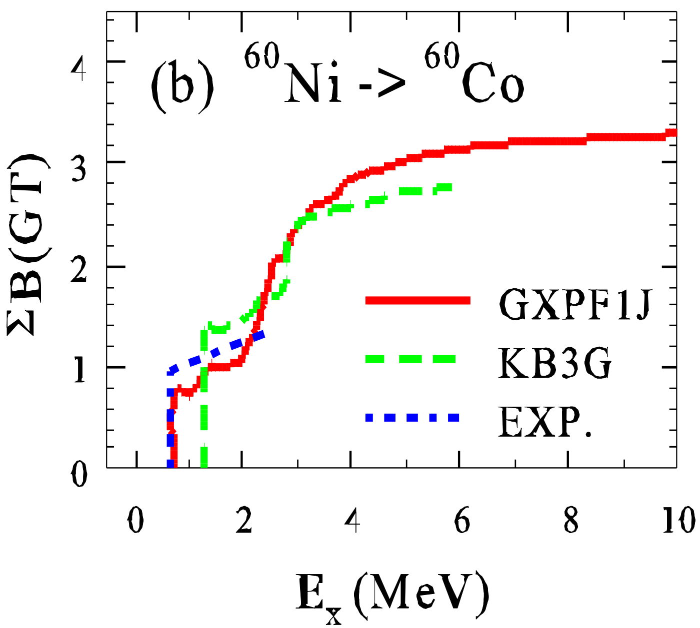
$^{58}Ni \rightarrow {}^{58}Co$

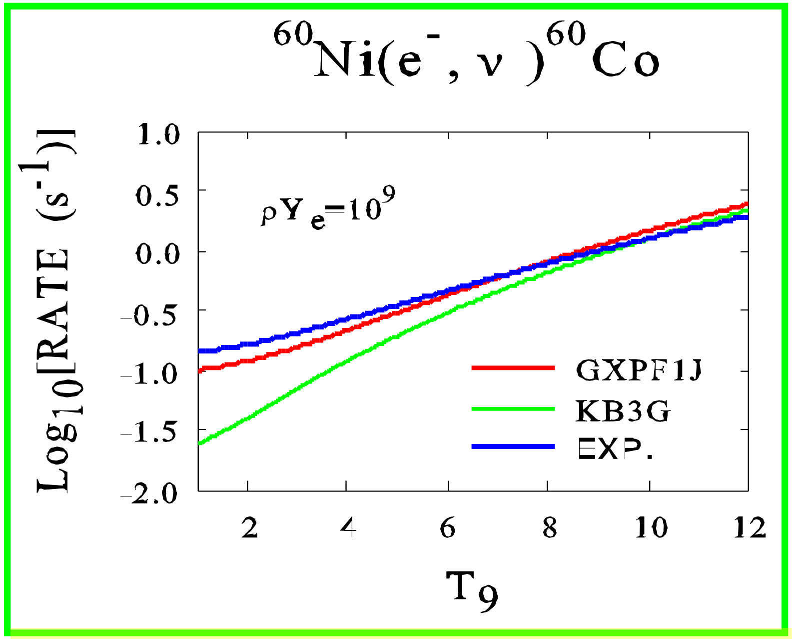




Exp: Hagemann et al., PL B579 (2004)

$^{60}Ni \rightarrow {}^{60}Co$





Exp: Anantaraman et al., PR C78 (2008)

Type-Ia supernova explosion

Accretion of matter to white-dwarf from binary star

→ supernova explosion when white-dwarf mass > Chandrasekhar limit

→ ^{56}Ni (N=Z)

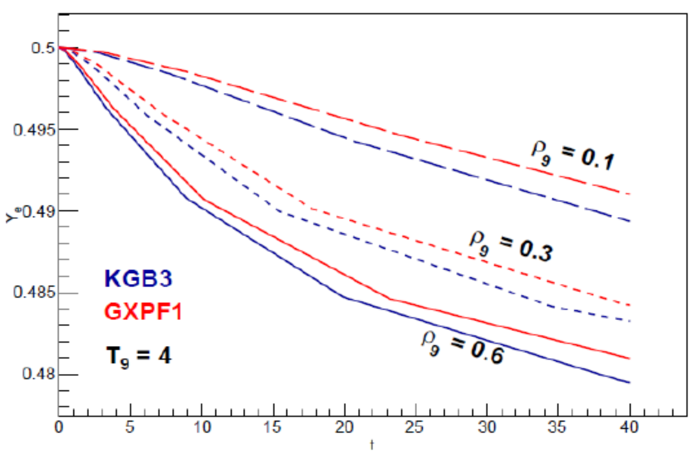
→ ^{56}Ni (e^-, ν) ^{56}Co Y_e =0.5 → Y_e < 0.5 (neutron-rich)

→ production of neutron-rich isotopes; more ^{58}Ni

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

NSE (Nuclear Statistical Equilibrium) calculation

GXPF1 計算ではKB3 計算に比べて、電子捕獲の強度が大幅に下がる（次ページ）ので、電子が減らない。

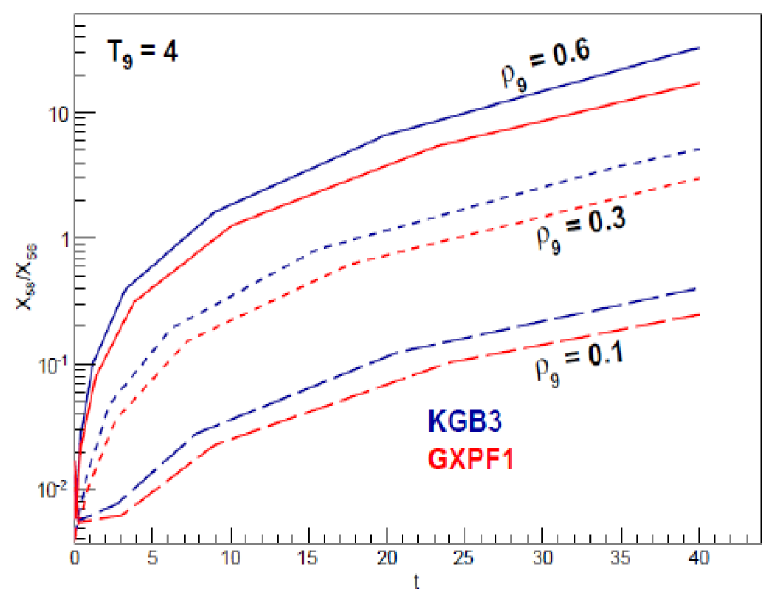


e-capture rates:

GXPF1J < KB3G

←→ Y_e (GXPF1J) > Y_e (KB3G)

Ratio between ^{58}Ni / ^{56}Ni



Famiano

Problem of over-production of ^{58}Ni

The Astrophysical Journal Supplement Series, 125:439–462, December

NUCLEOSYNTHESIS IN CHANDRASEKHAR MASS MODELS FOR TYPE Ia SUPERNOVAE AND CONSTRAINTS ON PROGENITOR SYSTEMS AND BURNING-FRONT PROPAGATION

Koichi Iwamoto,[1,2,3] Franziska Brachwitz,[4] Ken'ichi Nomoto,[1,2,3] Nobuhiro Kishimoto,[1]
Hideyuki Umeda,[2,3] W. Raphael Hix,[3,5] and Friedrich-Karl Thielemann[3,4,5]

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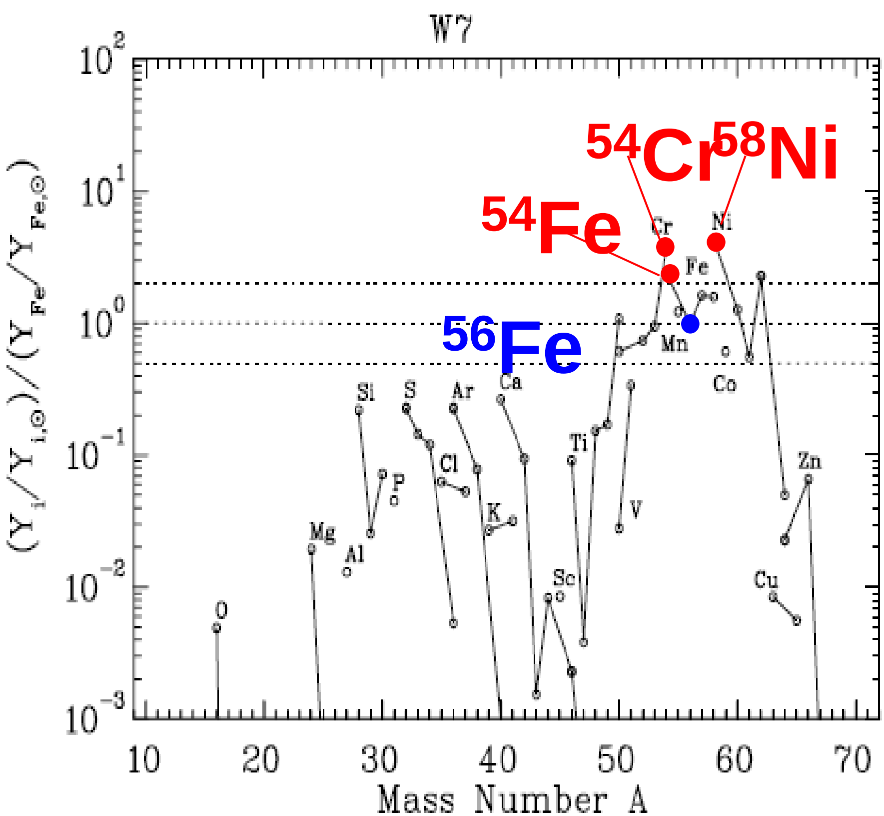
and ignition densities to put new constraints on the above key quantities. The abundance of the Fe group, in particular of neutron-rich species like ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{54,58}Fe, and ^{58}Ni, is highly sensitive to the electron captures taking place in the central layers. The yields obtained from such a slow central



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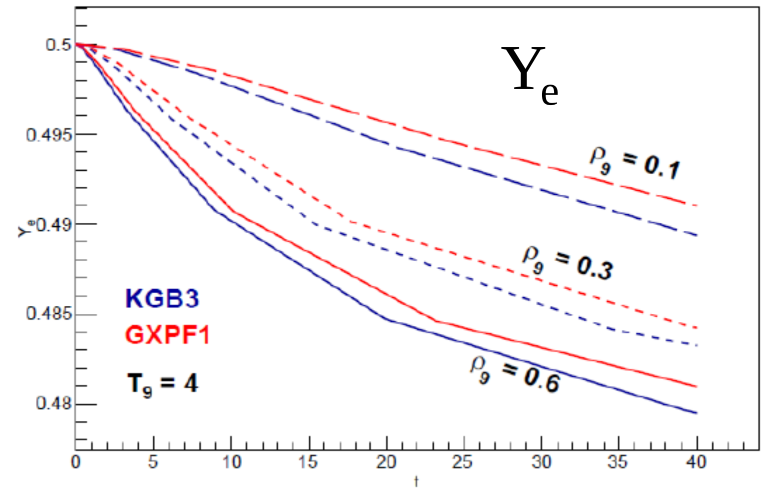
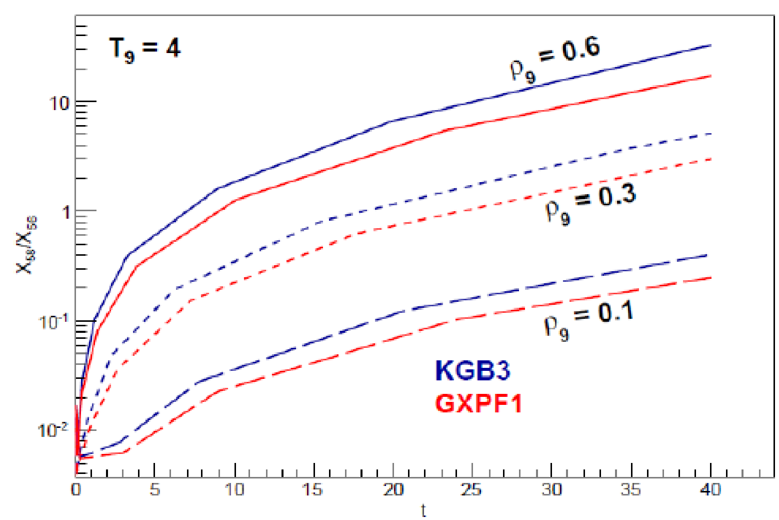
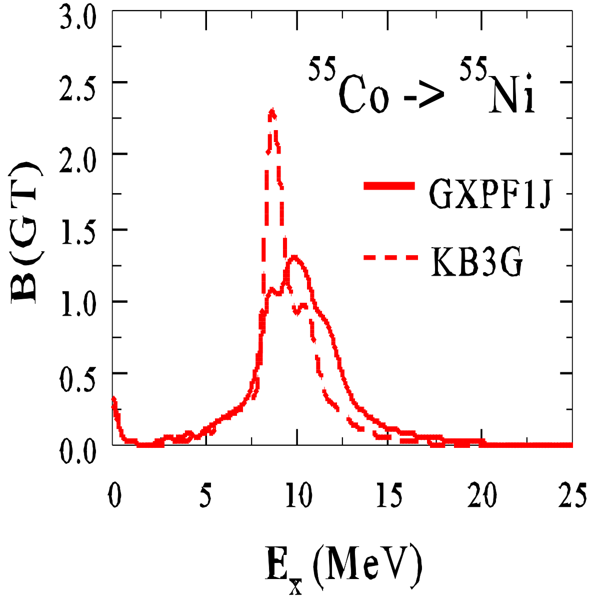
NSE(Nuclear Statistical Equilibrium) calculation



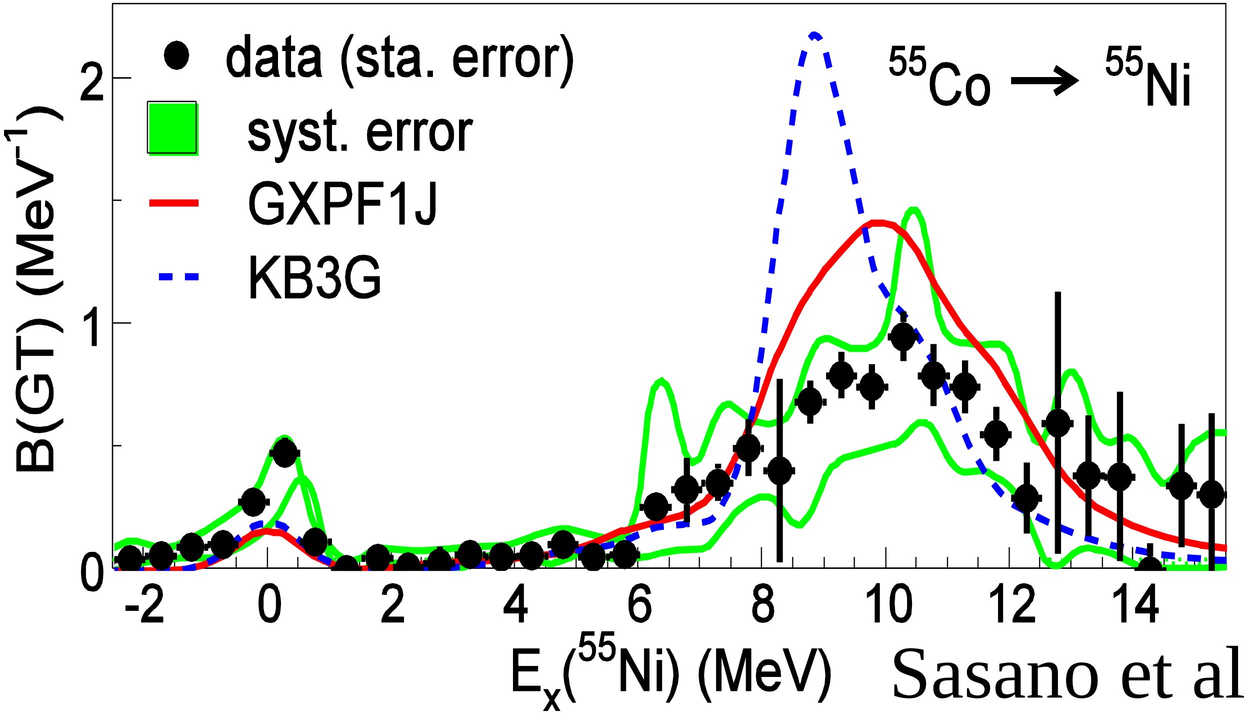
Ratio between ^{58}Ni / ^{56}Ni

GXPF1 -> ^{58}Ni/^{56}Ni decreases

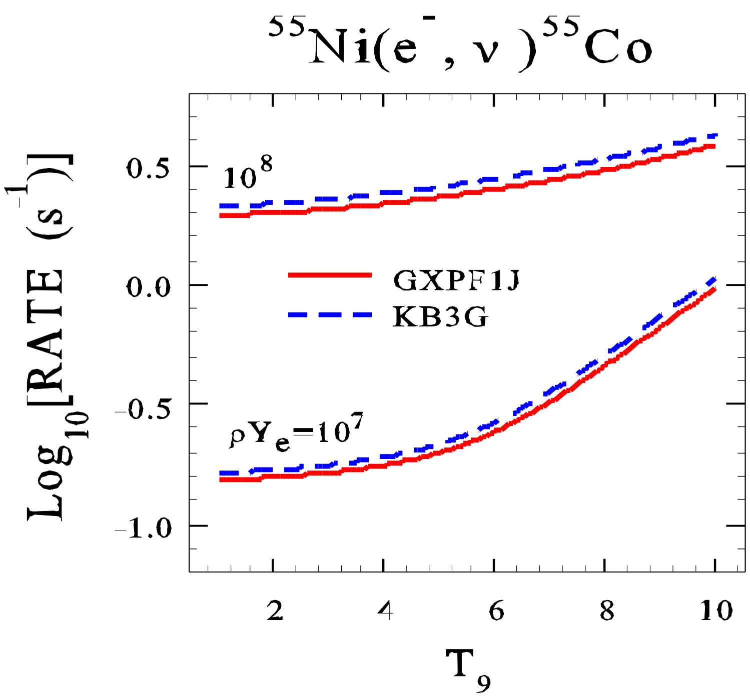




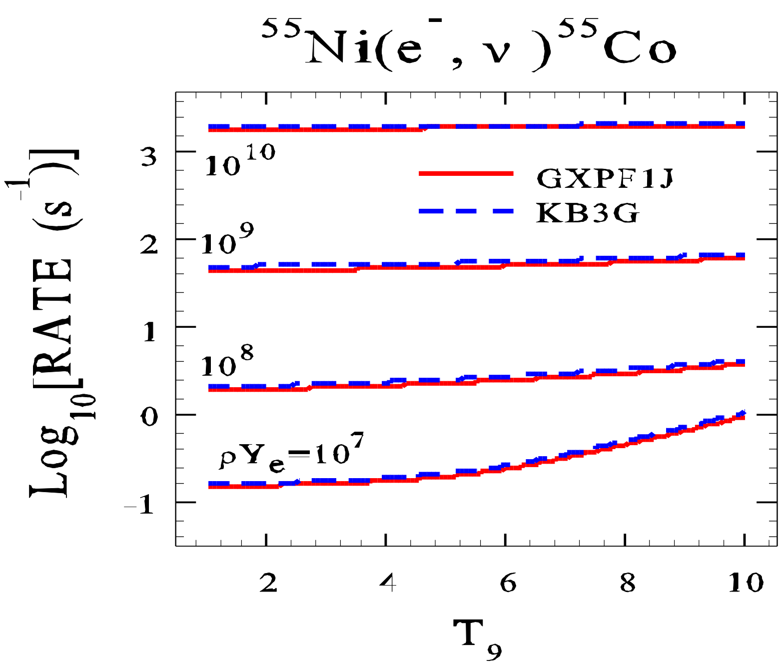
55Co -> 55Ni
GXPF1J
KB3G
B(GT)
Ex (MeV)



data (sta. error)
syst. error
GXPF1J
KB3G
55Co → 55Ni
B(GT) (MeV-1)
Ex(55Ni) (MeV)
Sasano et al.



55Ni(e-, ν)55Co
10^8
ρYe=10^7
GXPF1J
KB3G
Log10[RATE (s-1)]
T9



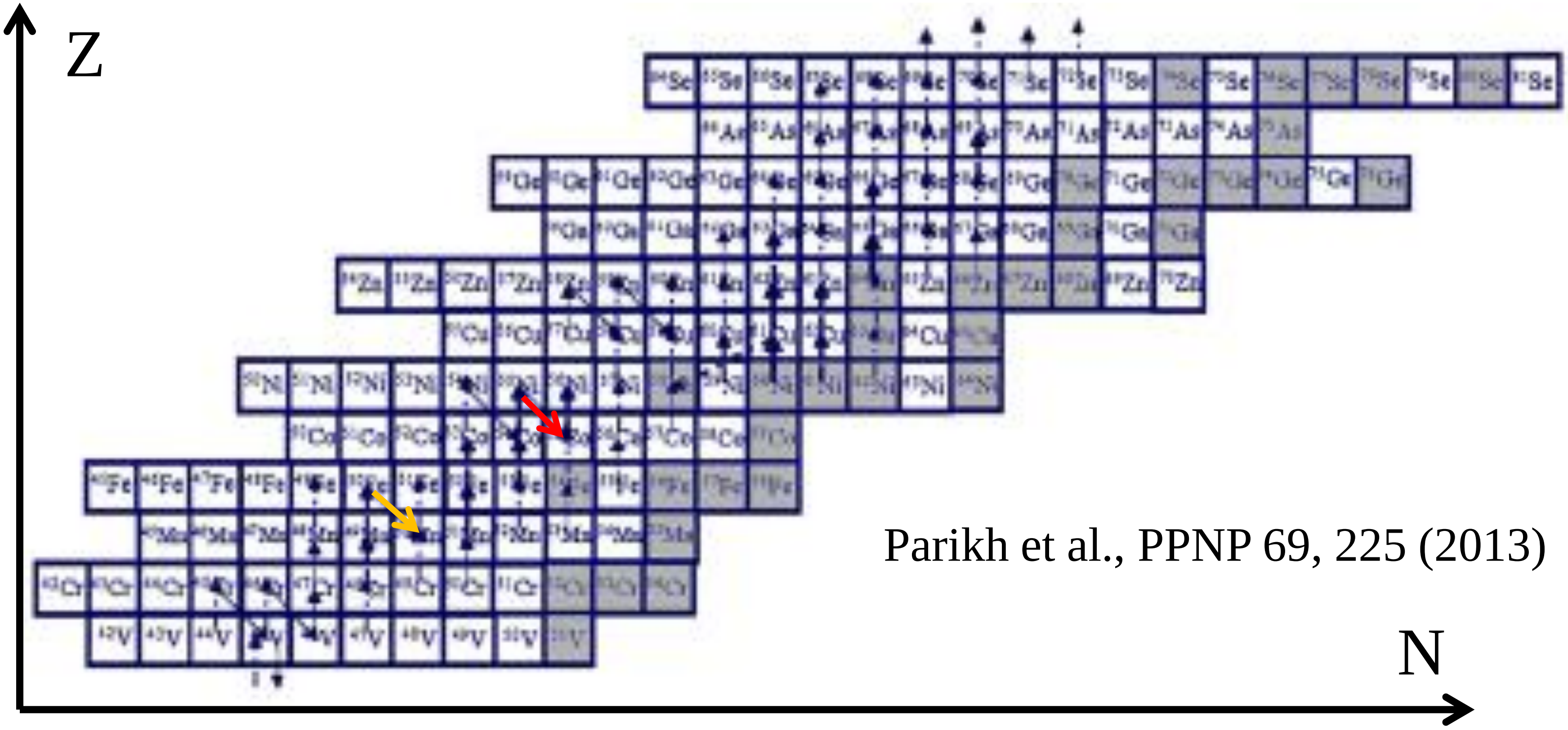
55Ni(e-, ν)55Co
10^10
10^9
10^8
ρYe=10^7
GXPF1J
KB3G
Log10[RATE (s-1)]
T9

rp-process and X-ray burst

(p, γ) & β^+-decay/e-capture

→ $^{50}Fe(,e^+\nu)^{50}Mn$ $^{50}Fe(e^-,\nu)^{50}Mn$

→ $^{55}Ni(e^-,\nu)^{55}Co$



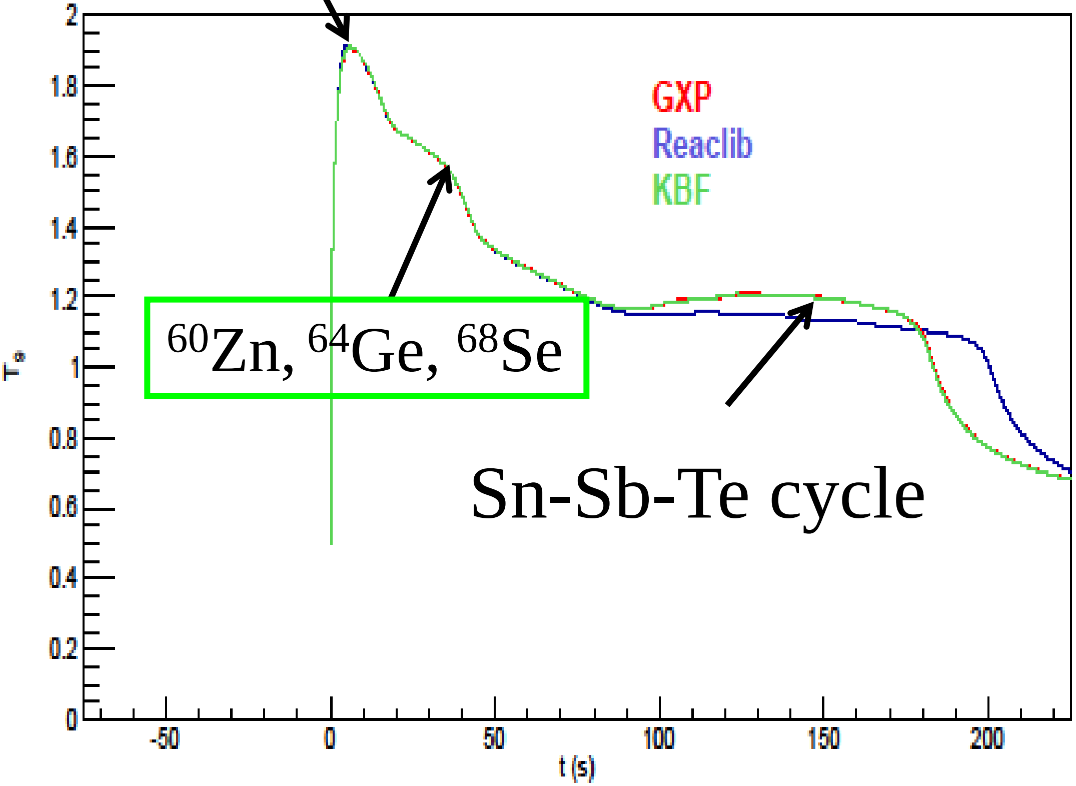
Parikh et al., PPNP 69, 225 (2013)

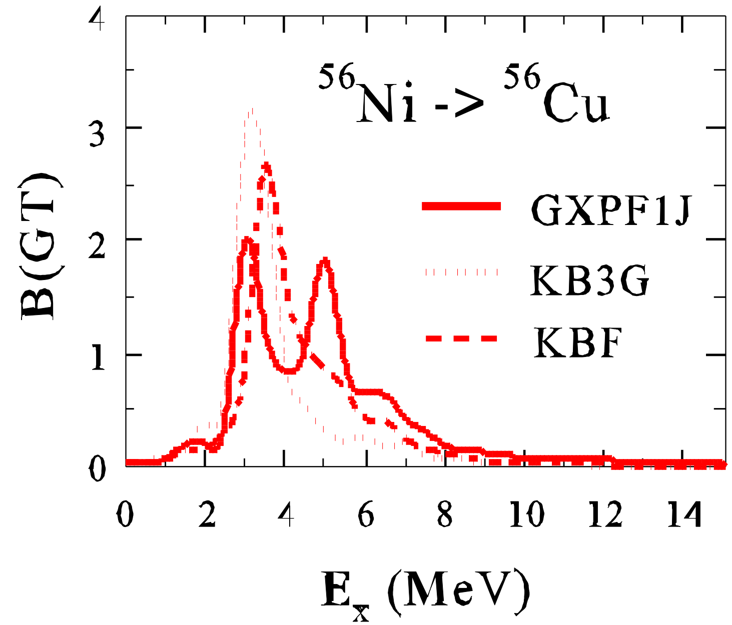
X-ray burst

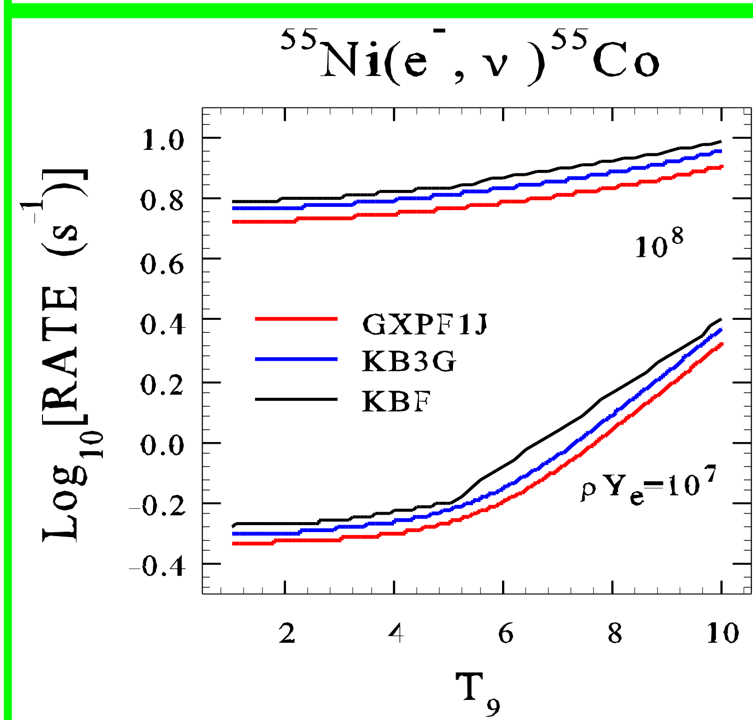
GXP_rp.mov   KBF_rp.mov

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

^{56}Ni







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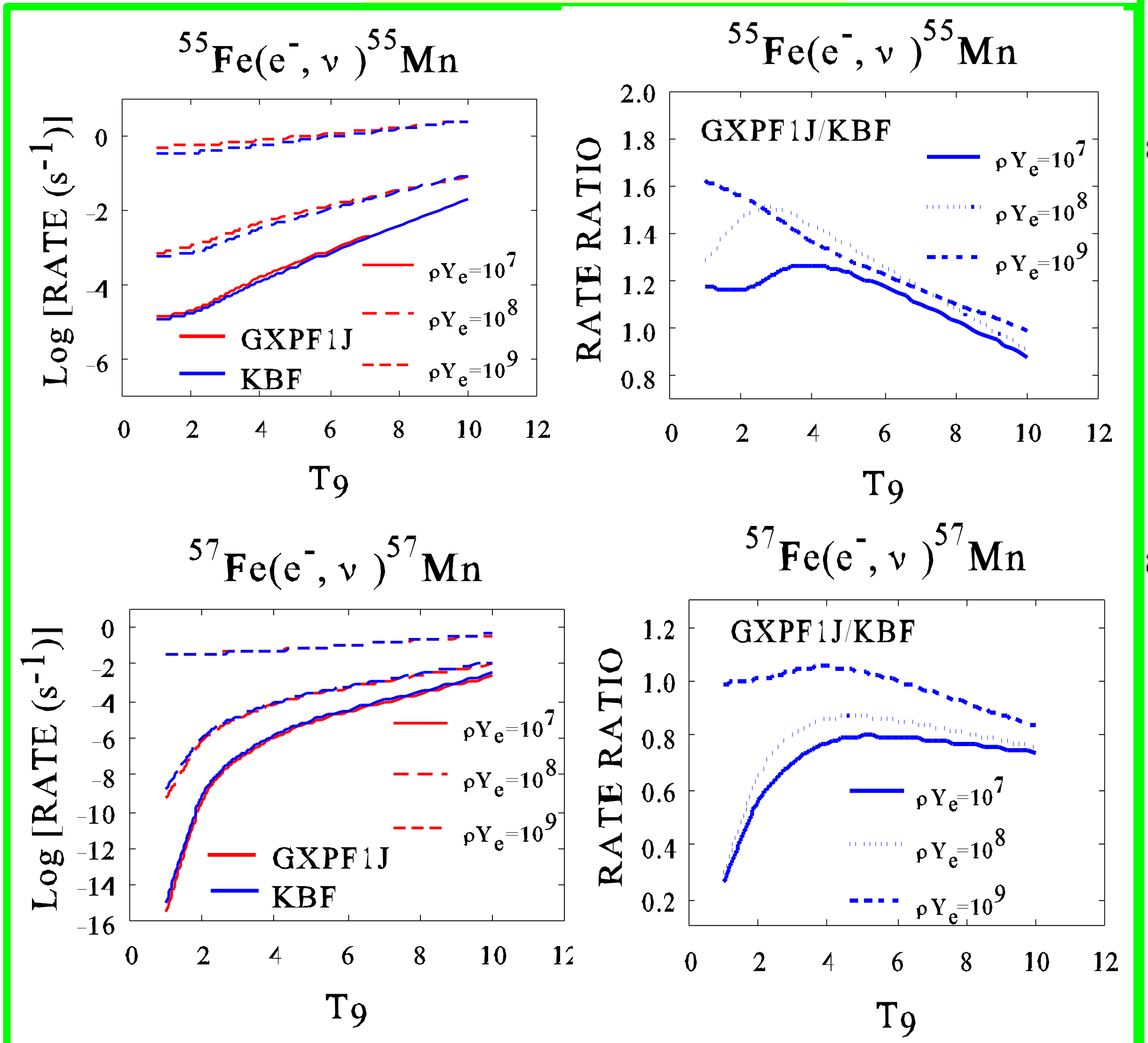
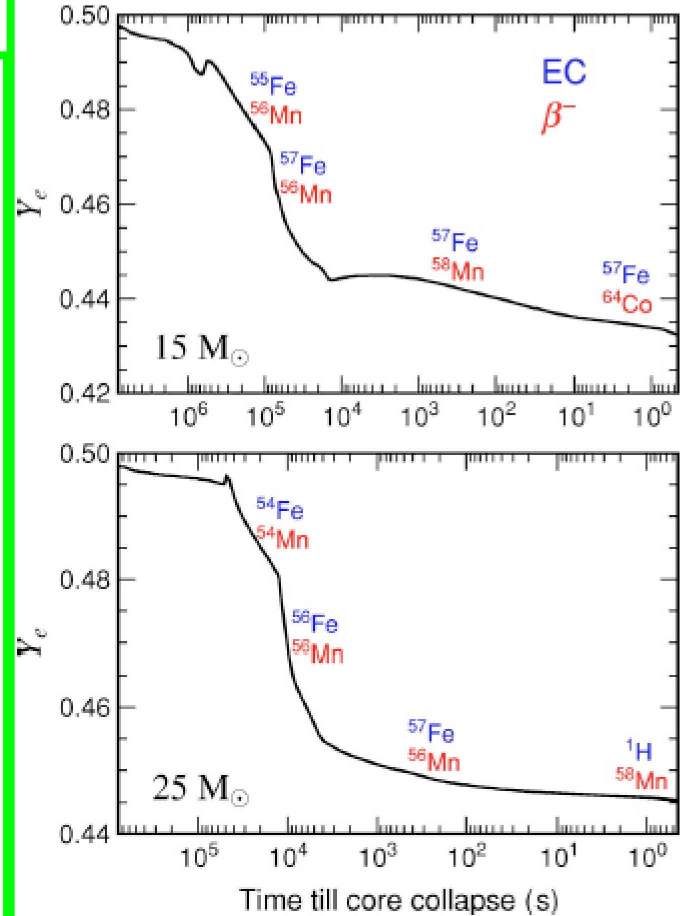
Type-II Core-Collapse SNe

Rates for ^{54}Fe, ^{55}Fe, ^{56}Fe, ^{57}Fe

GXPF1J vs. KBF



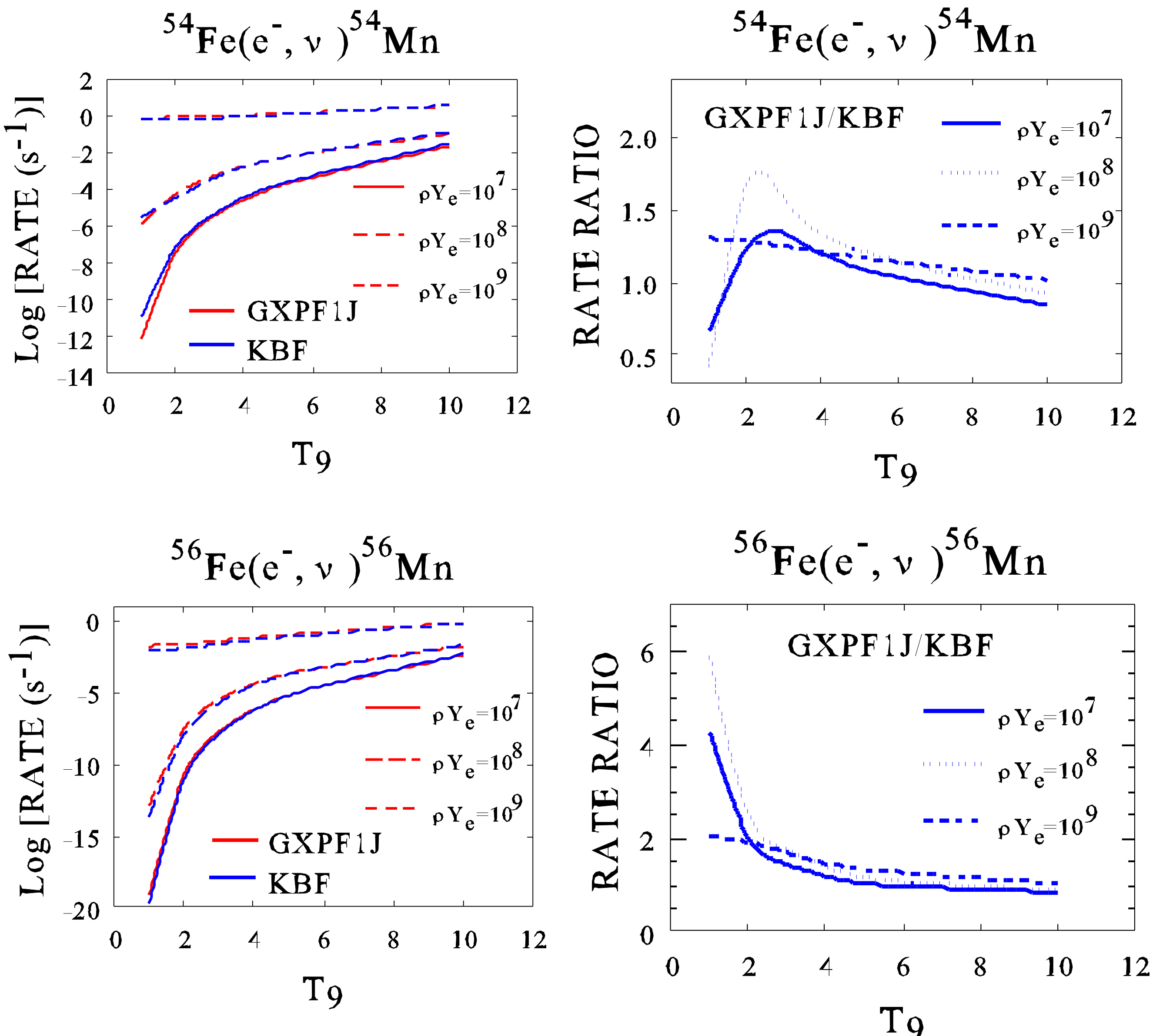
KBF



Langanke and Martinez-Pinedo, RMP 75 (2003)

Rates for ^{54}Fe, ^{56}Fe

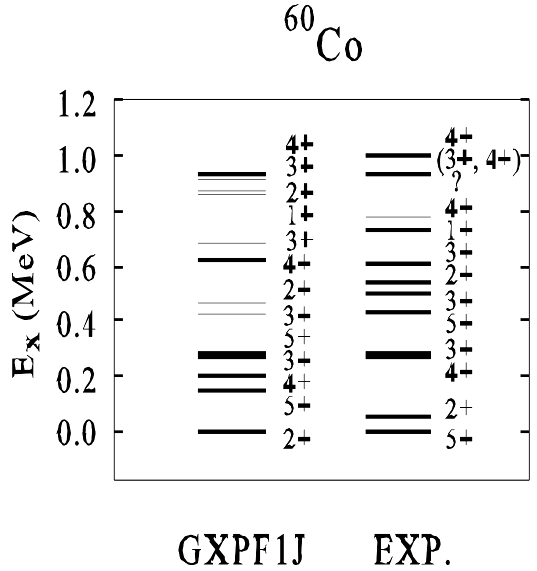
GXPF1J vs. KBF

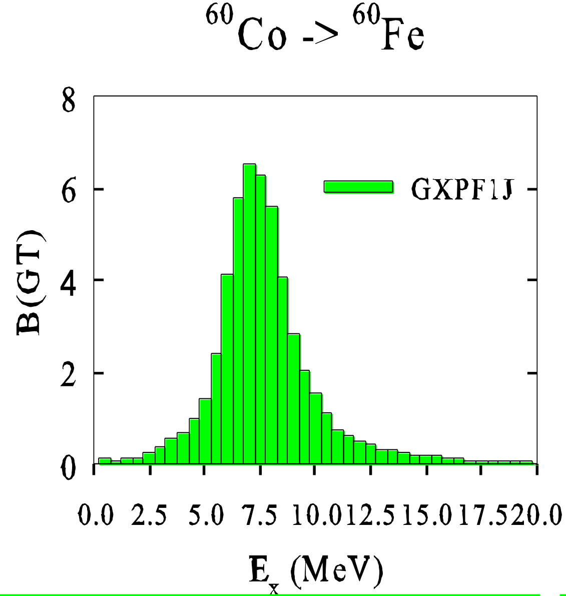


e-capture rates

GXP > KBF
for $^{54,55,56}Fe$
Ye ↓ for GXP

GXP < KBF
for ^{57}Fe
Ye ↑ for GXP

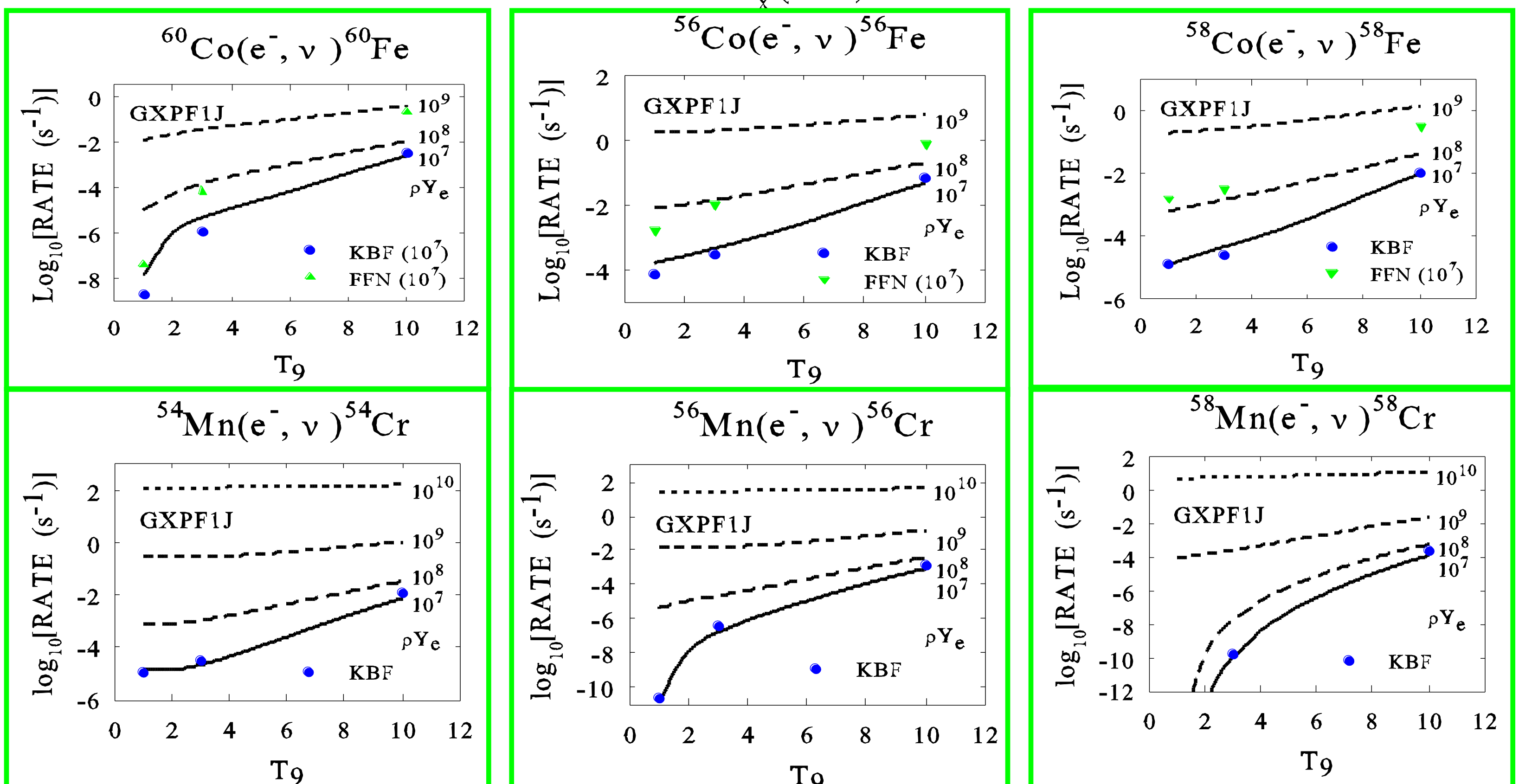




$\rho Y_e = 10^7 \sim 10^{10}$

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

▼ FFN: Astrophys. J. Suppl. (1982)



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}Ni, ^{55}Co, ^{58}Ni , ^{60}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**

Collaborators

M. Honma[a], T. Otsuka[b], T. Kajino[c,d], M. Famiano

[a]University of Aizu

[b]Department of Physics and CNS, University of Tokyo

[c]Department of Astronomy, University of Tokyo

[d]National Astronomical Observatory of Japan