Beta Decay and Electron Capture Reactions in Stars

Toshio Suzuki
Nihon University

EENEN10
June, 2010

1. Electron Capture Reactions in Ni Isotopes
   - GT strengths in Ni and Fe isotopes by GXPF1
   - Electron capture reactions in steller environments

2. Beta Decays of N=126 Isotones and r-Process Nucleosynthesis
   - Half-lives of the isotones with GT+FF transitions
   - Implications on the 3rd peak of the r-process nucleosynthesis

1. Electron Capture Reactions on Ni Isotopes

● GT Strengths in Ni and Fe Isotopes

New shell-model Hamiltonians in fp-shell: GXPF1, KB3G

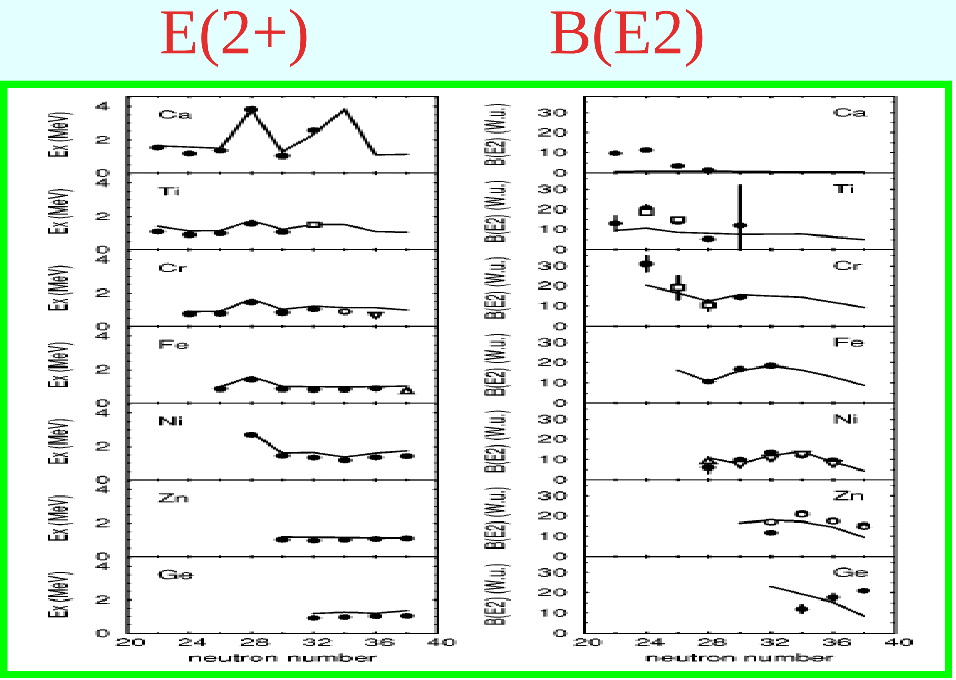
GXPF1: Honma et al., PR C65, 061301 (2002); C69, 034335 (2004)

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

○ KB3G A = 47-52 KB + monopole corrections

○ GXPF1 A = 47-66

- More attraction for T=0 m.e. than G-matrix
- E(1p3/2) – E(0f7/2) ～ 3 MeV cf. ～ 2 MeV for KB3, FPD6



Ca: New magic number
at N=34 (A=54)

^{56}Ni = soft core

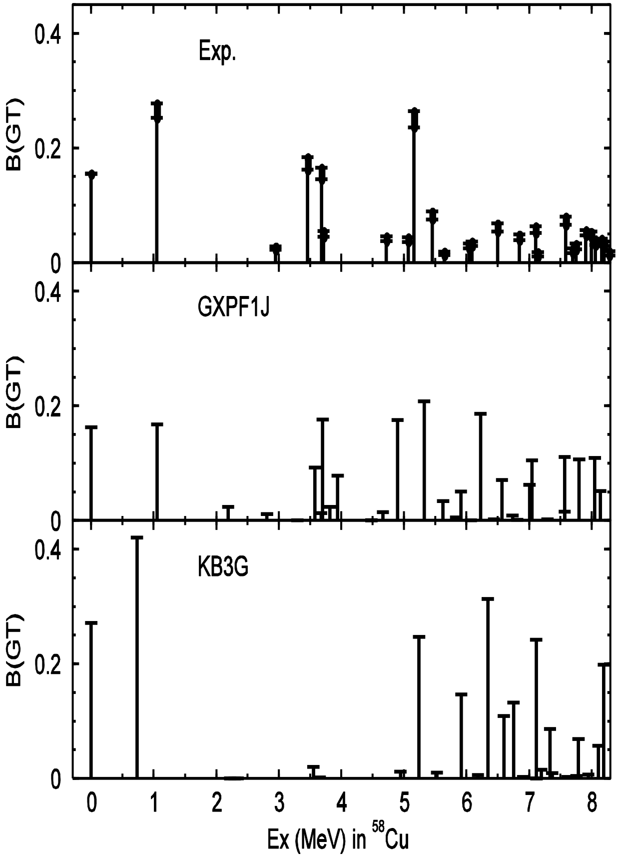
Breaking of 56Ni-core

$(f7/2)^{16}$: 69%（GXPF1)

B(GT-): 11.3 (GXPF1)
10.1 (KB3)
13.7 (closed core)

fp-shell
B(GT) for 58Ni

Exp: Fujita et al.

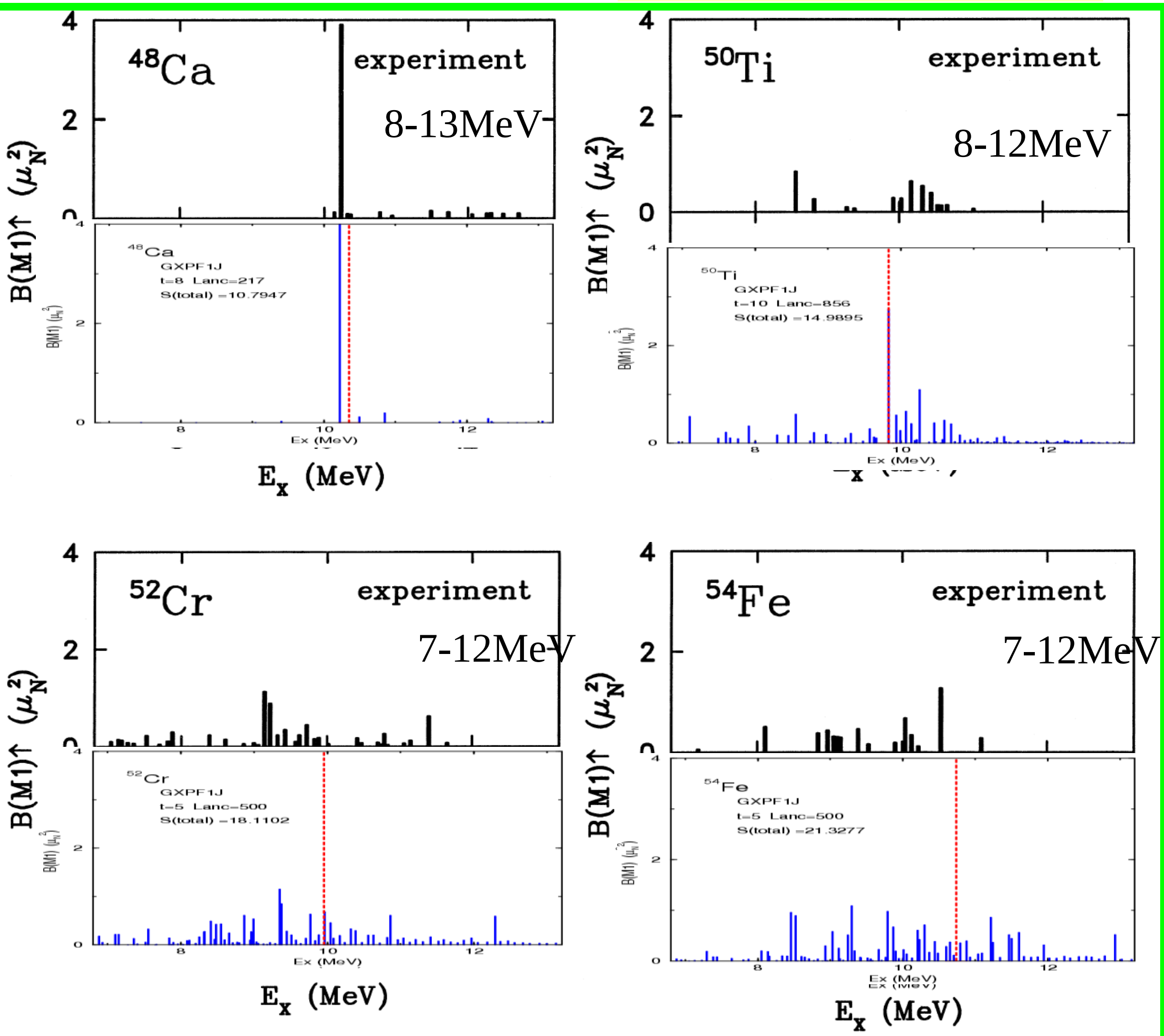


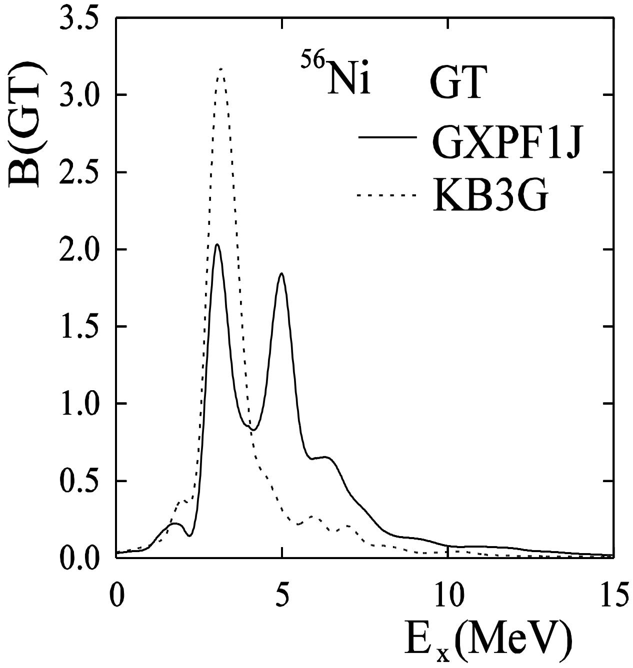
$g_A^{eff}/g_A^{free}=0.74$

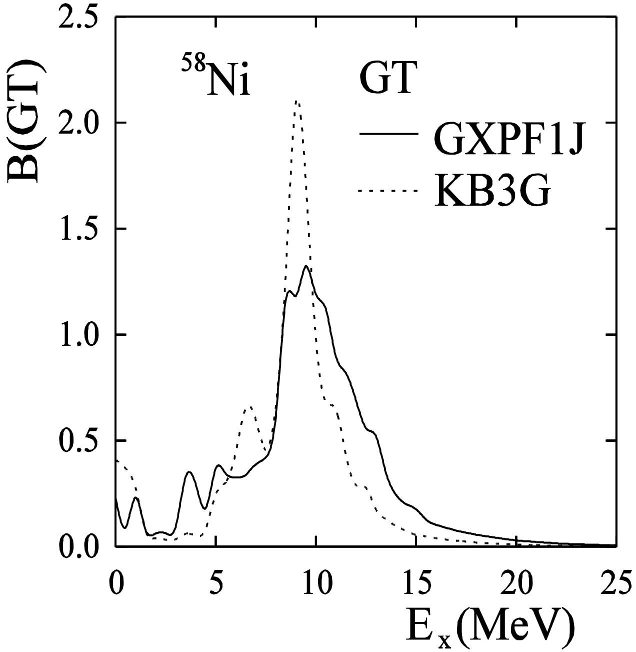
M1 strength (GXPF1J)

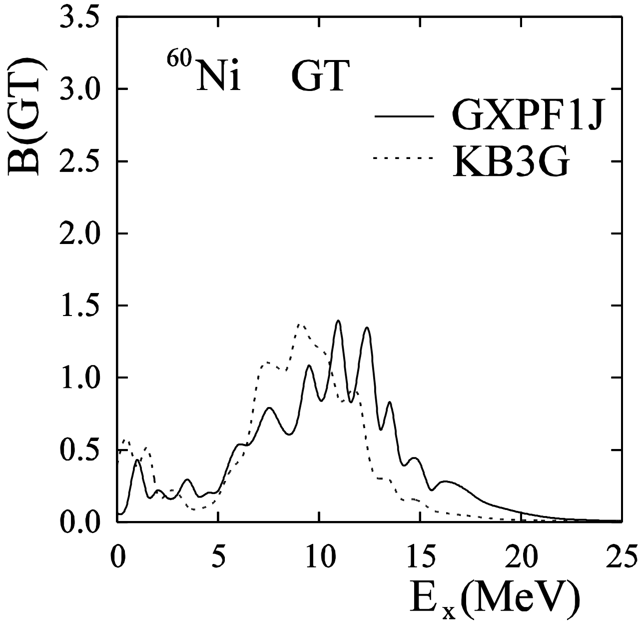
Honma

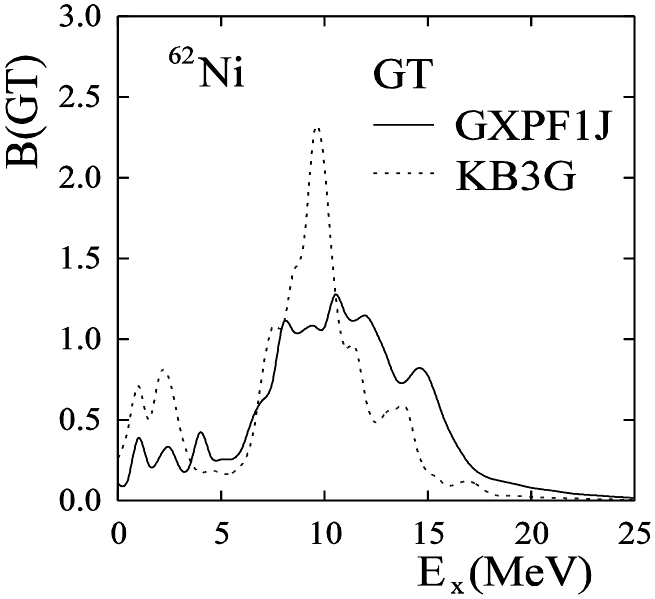
$g_S^{eff}/g_S=0.75\pm0.2$

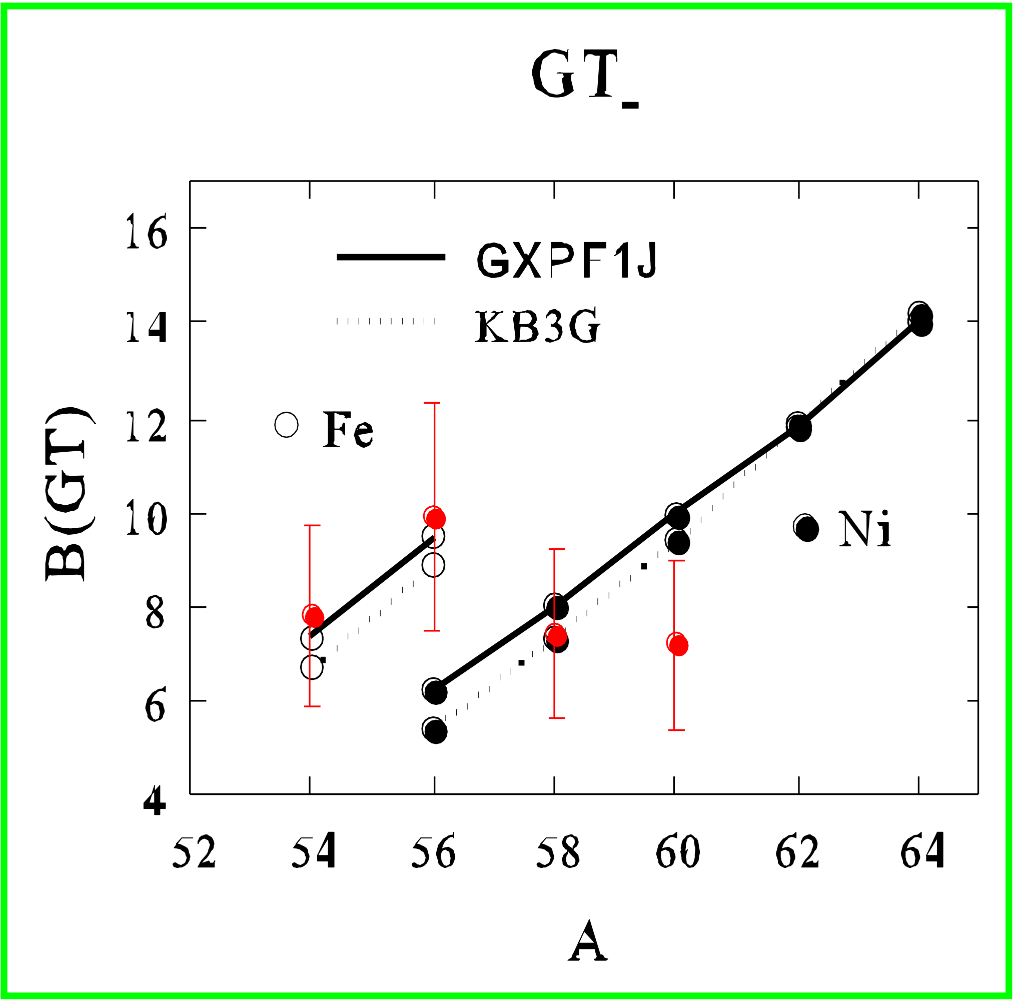


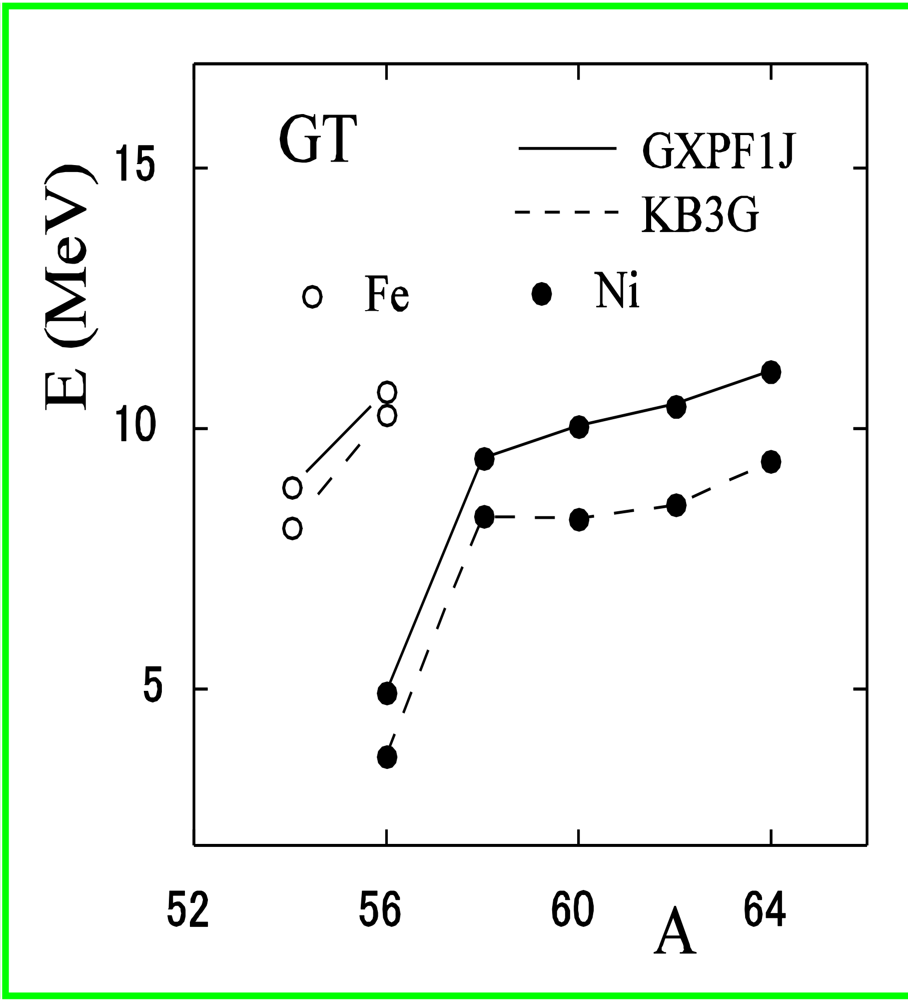

^{56}Ni GT
GXPF1J
KB3G
B(GT)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
5
10
15
E_x(MeV)


^{58}Ni GT
GXPF1J
KB3G
B(GT)
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
25
E_x(MeV)


^{60}Ni GT
GXPF1J
KB3G
B(GT)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
5
10
15
20
25
E_x(MeV)


^{62}Ni GT
GXPF1J
KB3G
B(GT)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
5
10
15
20
25
E_x(MeV)



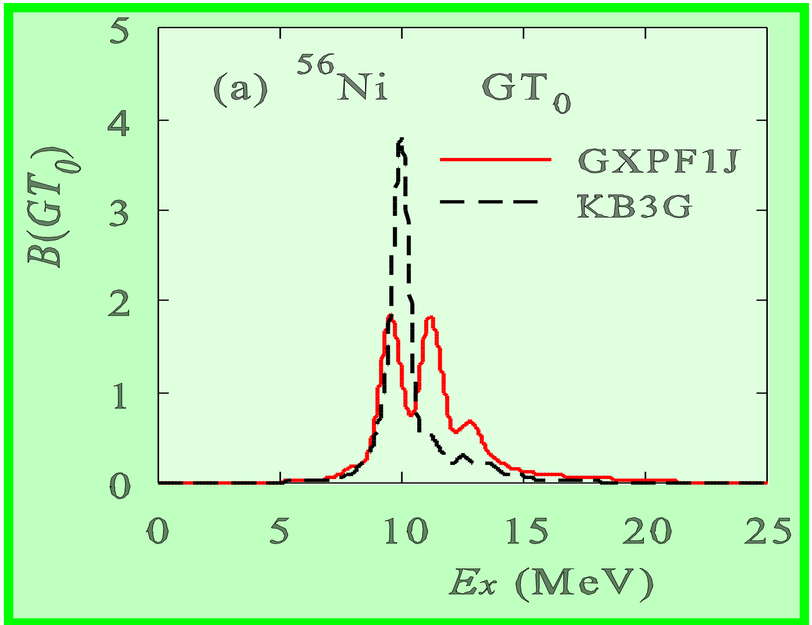


$B(GT_+)$

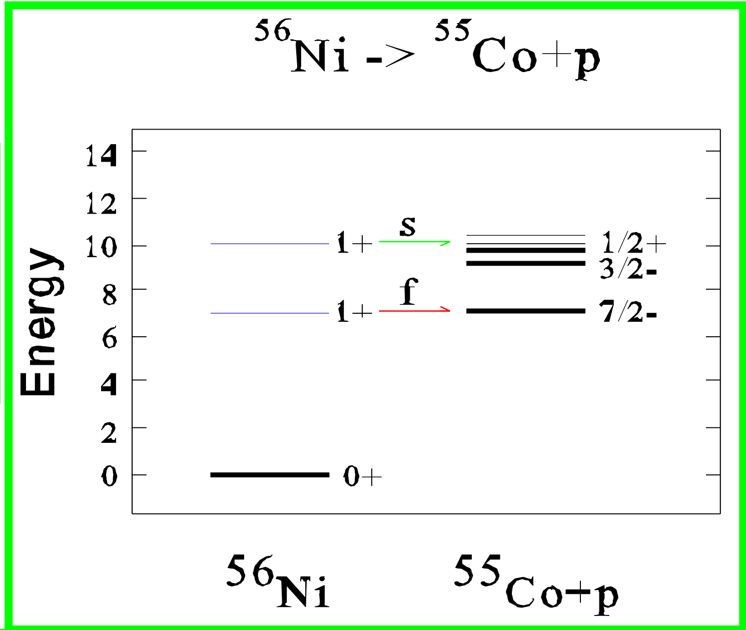
	GXPF1J	EXP.
54Fe	4.0	3.3+/-0.5
56Fe	2.9	2.8+/-0.3
58Ni	4.7	3.8+/-0.4
60Ni	3.4	3.1+/-0.1

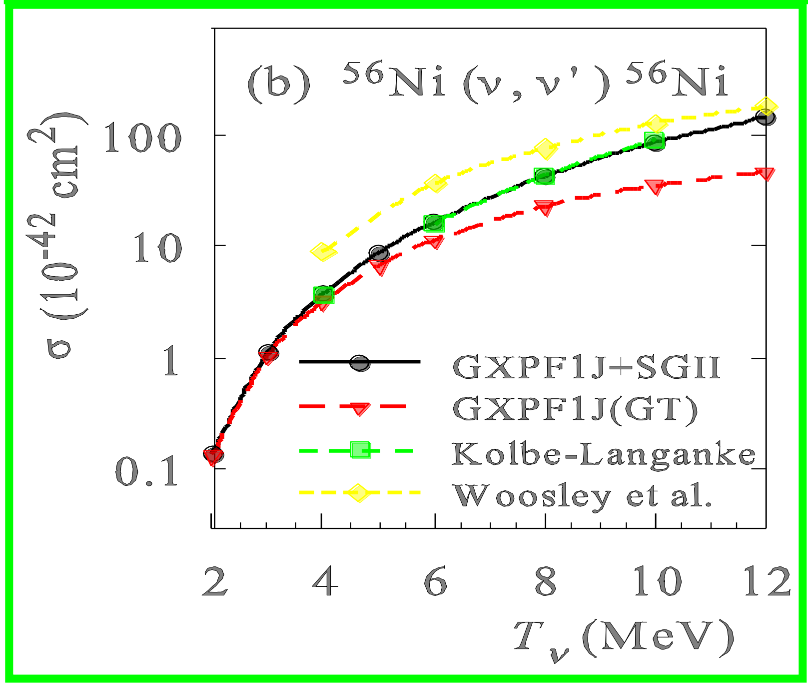
EXP: GT_-; Rapaport et al., NP A410, 371 (1983)
$0<E_x<13\text{-}15$ MeV
GT_+; Caurier et al., NP A653, 439 (1999)
$0<E_x<8$ MeV

●Neutral current reaction on ^{56}Ni

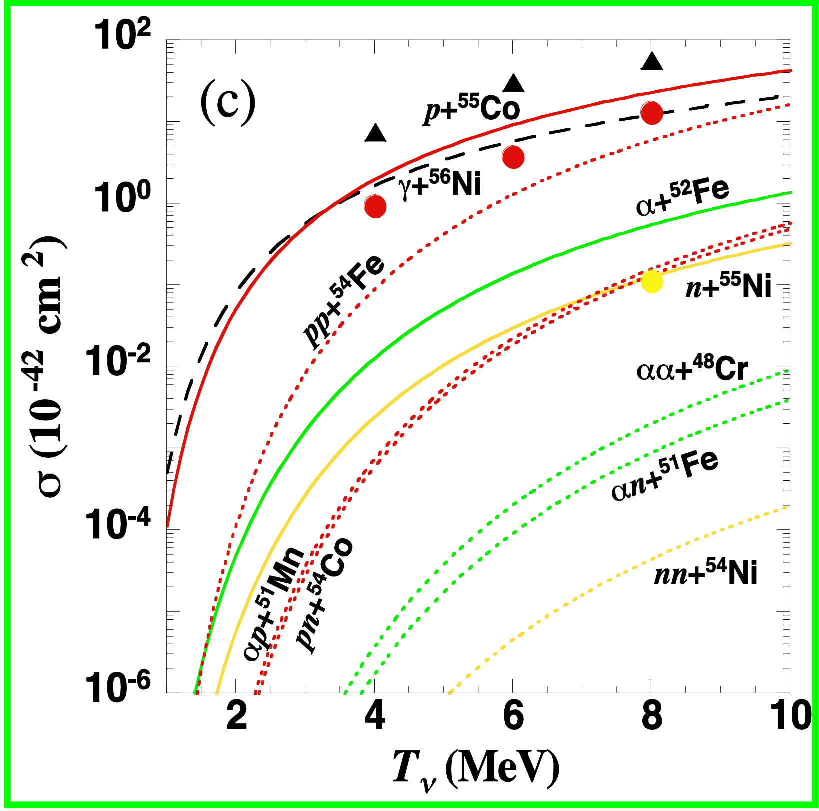


B(GT)=6.2
(GXPF1J)
B(GT)=5.4
(KB3G)



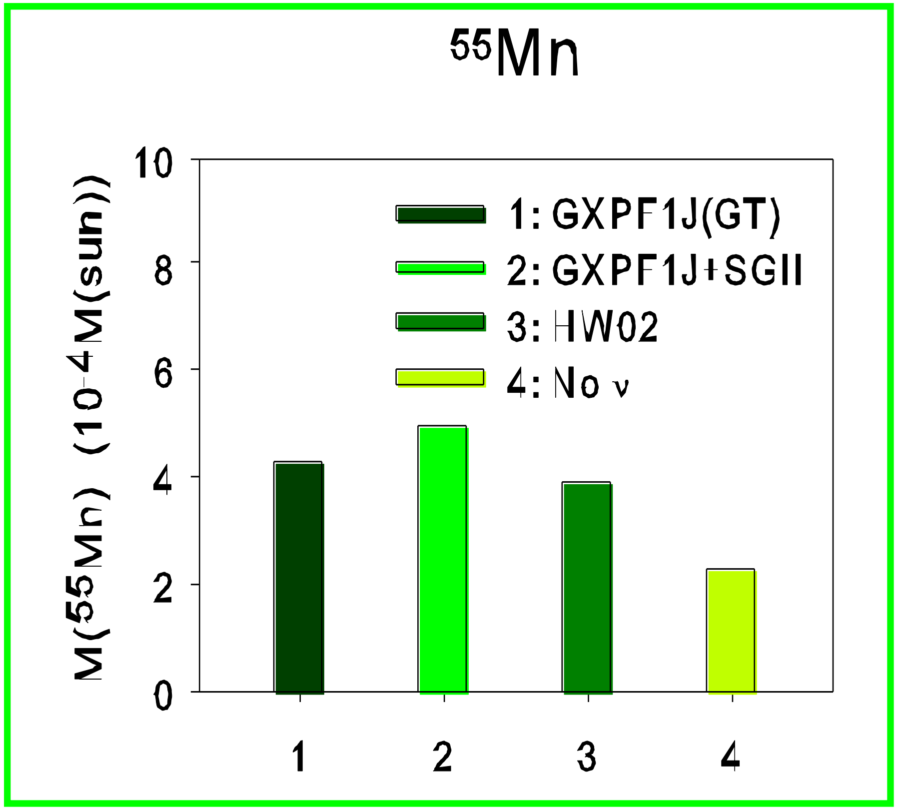


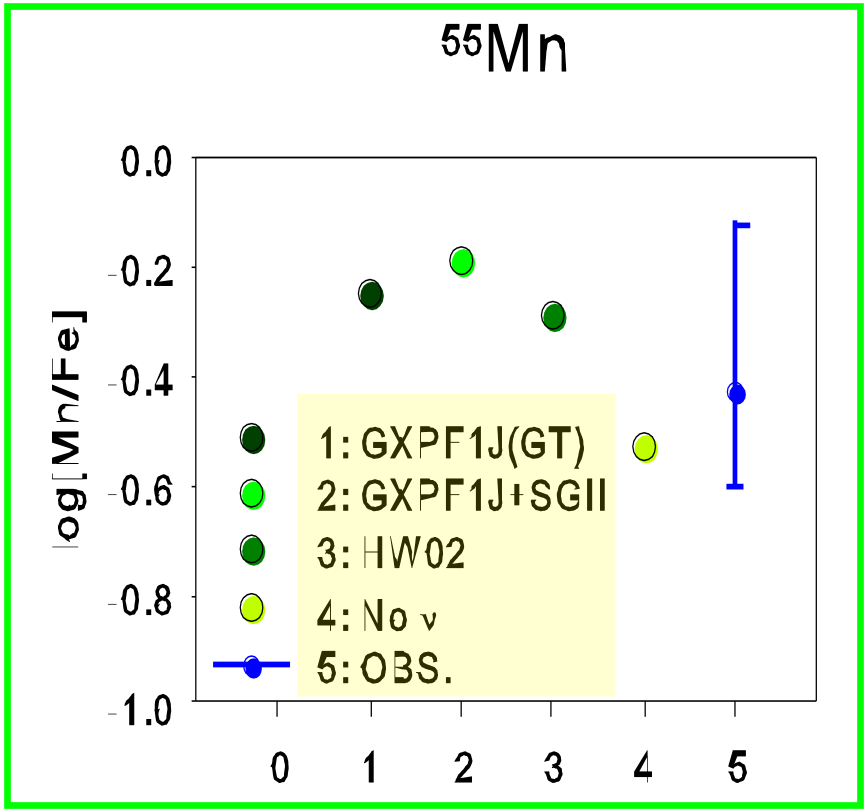
cf:
HW02
▲gamma
●p
●n



Synthesis of Mn in Population III Star

$^{56}\mathrm{Ni}(\nu,\nu'p)^{55}\mathrm{Co}, \quad ^{55}\mathrm{Co}(e^{-},\nu)^{55}\mathrm{Fe}(e^{-},\nu)^{55}\mathrm{Mn}$





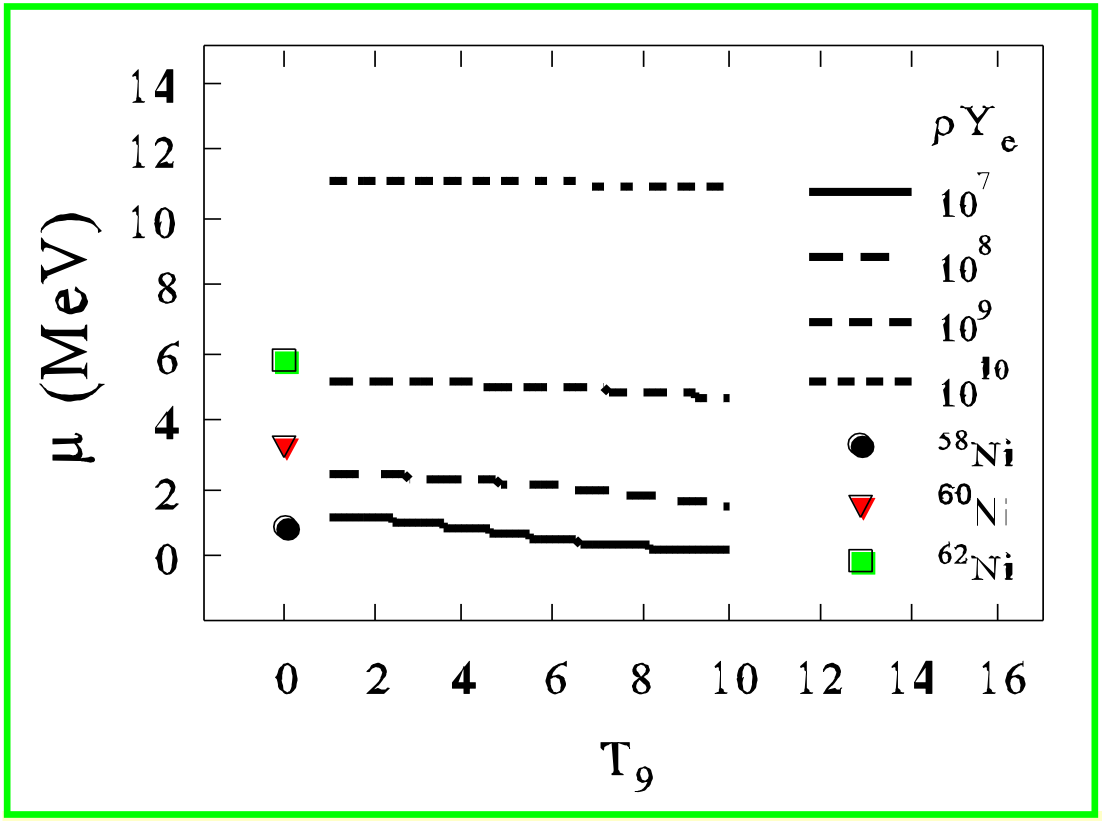
$^{54}\mathrm{Fe}(p,\gamma)^{55}\mathrm{Co}$

Yoshida, Umeda, Nomoto

Suzuki et al.,
PR C79 (2009)

OBS: Cayrel et al.,
Astron. Astrophys.
416 (2004)

●Electron-capture rate in steller environment



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

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

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

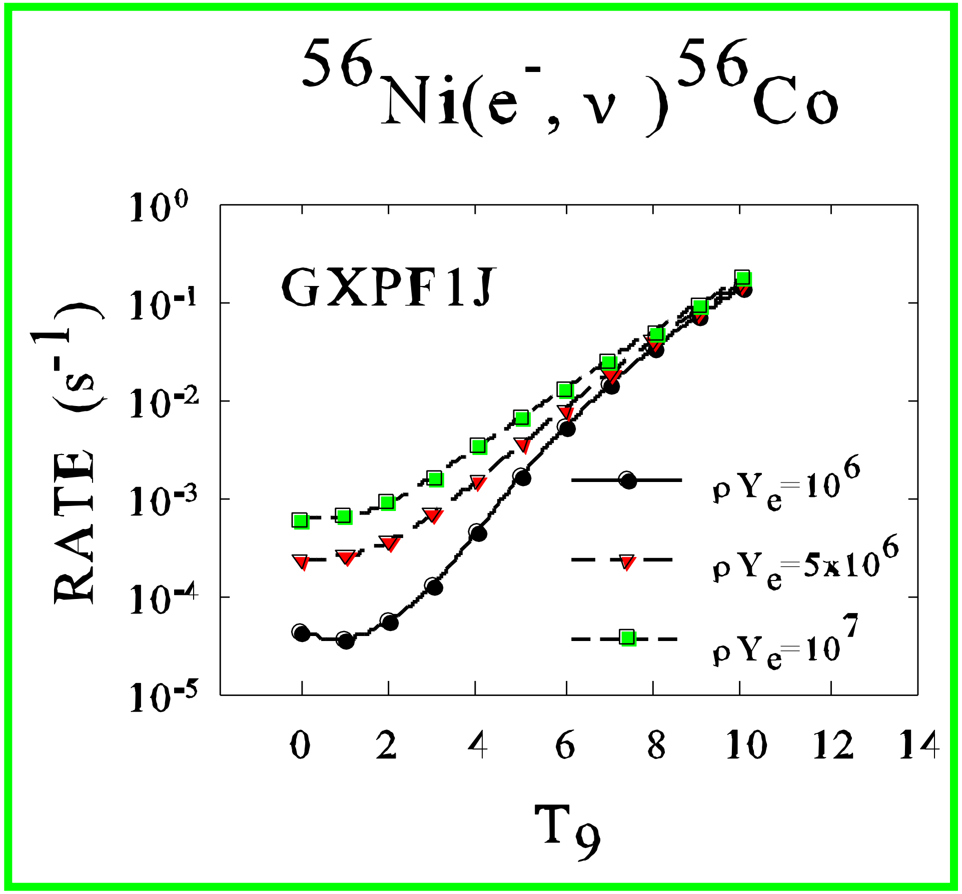
$$\lambda = \frac{ln\,2}{6146(s)} \sum_j B_j(GT) \int_{\omega_e}^{\infty} \omega p (Q_j + \omega)^2 F(Z,\omega) S_e(\omega) d\omega$$

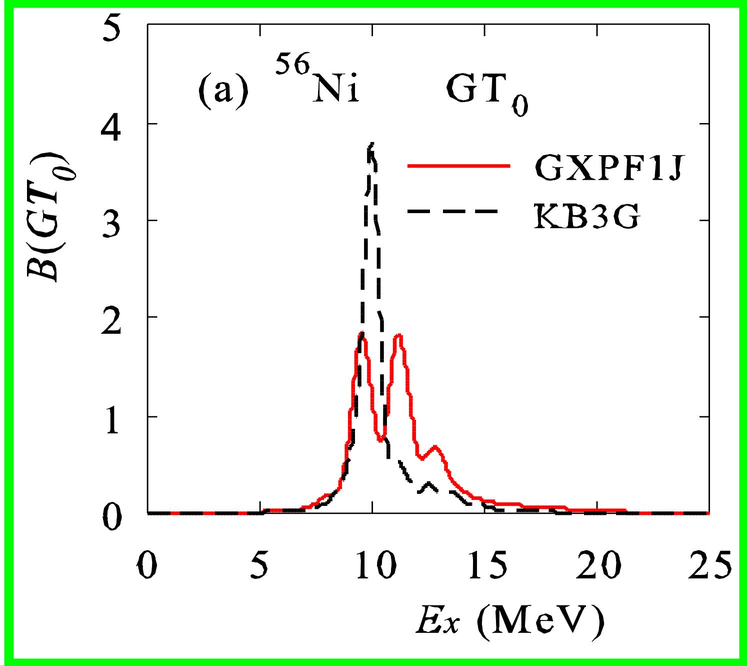
$$Q_j = (M_p c^2 - M_d c^2 - E_j) / m_e c^2$$

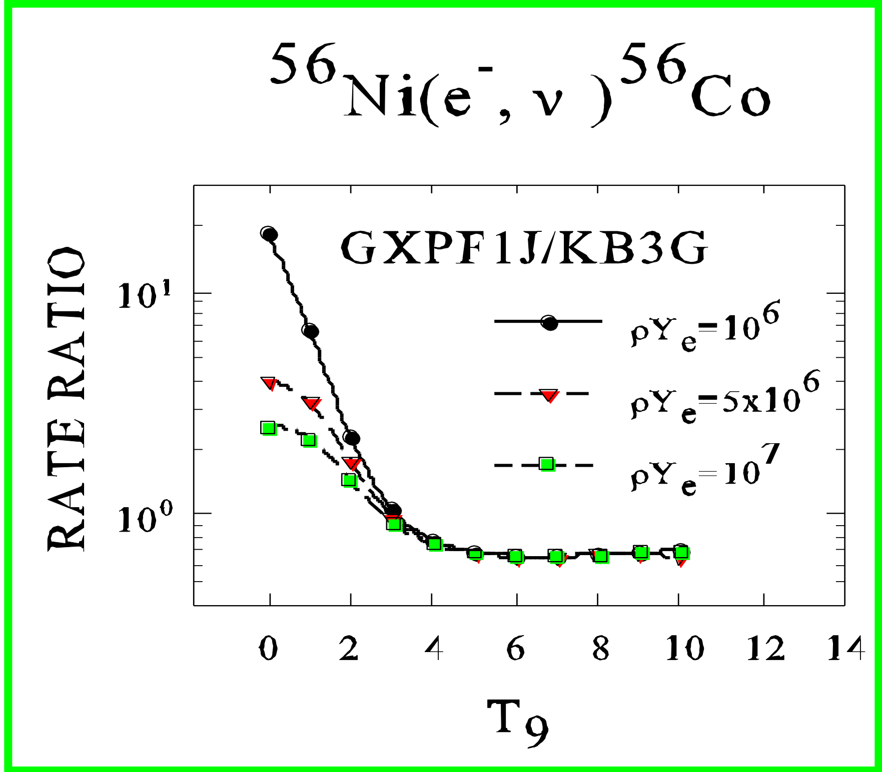
$$T = T_9 \times 10^9 K, \qquad S_e(E_e) = \frac{1}{exp[(E_e - \mu_e)/kT] + 1}$$

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

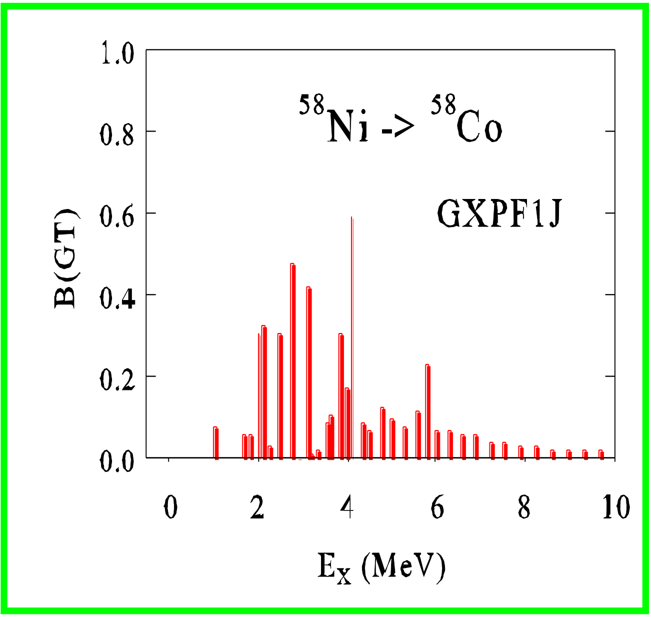
Electron-capture rate on ^{56}Ni

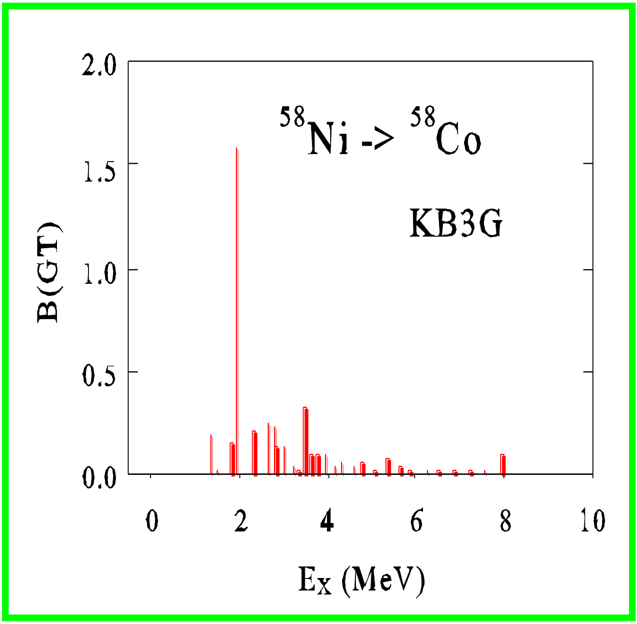


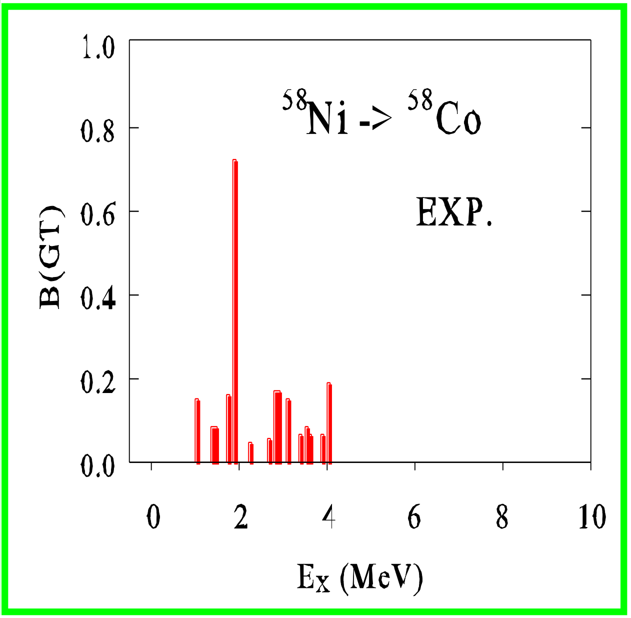


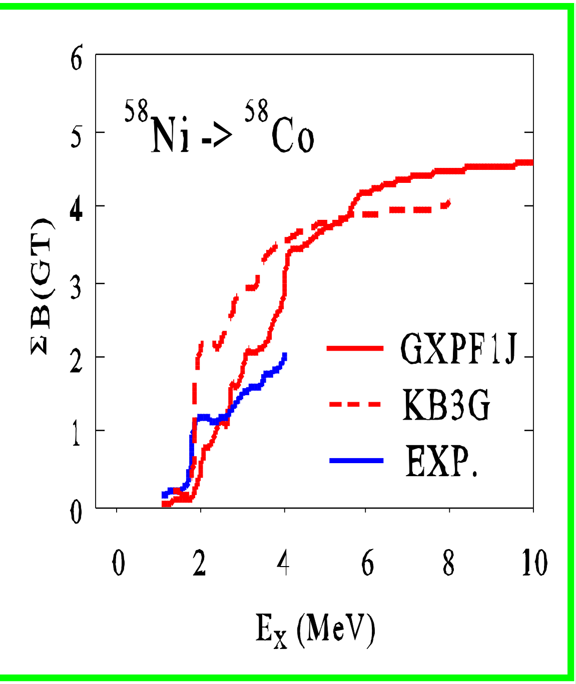


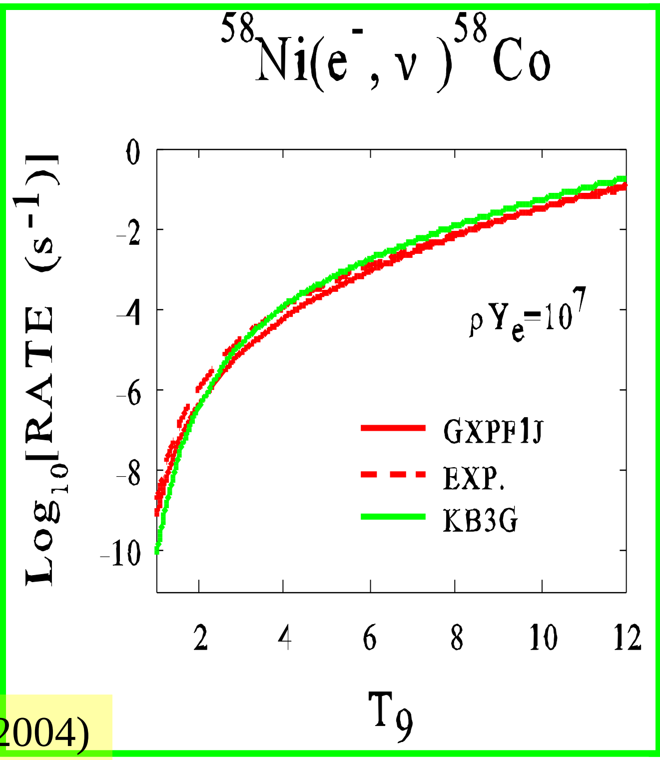
GXPF1: 30% reduction at $T_9>4$
Enhancement at $T_9<2$
compared to KB3G

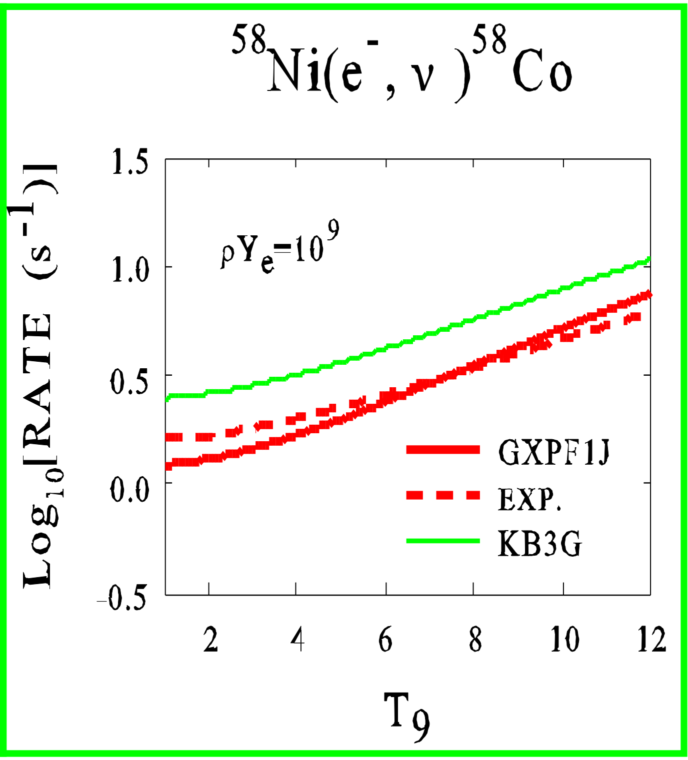




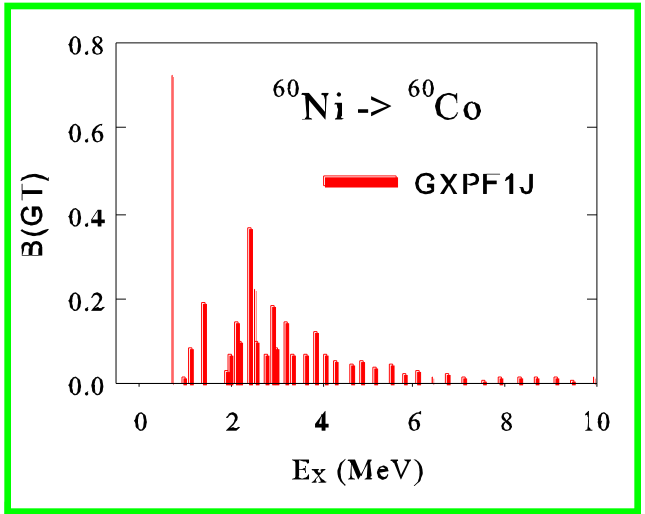


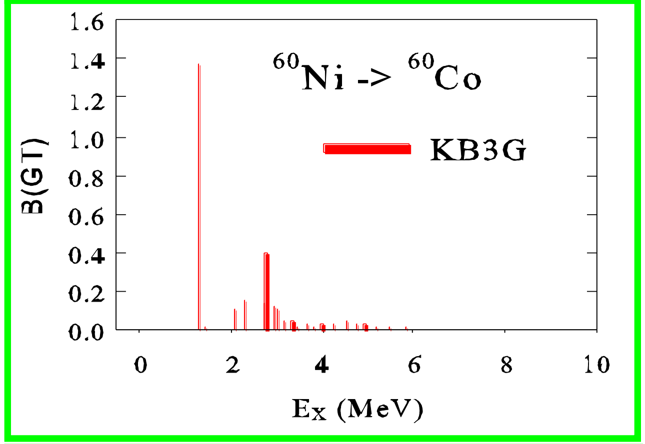


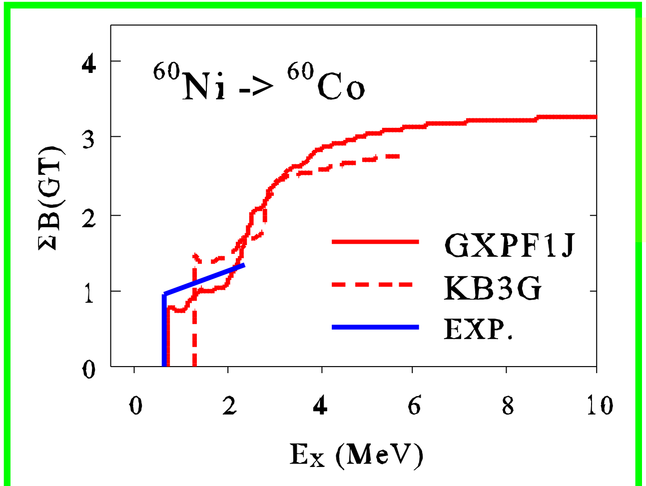




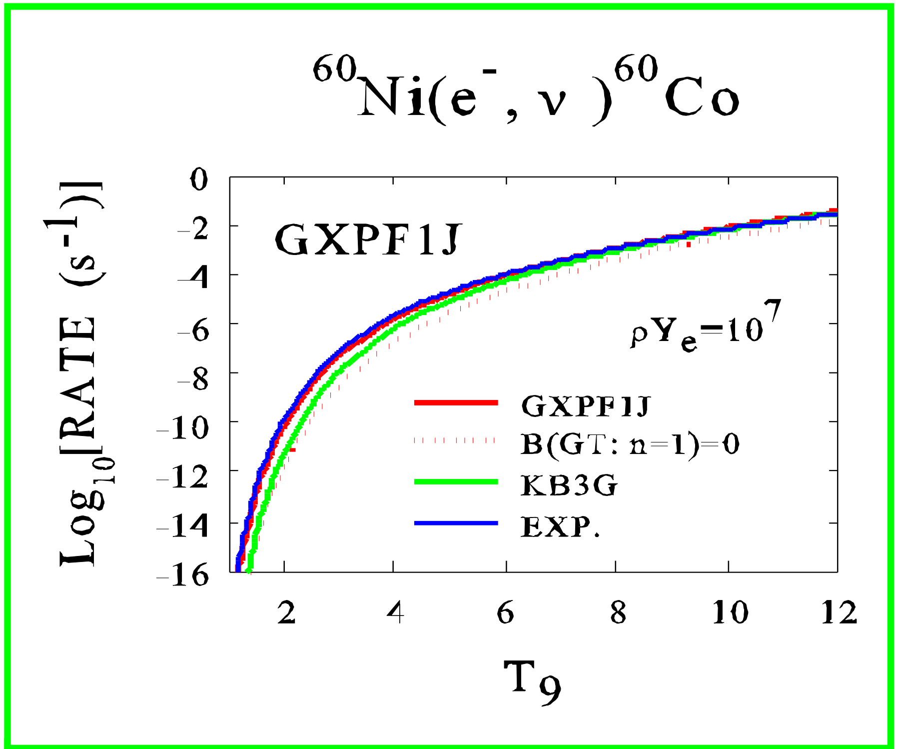
Exp: Hagemann et al., PL B579 (2004)

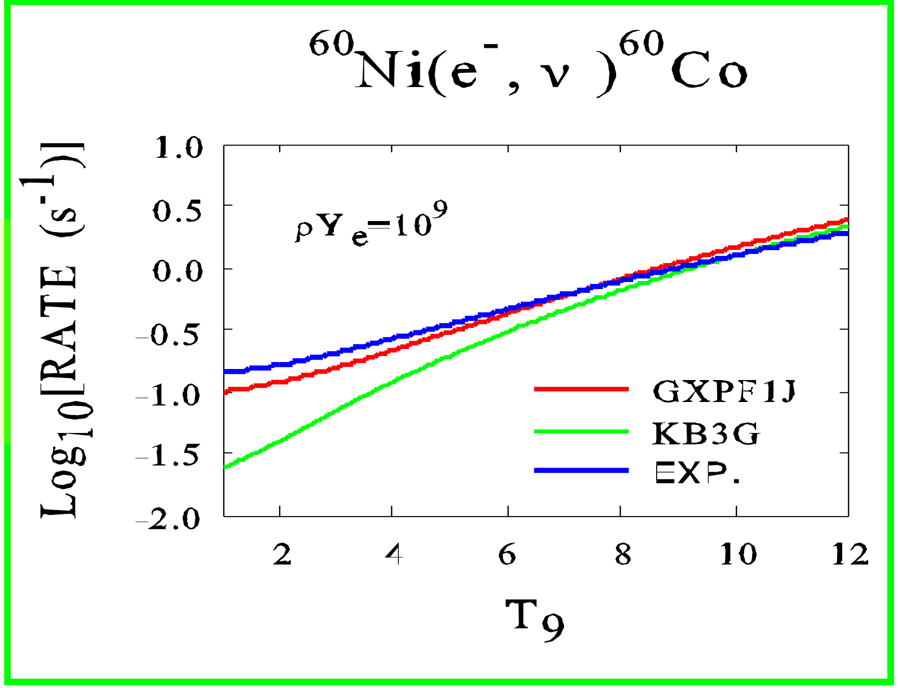






Exp:
Anantaraman
et al.,
PR C78 (2008)

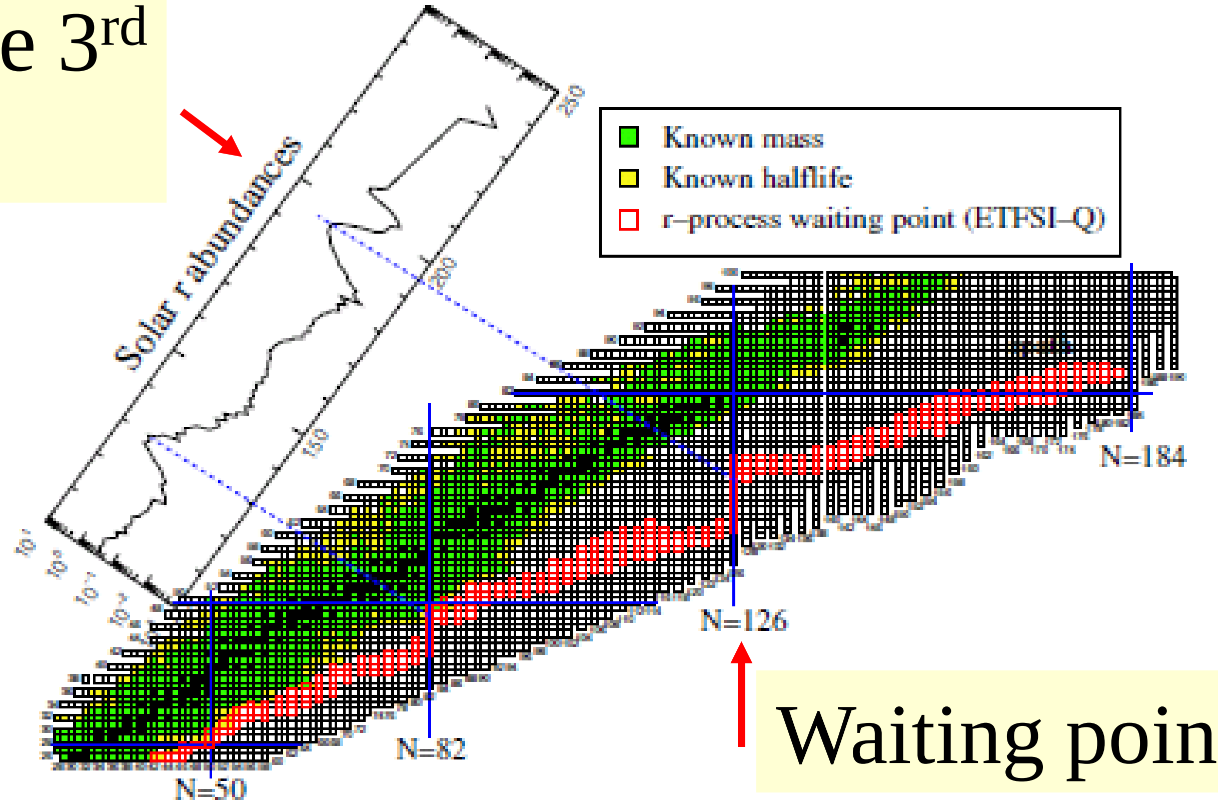




2. R-Process Nucleosynthesis and Beta Decays of N=126 Isotones

H Grawe *et al*

Focus on the 3rd peak region



Waiting point nuclei

Figure 18. The figure shows the range of r-process paths, defined by their waiting point nuclei. After decay to stability the abundance of the r-process progenitors produce the observed solar r-process abundance distribution. The r-process paths run generally through neutron-rich nuclei with experimentally unknown masses and half lives. In this calculation a mass formula based on the ETFSI model and special treatment of shell quenching [79] has been adopted (courtesy of Kratz and Schatz).

Structure of N=126 Isotones

Z=64-72 (A=190-198): proton-hole states of ^{208}Pb

- Shell-model calculations:
  Kuo-Herling G + mod.

Steer et al., PR C78, 061302 (2008)

Ryndstrom et al., NP A512, 217 (1990)

Energy levels of Z=77-81 nuclei well described

PHYSICAL REVIEW C 78, 061302(R) (2008)

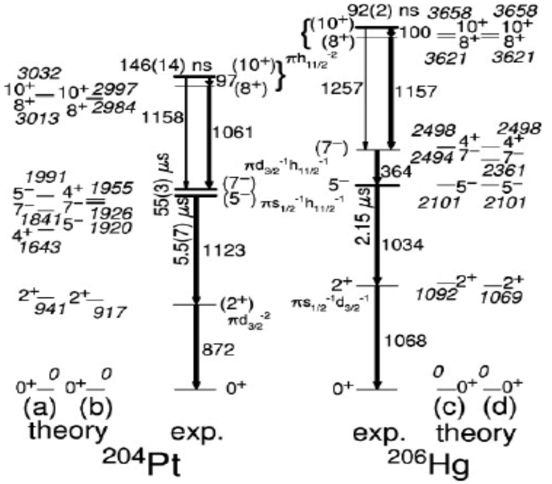


FIG. 3. Experimental and calculated partial level schemes of the $N = 126$ ^{204}Pt and ^{206}Hg [9] nuclei. Arrow widths denote relative intensities of parallel decay branches. The dominant state configurations are indicated. (a) and (d) are calculations using the Rydsrtöm matrix elements, while (b) and (c) are with the modified ones, as described in the text.

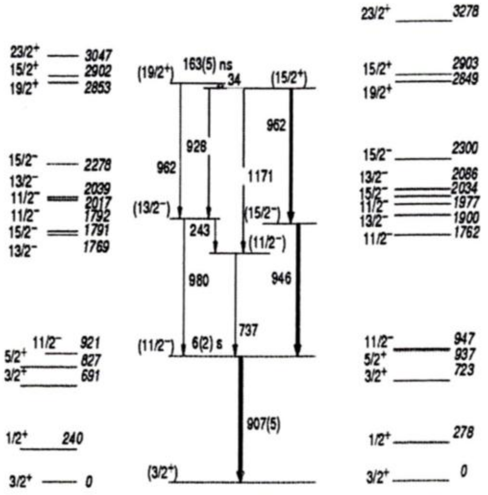


FIGURE 3. Experimental (middle) and calculated level schemes of ^{205}Au. Calculations using Rydsrtöm matrix elements are shown on the left, while calculations with the modified TBMEs are the right hand side.

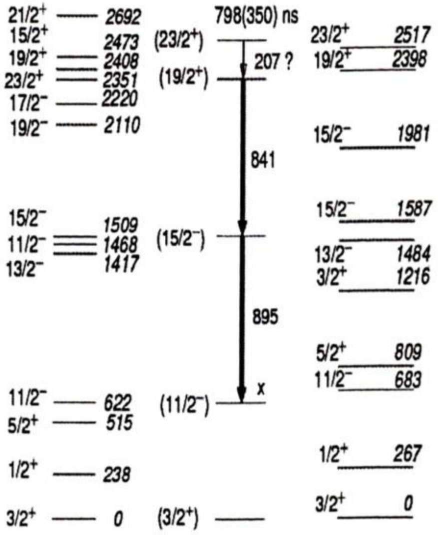


FIGURE 4. Same as figure 3, but for ^{203}Ir. The experimental level scheme is preliminar

Beta Decays of N=126 Isotones

Z=64-72 (A=190-198)

- **Shell-model calculations:**

Kuo-Herling G + mod. **Steer et al., PR C78, 061302 (2008)**
Ryndstrom et al., NP A512, 217 (1990)

Energy levels of Z=77-81 nuclei well described

- **GT (1^+) + FF (first-forbidden: 0-, 1-, 2-) transitions**

$$O(1^+) = g_A \sigma t_-$$

$$O(0^-) = g_A [\frac{\sigma \square p}{m} + \frac{\alpha Z}{2R} i\sigma \square r] t_-$$

$$O(1^-) = [g_V \frac{p}{m} - \frac{\alpha Z}{2R} (g_A \sigma x r - i g_V r] t_-$$

$$O(2^-) = i \frac{g_A}{\sqrt{3}} [\sigma x r]^2_\mu \sqrt{p_e^2 + q_\nu^2}\, t_-$$

$$\Lambda(s^{-1}) = \ln 2 / t = f / 8896(s)$$

$$f = \int_1^{w_0} C(w) F(Z, w) p w (w_0 - w)^2 dw$$

$$C(w) = K_0 + K_1 w + K_{-1} / w + K_2 w^2$$

$$K_N : \quad \vec{r}, \quad [\vec{r} \times \vec{\sigma}]^\lambda \quad (\lambda = 0, 1, 2)$$

$$\gamma_5, \quad \vec{\alpha}$$

Warburton et al., Ann.Phys. 187 (1988)

Resuts thus far: SM (GT), QRPA, CQRPA etc.
Theoretical half-lives prediction: N=126 scattered

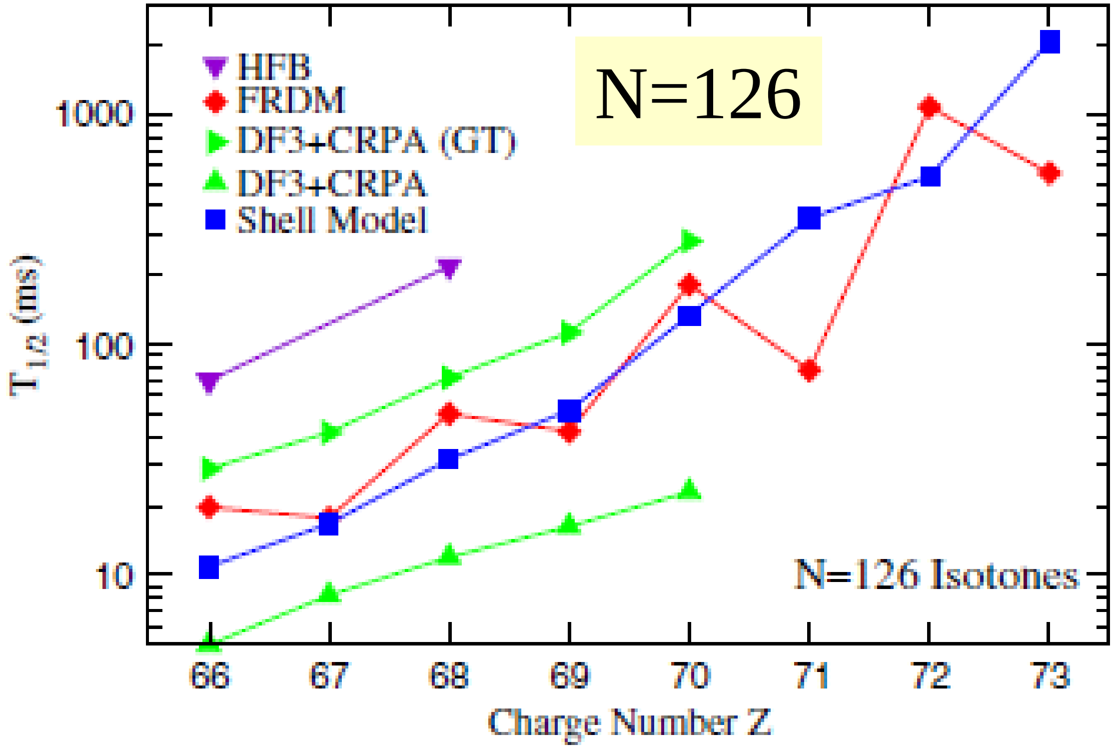


Figure 26. Theoretical half life predictions for $N = 126$ isotones in the shell model [299], the HFB [76], FRDM [57] and the DF3+CQRPA [77] approaches.

N=82

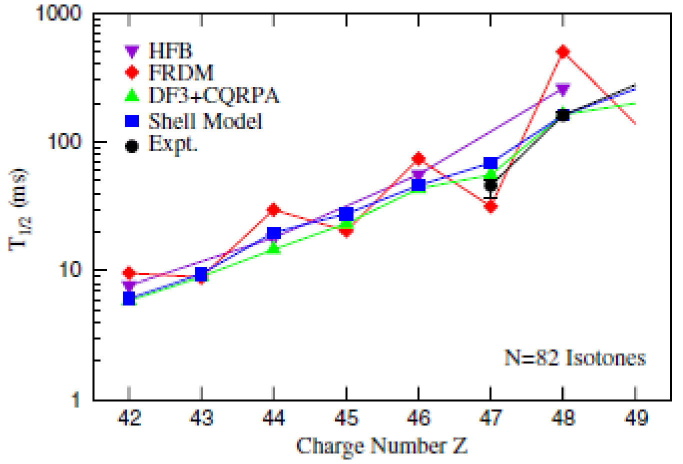
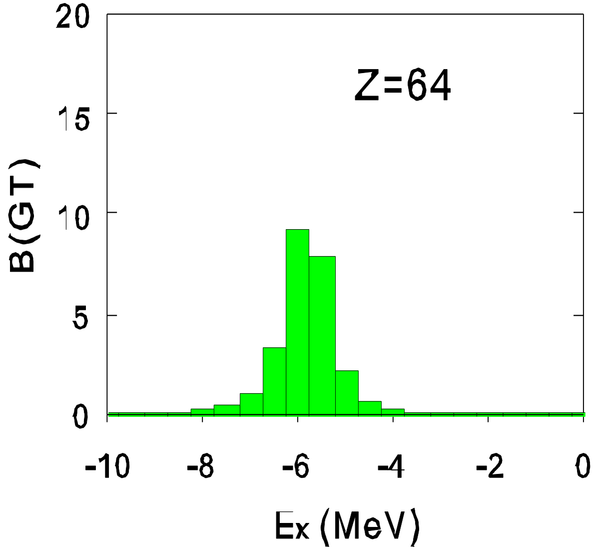


Figure 23. Half lives for $N = 82$ isotones in various approaches HFB [76
DF3+CQRPA [77] and shell model [296] in comparison with experimental dat
^{130}Cd [16] and ^{131}In [8].

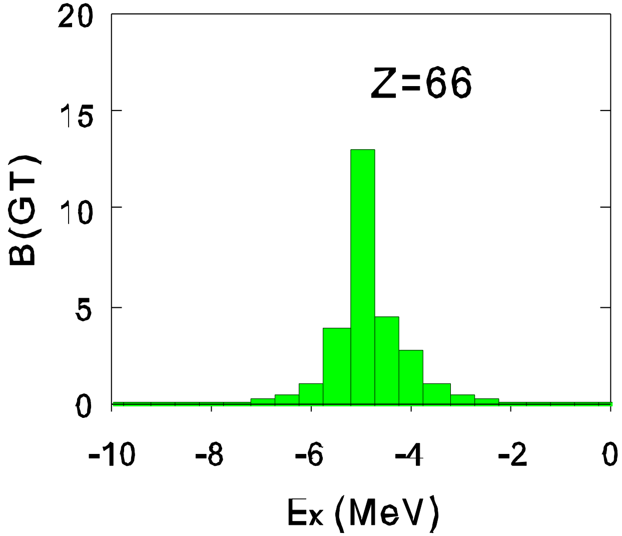
SM (GT): Langanke, Martinez-Pinedo, RMP 75, 819 (2003)
QRPA: Moller, Pfeiffer and Kratz, PR C67, 055802 (2003)
CQRPA: Borzov, PR C67, 025802 (2003)

Grawe, Langanke,
Martinez-Pinedo,
RPP 70, 1525 (2007)

GT strengths



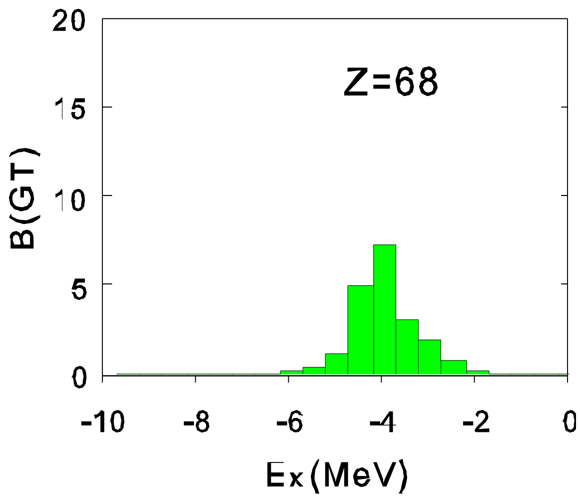
∑B(GT)=14.4



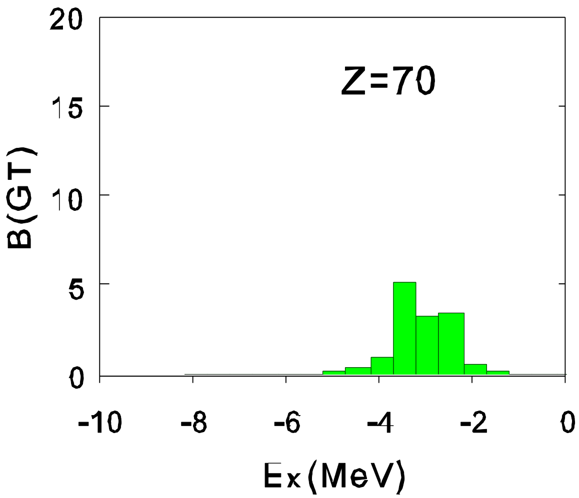
∑B(GT)=14.6

$Q=g_A^{eff}/g_A=0.7$
Q^2 to be multilied

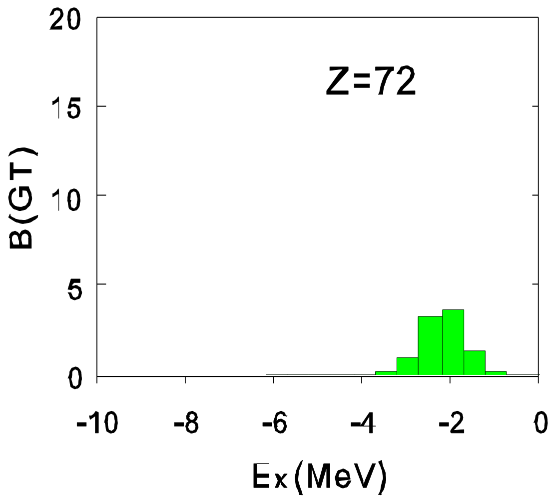
$E_x=0$ ⟵⟶ g.s. of the parent nuclei



∑B(GT)=11.7

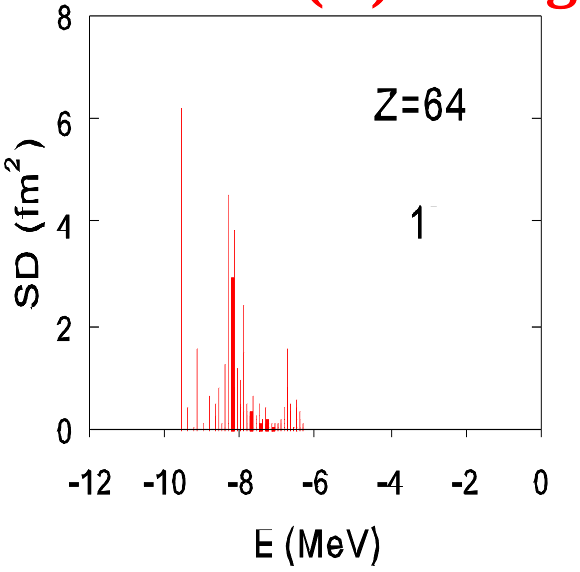


∑B(GT)=8.5

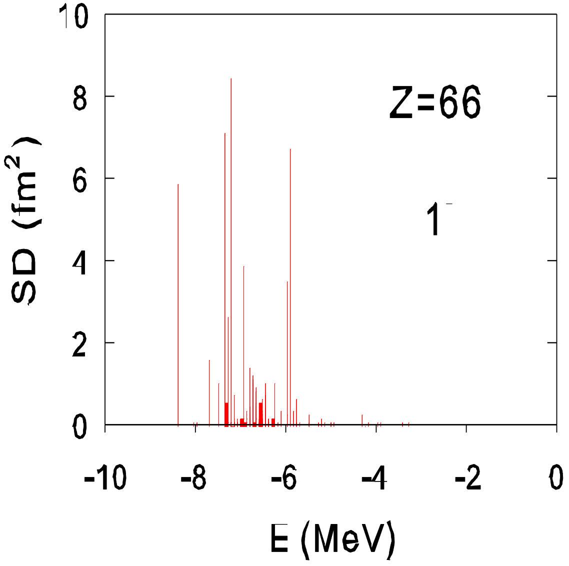


∑B(GT)=5.6

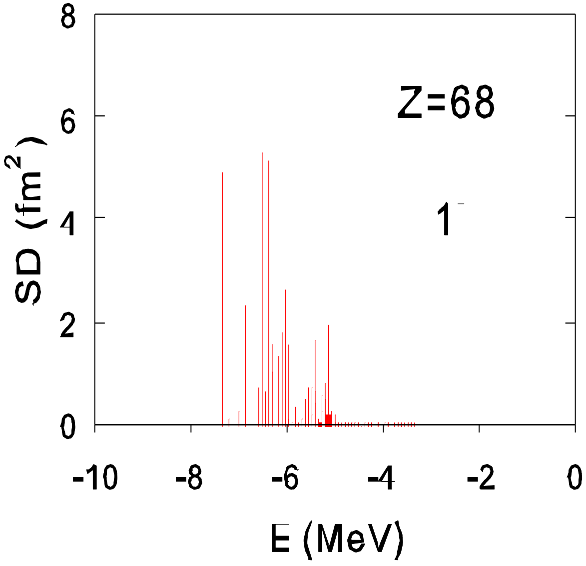
SD (1^-) strengths



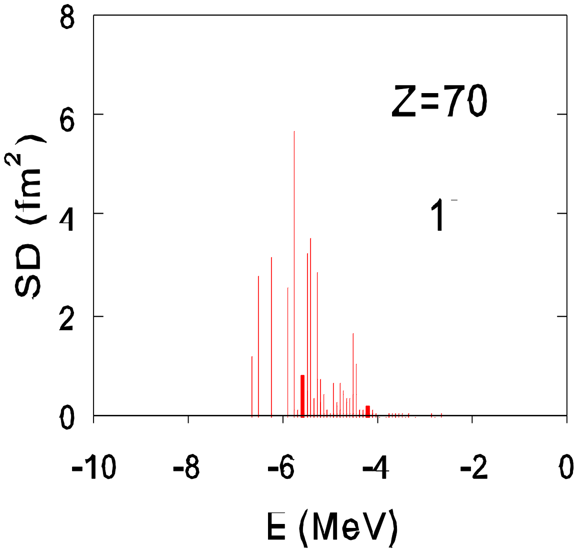
ΣSD1=55.5 fm^2



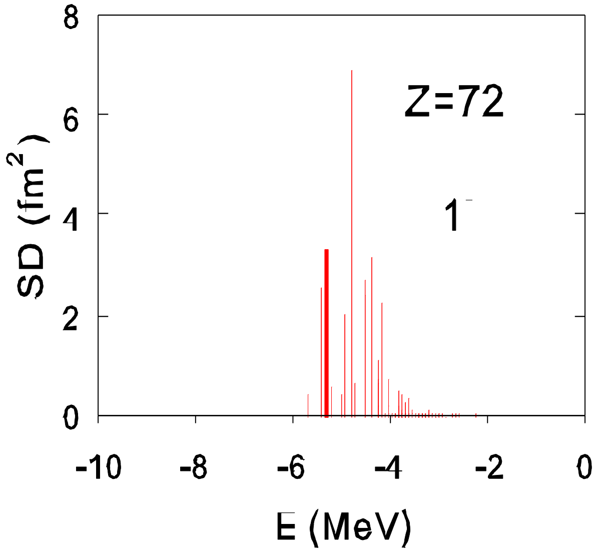
ΣSD1=49.2 fm^2



ΣSD1=43.9 fm^2



ΣSD1=40.1 fm^2



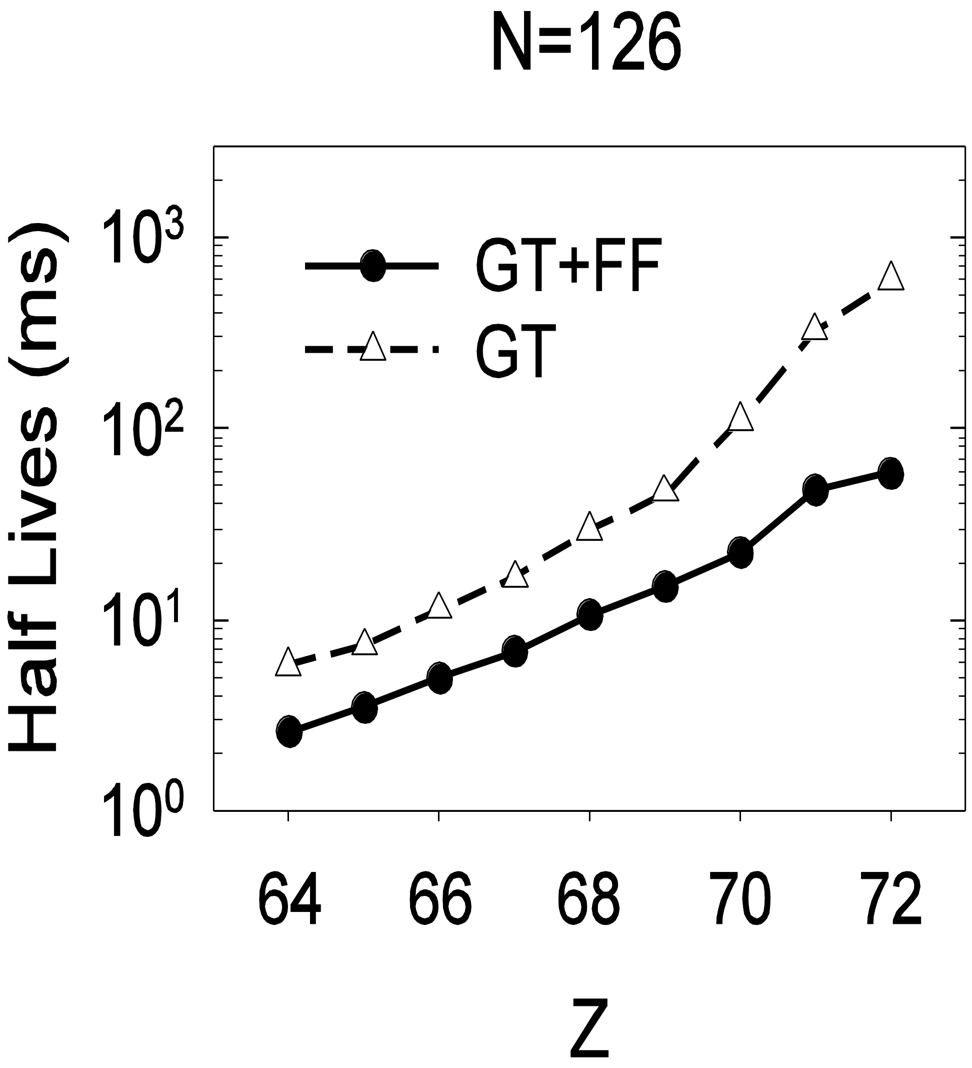
ΣSD1=35.1 fm^2

SD 1^-

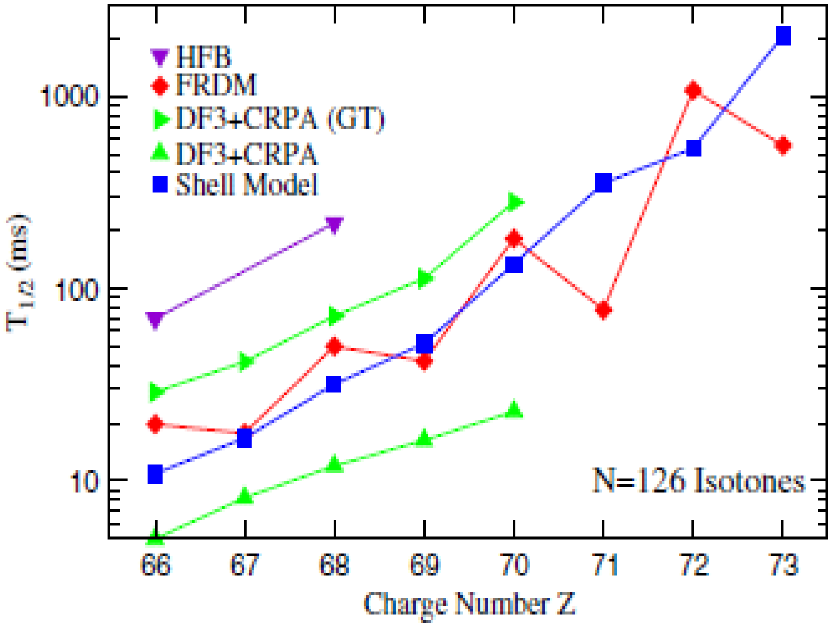
$r[Y_1 x \boldsymbol{\sigma}]^1$

E=0: g.s. of
the parent nuclei

Shell Model calculations



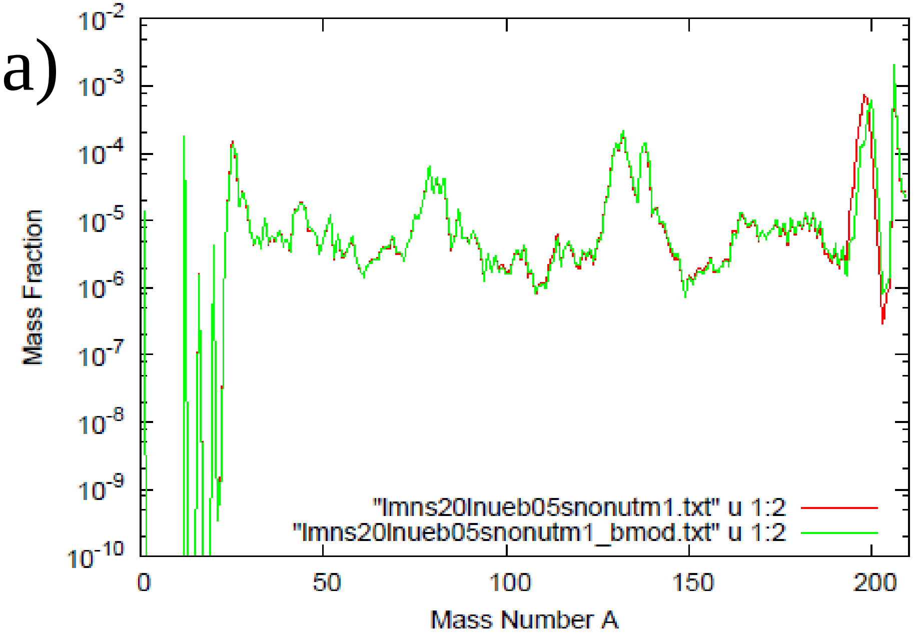
cf.



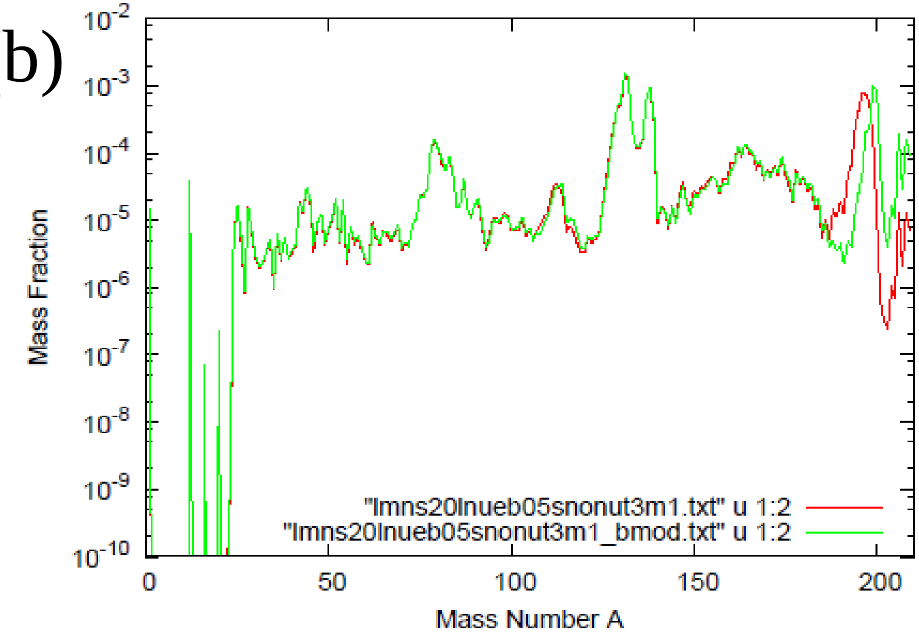
Grawe, Langanke, Martinez-Pinedo, RPP 70, 1525 (2007)

$Q=g_A^{eff}/g_A=0.7$

(a)



(b)



Yoshida

r-process nucleosynthesis

Constant Entropy Wind Model

$M_{NS}=2.0M_{sun}$

$R_{NS}=10$ km

$S=400\ k_B\ (\gamma, e^-, e^+)$

$dm/dt=1.1\times10^{-6}\ M_{sun}$

$T_9=(T_{09}-T_{\alpha9})\exp(-t/\tau)+T_{\alpha9}$

$T_{09}=9,\ \ T_{\alpha9}=1$

$Y_{e\_ini}=0.40$

(a) $\tau= 0.053$ s

(b) $\tau=0.16$ s

Half-lives:

🟥 Standard (Moller et al.)

🟩 Modified

Summary

- **Successful description of GT strengths in fp-shell nuclei by new shell model Hamiltonians; GXPF1**
- **Fragmented GT strength in Ni isotopes**

→ Decrease of e-capture rates in ^{56}Ni, ^{58}Ni isotopes in steller environment at T_9 >3 compared to KB3G

Capture rates depend sensitively on the distribution of the GT strength at low excitation energies; e.g. Increase of rates in ^{60}Ni

· Shell model calculations for beta-decay half-lives including both GT and FF transitions
→ Very short half-lives for beta decays of N=126 isotones, waiting point nuclei for the r-process
→ The 3rd peak of the r-process element abundances is shifted toward larger mass number region.

Collaborators

M. Honma[a], T. Yoshida[b], K. Higashiyama[c],
H. Umeda[b], K. Nomoto[b], T. Kajino[b,d],
T. Otsuka[e], Y. Utsuno[f],
H. Mao[g]

[a]University of Aizu
[b]Department of Astronomy, University of Tokyo
[c]Chiba Institute of Technology
[d]National Astronomical Observatory of Japan
[e]Department of Physics and CNS, University of Tokyo
[f]JAEA
[g]ENSPS, Strasbourg