Neutrino-Nucleus Reactions Based on Recent Progress of Shell Model Calculations

Toshio Suzuki (Nihon University)

- ○ New shell model calculations in p-shell
  modified shell model Hamiltonian (SFO) with
  improved spin-dependent transitions and moments

  Suzuki, Fujimoto, Otsuka
- ○ Neutrino-nucleus reactions on ^{12}C, ^{4}He

  Suzuki, S. Chiba (JAEA), O. Iwamoto (JAEA), Kajino (NAO)
- ○ New shell model Hamiltonian in fp-shell by Honma et al.
- ○ Neutrino-nucleus reactions on Fe and Ni isotopes

  Suzuki, Higashiyama, Otsuka, Kajino, Balantekin

New Shel-Model interaction in p-shell: SFO

Suzuki, Fujimoto & Otsuka, PR C67, 044302 (2003)

$\Delta\ \varepsilon = \varepsilon(0p_{1/2}) - \varepsilon(0p_{3/2}) \uparrow$ (0.3 MeV → 3.92 MeV)

$|\ \Delta V_M^{T=0}$ (n-p spin-flip) $| \uparrow$ M=monopole

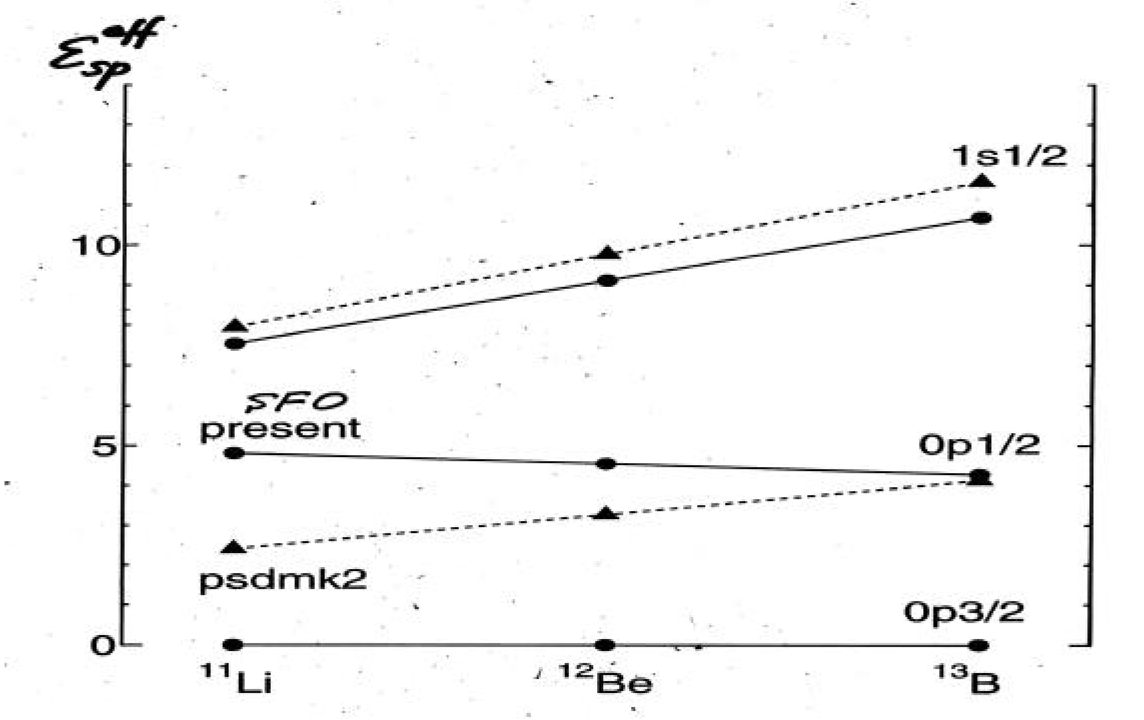
$0p_{1/2}$

↓ ↑

$0p_{3/2}$

p   n

N=8



Spin-tensor decomposition of nuclear effective interactions

$$V = \sum_k V_k$$

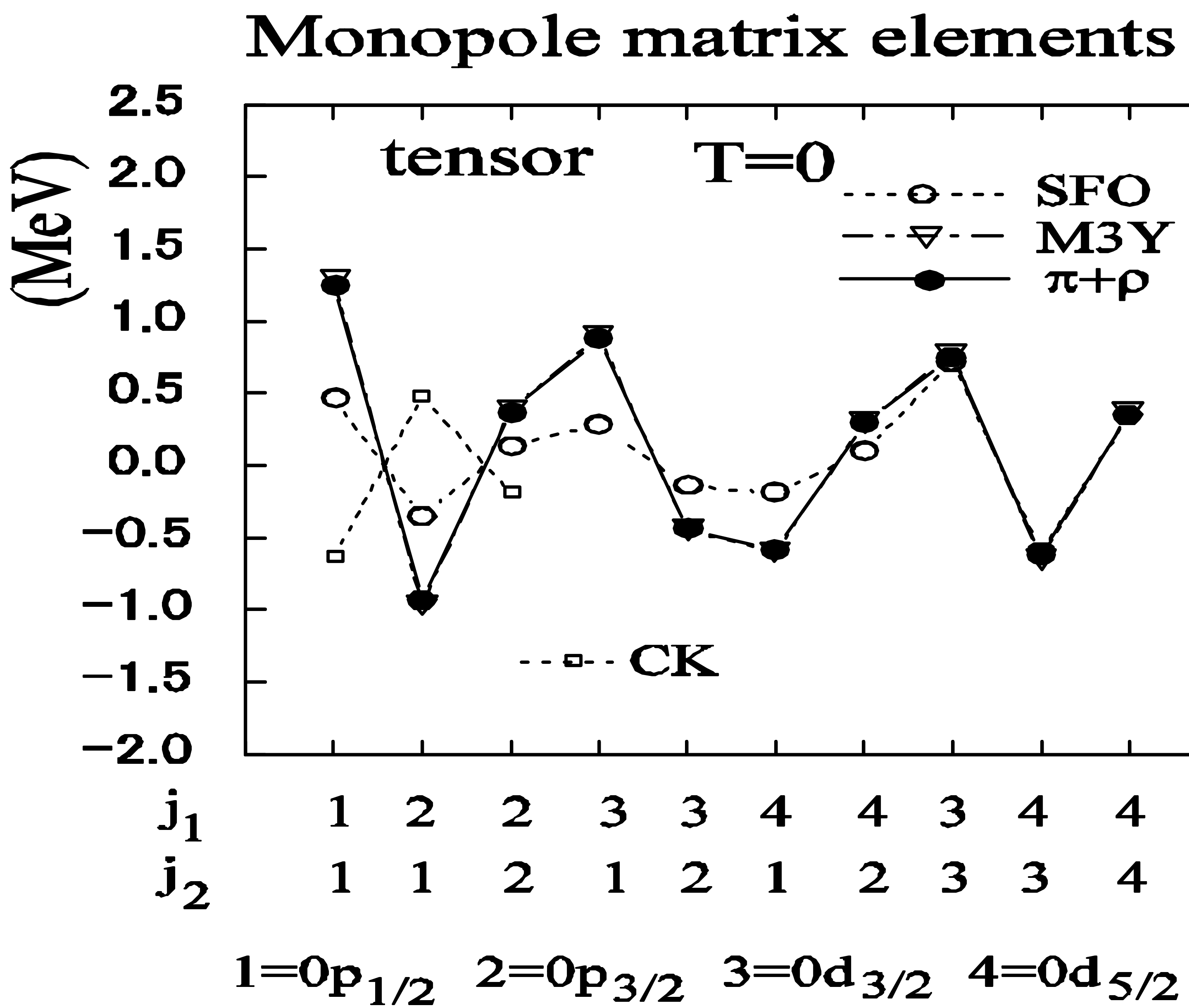
$$k = 0: central, \quad k = 1: spin-orbit, \quad k = 2: tensor$$

$$< abJT | V_k | cdJT > = (-)^J (2k+1) \sum_{LL'SS'} < ab | LSJ > < cd | L'S'J >$$

$$\begin{Bmatrix} L & S & J \\ S' & L' & k \end{Bmatrix} \sum_{J'} (-)^{J'} (2J'+1) \begin{Bmatrix} L & S & J' \\ S' & L' & k \end{Bmatrix} \sum_{j'_a j'_b j'_c j'_d} < a'b' | LSJ' > < c'd' | L'S'J' >$$

$$< a'b'J'T | V | c'd'J'T >$$

$$where \quad a = \{n_a l_a j_a\}, \quad a' = \{n_a l_a j_a'\} \quad etc.$$



Monopole matrix elements
tensor T=0
SFO
M3Y
π+ρ
CK
(MeV)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
j1 1 2 2 3 3 4 4 3 4 4
j2 1 1 2 1 2 1 2 3 3 4
1=0p1/2 2=0p3/2 3=0d3/2 4=0d5/2

Effects of Tensor Force on Shell Evolution

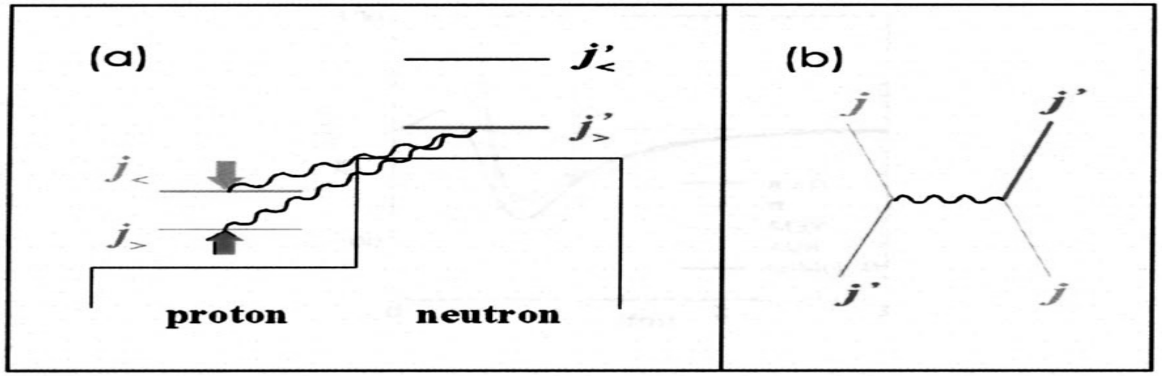


FIG. 1: (a) Schematic picture of the monopole interaction produced by the tensor force between a proton in $j_{>,<} = l \pm 1/2$ and a neutron in $j'_{>,<} = l' \pm 1/2$. (b) Exchange processes contributing to the monopole interaction of the tensor force.

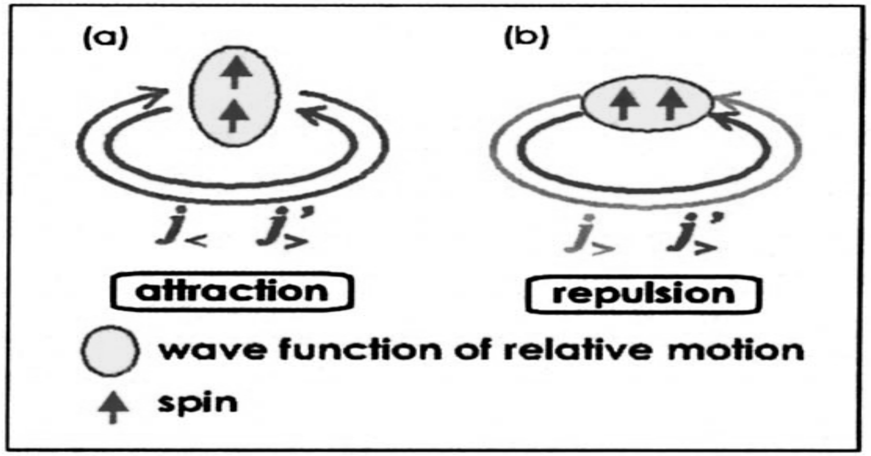
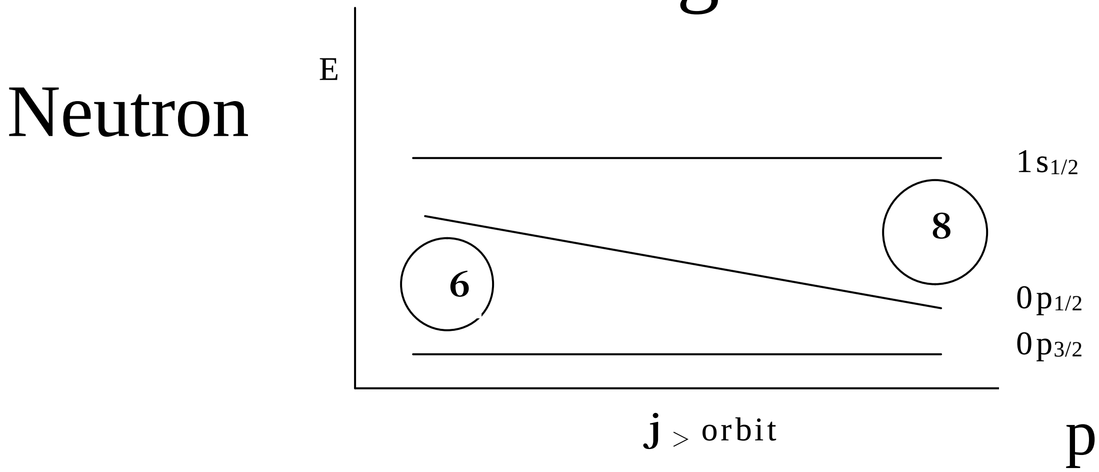
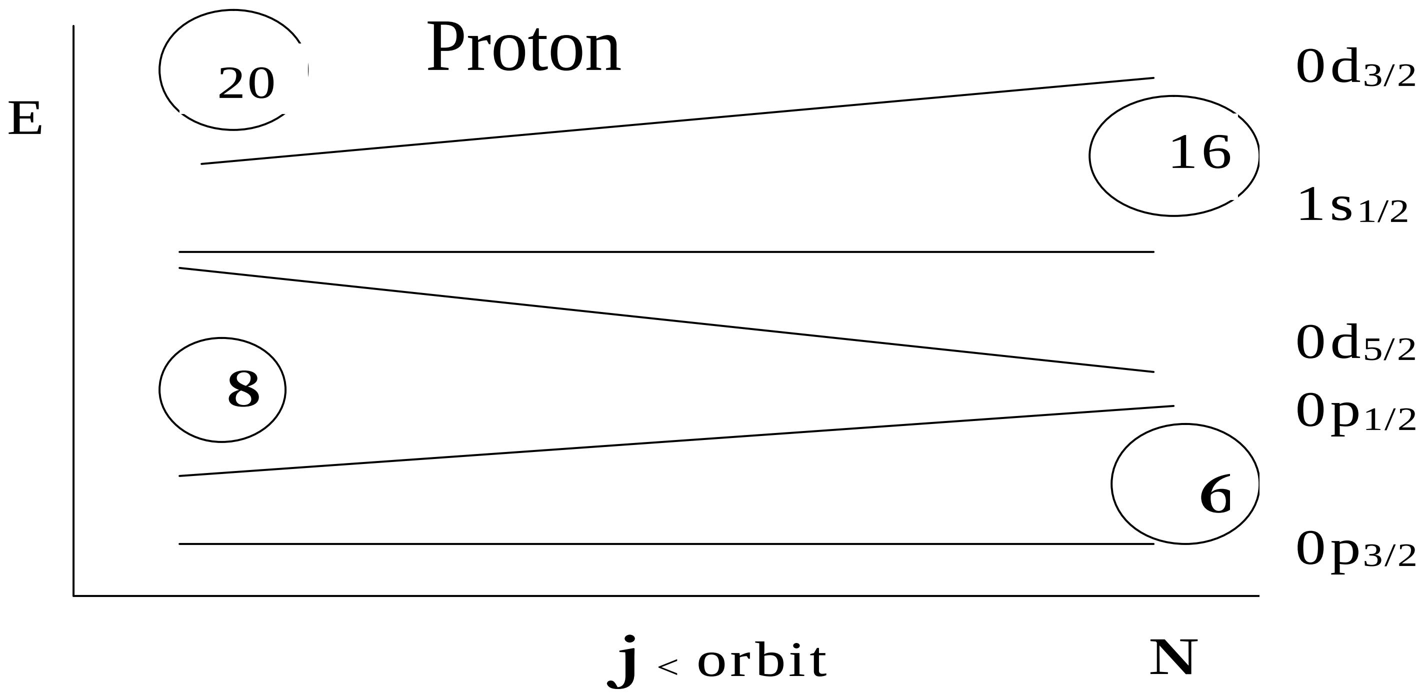


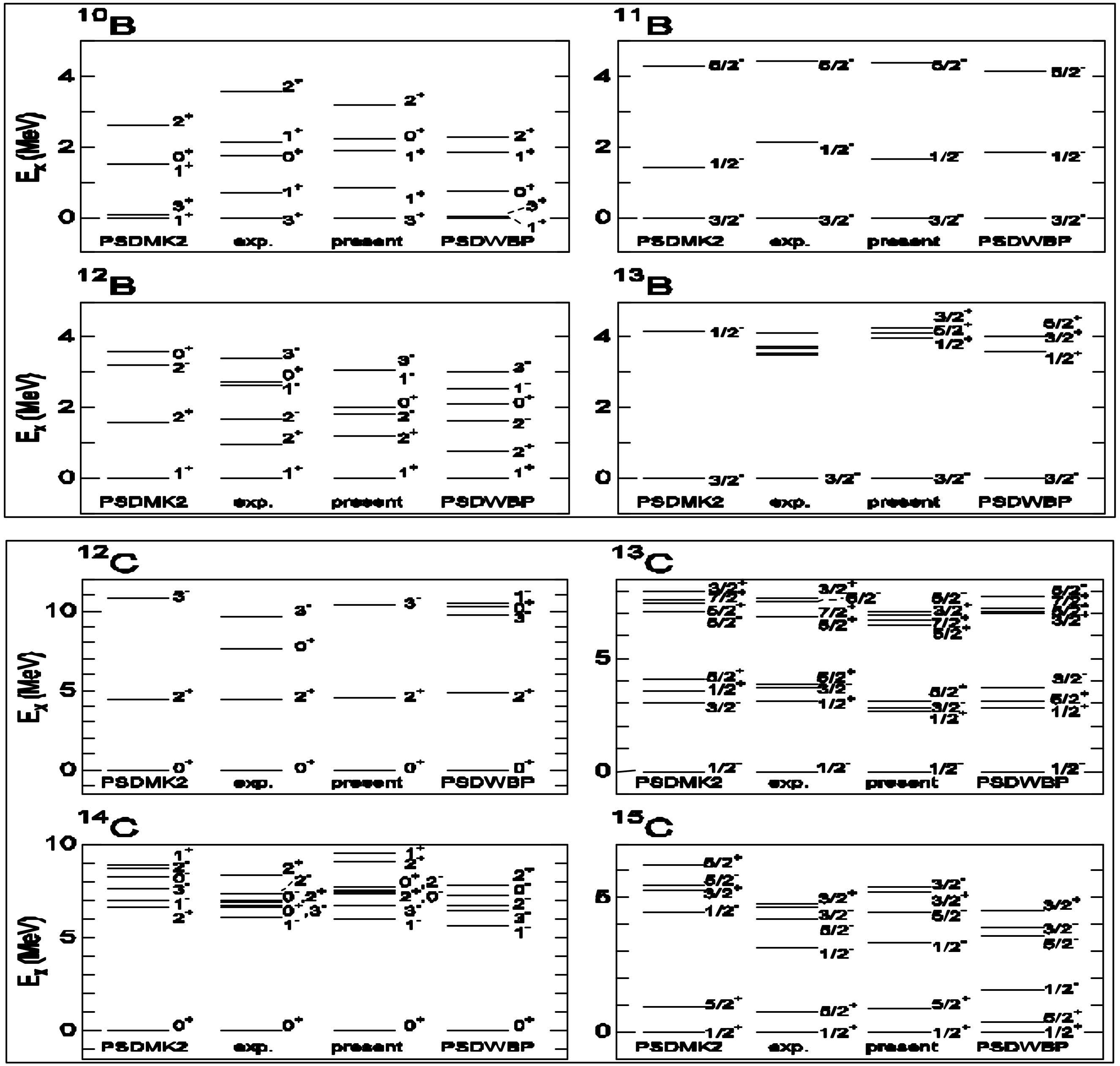
FIG. 2: Intuitive picture of the tensor force acting two nucleons on orbits j and j'.

Effective Single-Particle Energy

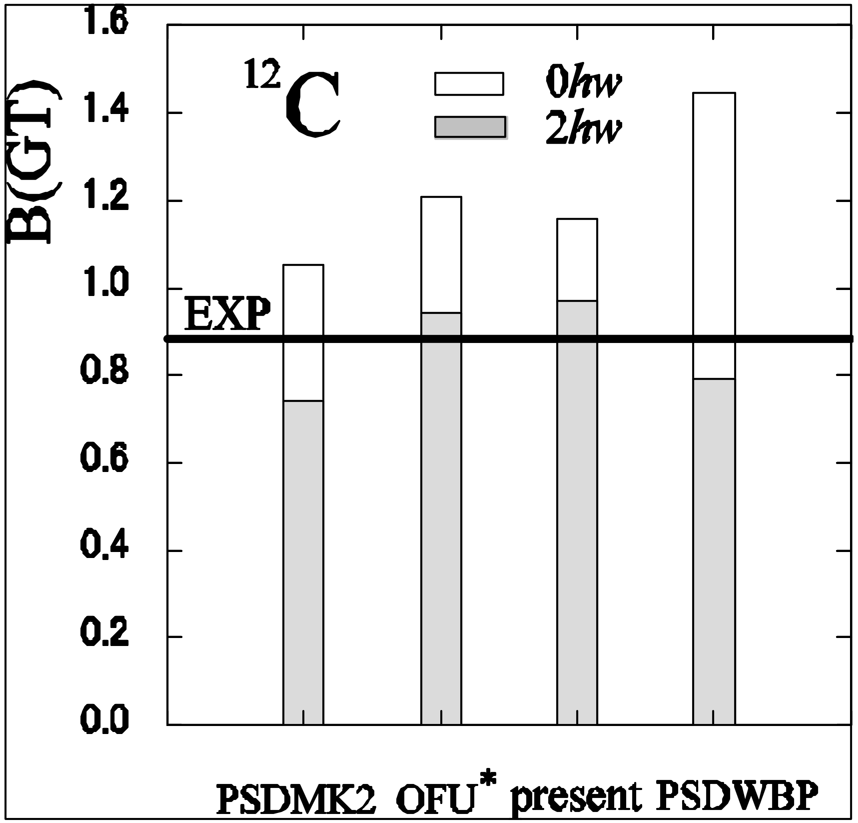




Energy levels of B and C isotopes

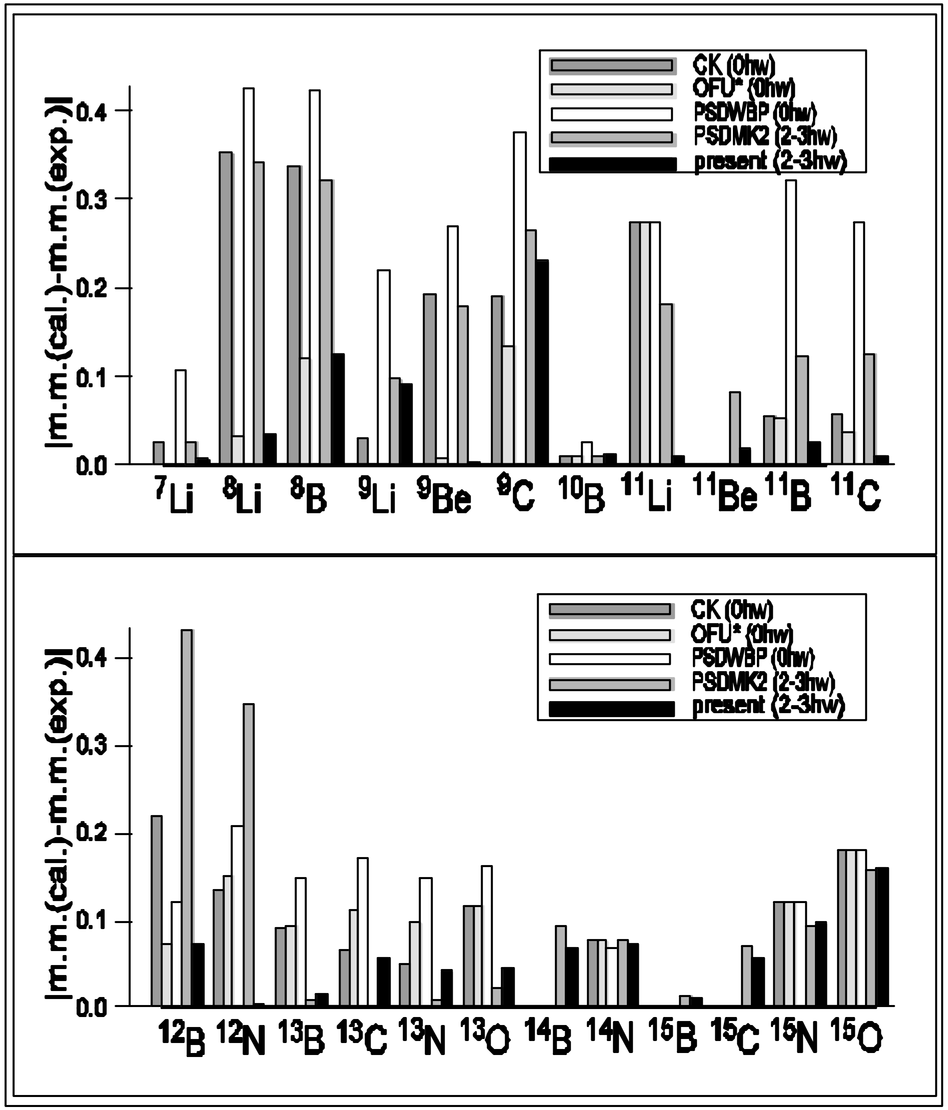


B(GT) values for ^{12}C -> ^{12}N



present = SFO

Magnetic moments of p-shell nuclei

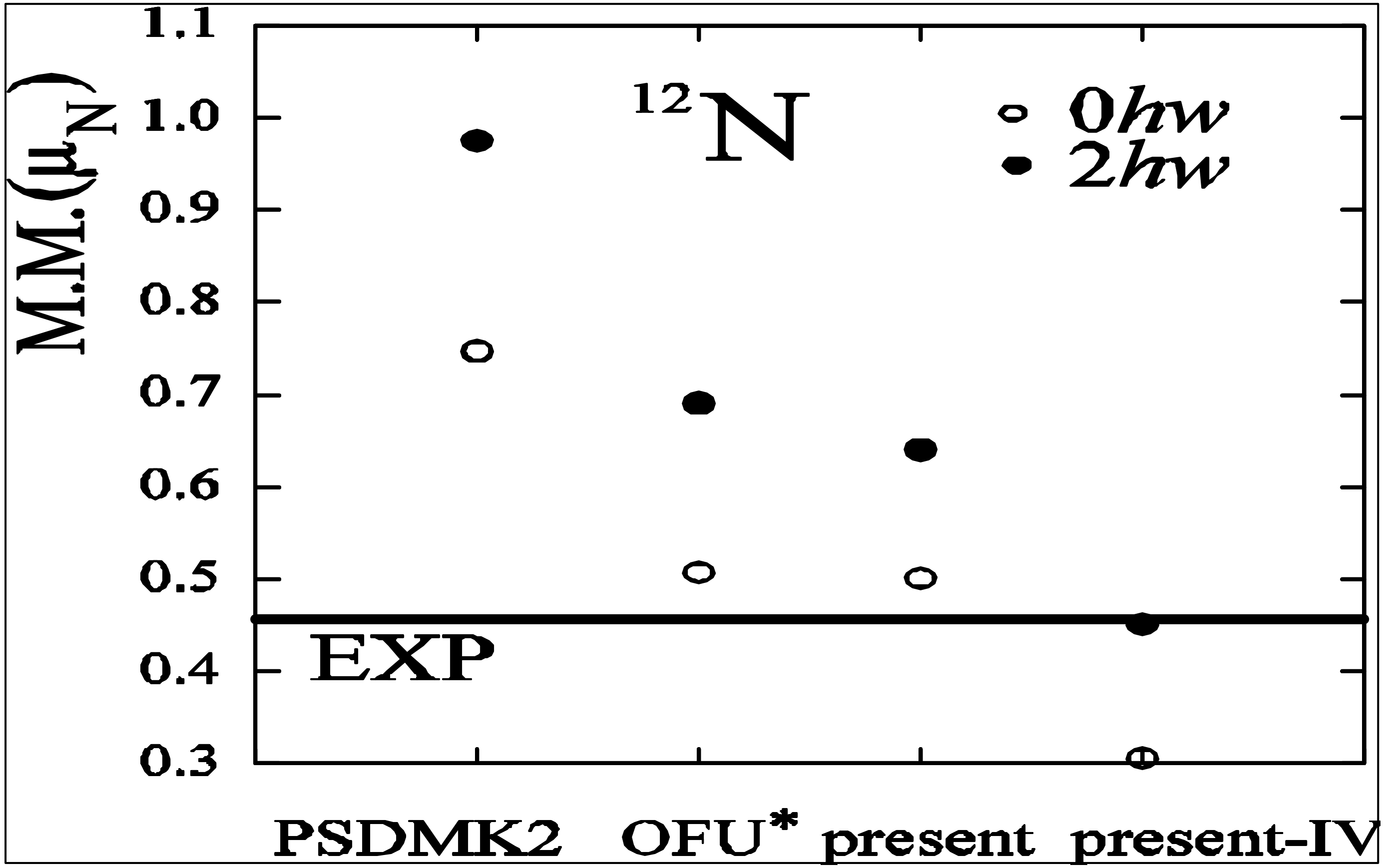


Magnetic Moments

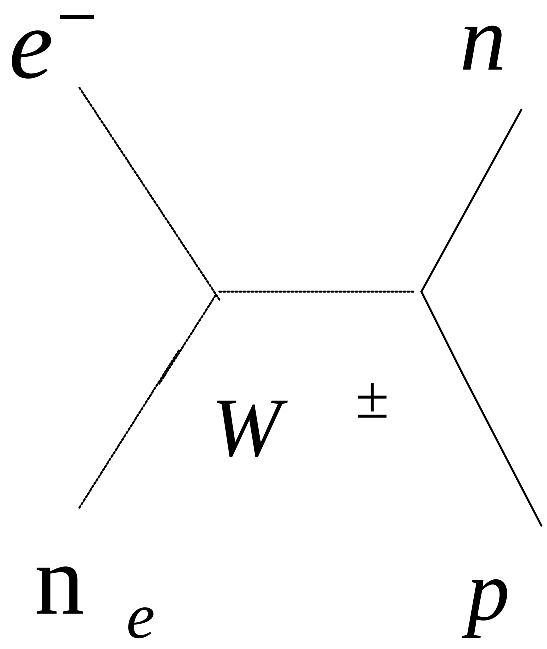
s.p. ： $[\pi p_{1/2} \times \nu p_{3/2}]^{1}_{1}$

$(-g_{\pi}^{?} + 1/2\, g_{\pi}^{s}) + 1/2\, g_{\nu}^{s} = -0.12\mu_{N}$

CK： $\mu = 0.778\mu_N$ ← Mixing of p1/2 and p3/2



Charge-Exchange Neutrino-Nucleus Reactions



$$H = \frac{G}{\sqrt{2}} j_{\ell}^{\mu} \cdot J_{\mu}^{h}$$

$$j_{\ell}^{\mu} = \overline{u}_e \gamma^{\mu} (1 + \gamma^5) u_{\nu}$$

$$J_{\mu}^{h} = V_{\mu} + A_{\mu}$$

$$\vec{V} \approx \frac{i}{2m} \vec{s} \times \vec{q} + \frac{1}{2m} (\vec{p} + \vec{p}\,')$$

$$\vec{A} \approx g_A \vec{s}$$

Spin-dependent excitations

- Gamow-Teller (1^+): $\vec{s}\ \ t_{\pm}$
- Spin-diole (0^-, 1^-, 2^-): $[\vec{s}\times\vec{r}]^J\ t_{\pm}$

Multipoles

1^+: $E_5 1$, $M1$, $C_5 1$, $L_5 1$

2^-: $E_5 2$, $M2$, $C_5 2$, $L_5 2$

1^-: $M_5 1$, $E1$, $C1$

0^-: $C_5 0$, $L_5 0$

Folding over neutrino spectrum

$$s_{E_x} = \int s_{E_x}(E)\, f(E)\, dE$$

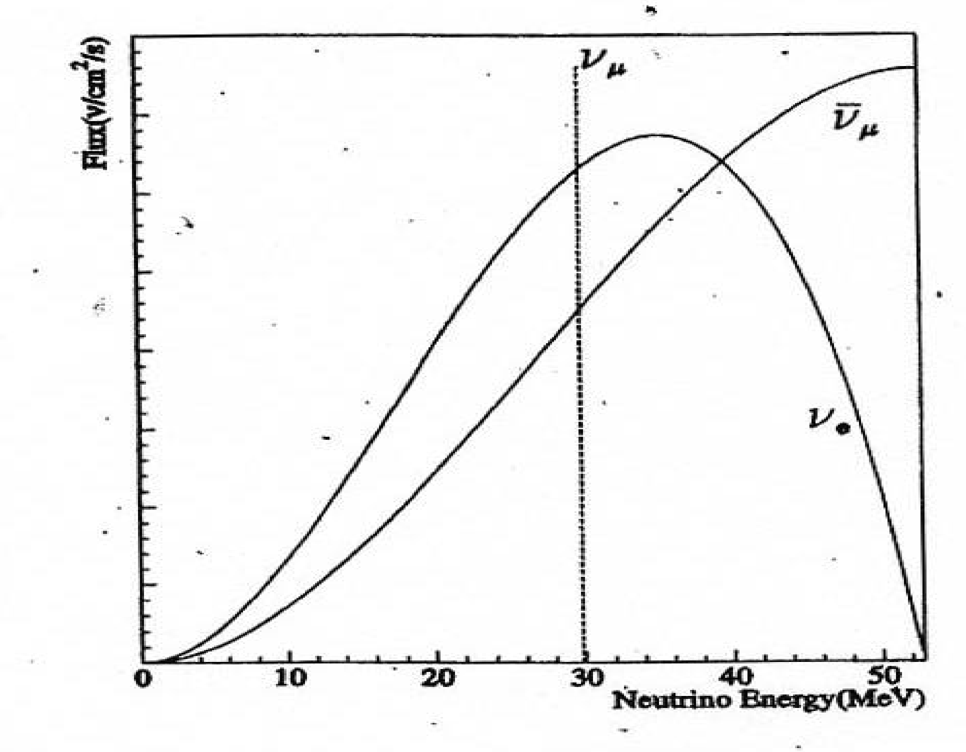
$$s_{E_x}(E) = \int \frac{d s_{E_x}}{d\Omega} d\Omega$$

● DAR n_e spectrum

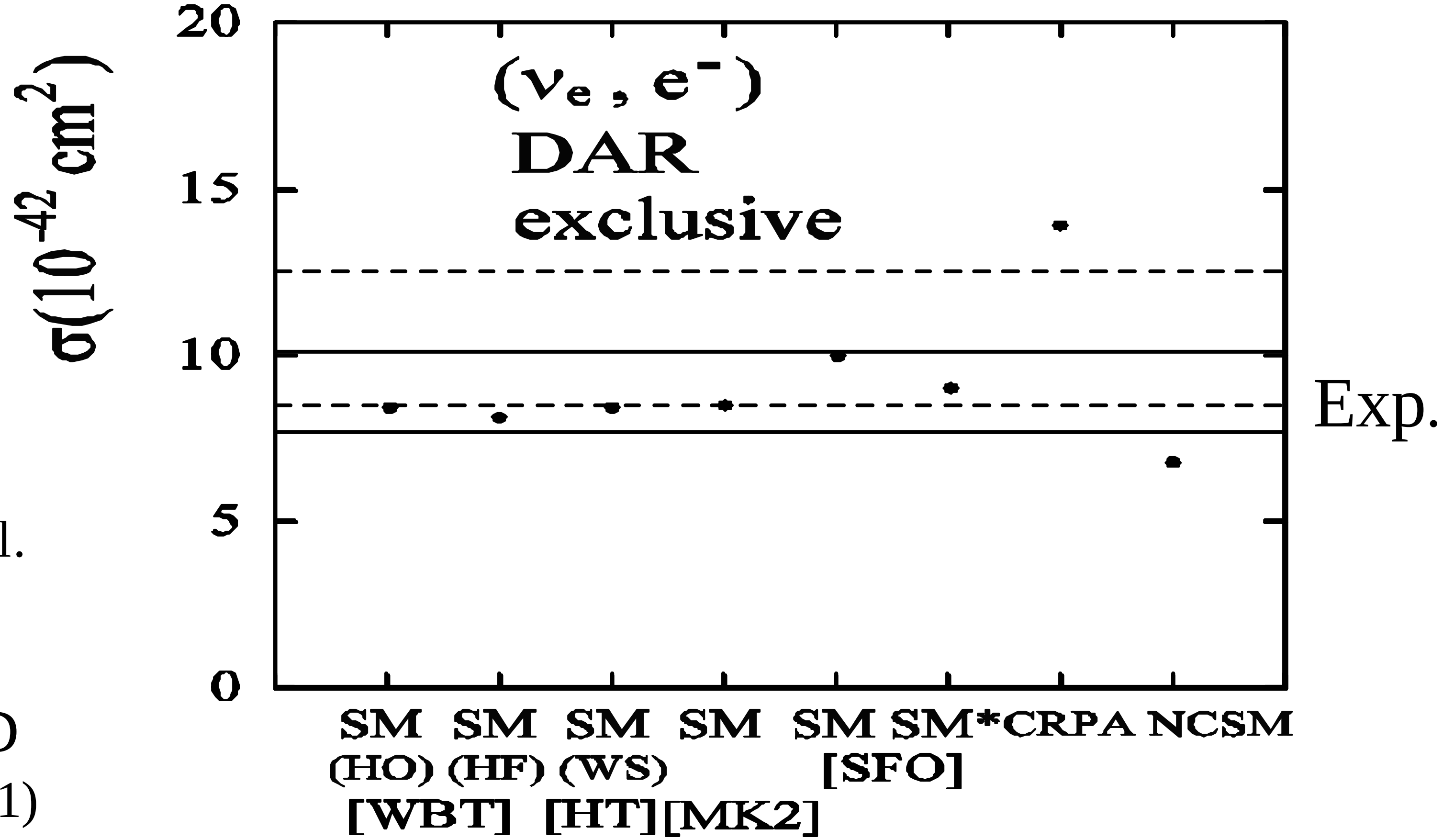
$$p^+ \rightarrow m^+ + n_m$$

$$m^+ \rightarrow e^+ + n_e + \bar{n}_m$$

<E(ν $_e$)>～35 MeV



- WBT: Warburton-Brown
  Volpe, Auerbach, Colo, Suzuki, Van Giai, PR C62 (2000)
- HT: Hayes-Towner, PR C62, 015501 (2000)
  p:Cohen-Kurath (8-16)2BME, sd: USD of Wildenthal, pf: KB3,
  p-sd and others: Millener-Kurath
- SFO*: g^{eff}_A/g_A=0.95
- NCSM: Hayes-Navratil-Vary, PRL 91 (2003) AV8'(2-body) + TM'(99) (3-body)
- CRPA: Kolb-Langanke-Vogel, NP A652, 91 (1999)

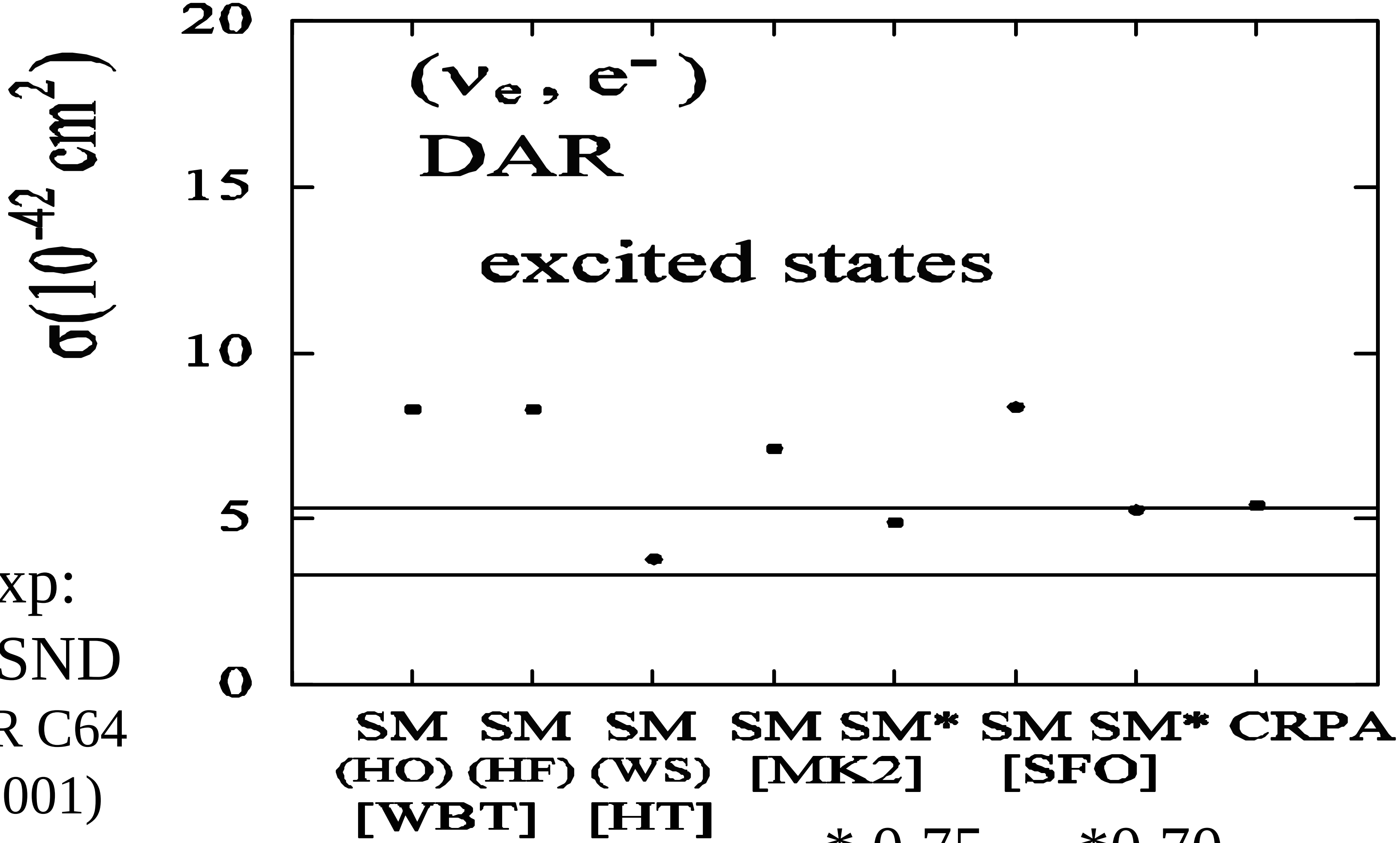


Allenet.al. (1990)

Exp: LSND
PR C64 (2001)

Inclusive = Exclusive ($1^+_{g.s.}$) + Excited state

? $3\hbar$ w



Exp:
LSND
PR C64
(2001)

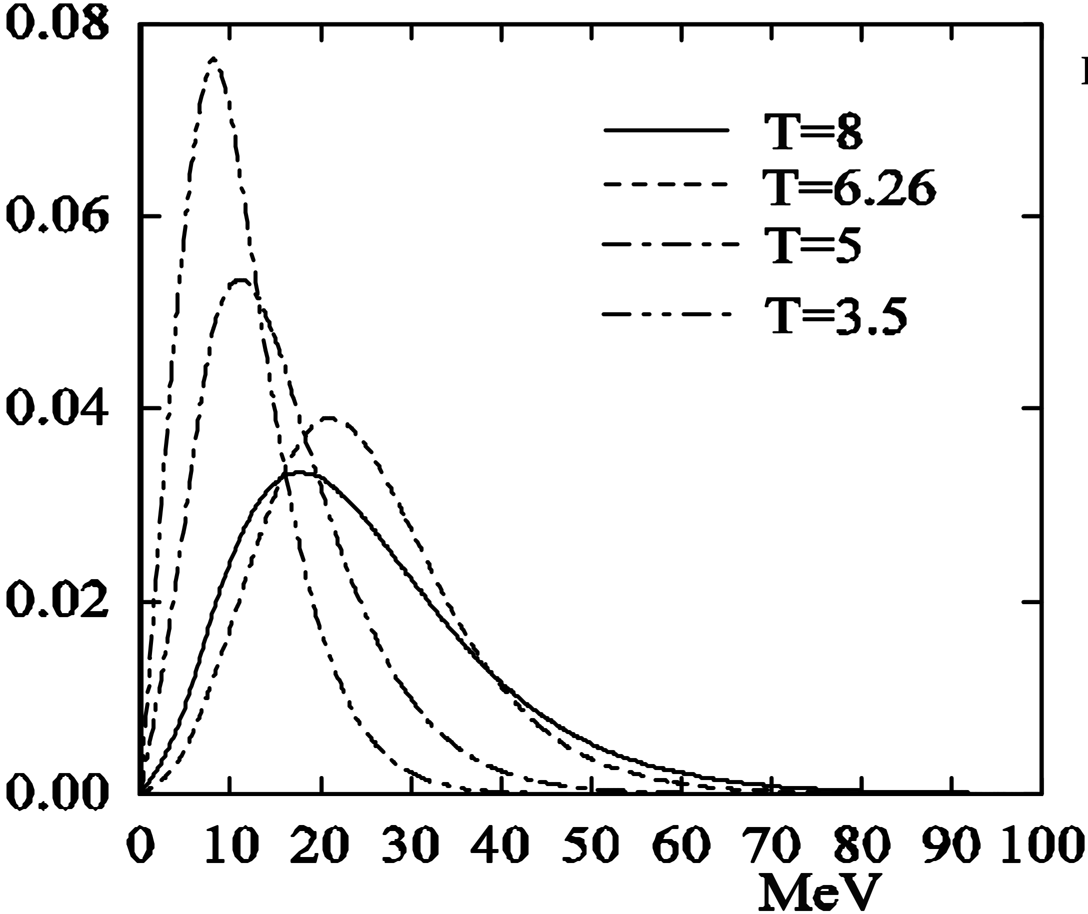
* 0.75 *0.70

Supernovae ν Spectra

$\sigma \propto E^2$

<E> & tail part

$$f(E) = N \frac{E^2 / T^3}{1 + \exp[E/T - a]}$$



$n_m, n_t : \langle E \rangle = 25\ MeV$

$(T, a) = (8 MeV, 0)$

$(6.26 MeV, 3)$

$n_e : \langle E \rangle = 11\ MeV$

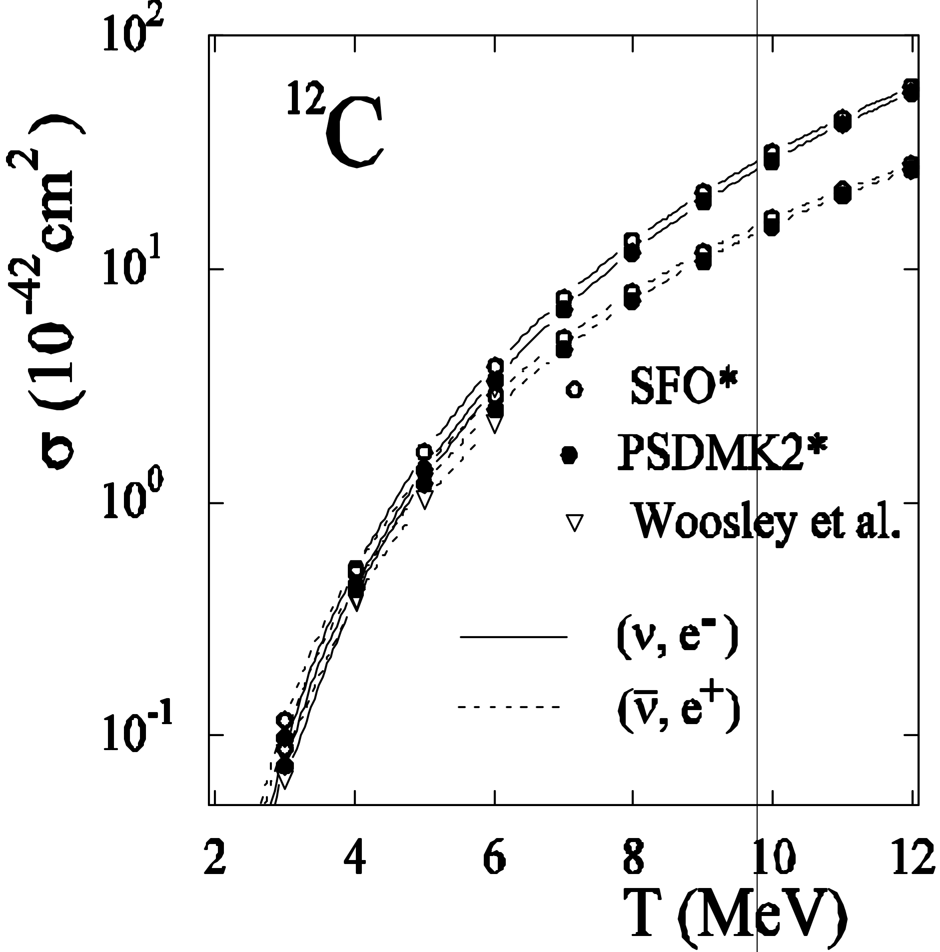
$(T, a) = (3.5 MeV, 0)$

$\overline{n}_e : \langle E \rangle = 16\ MeV$

$(T, a) = (5 MeV, 0)$

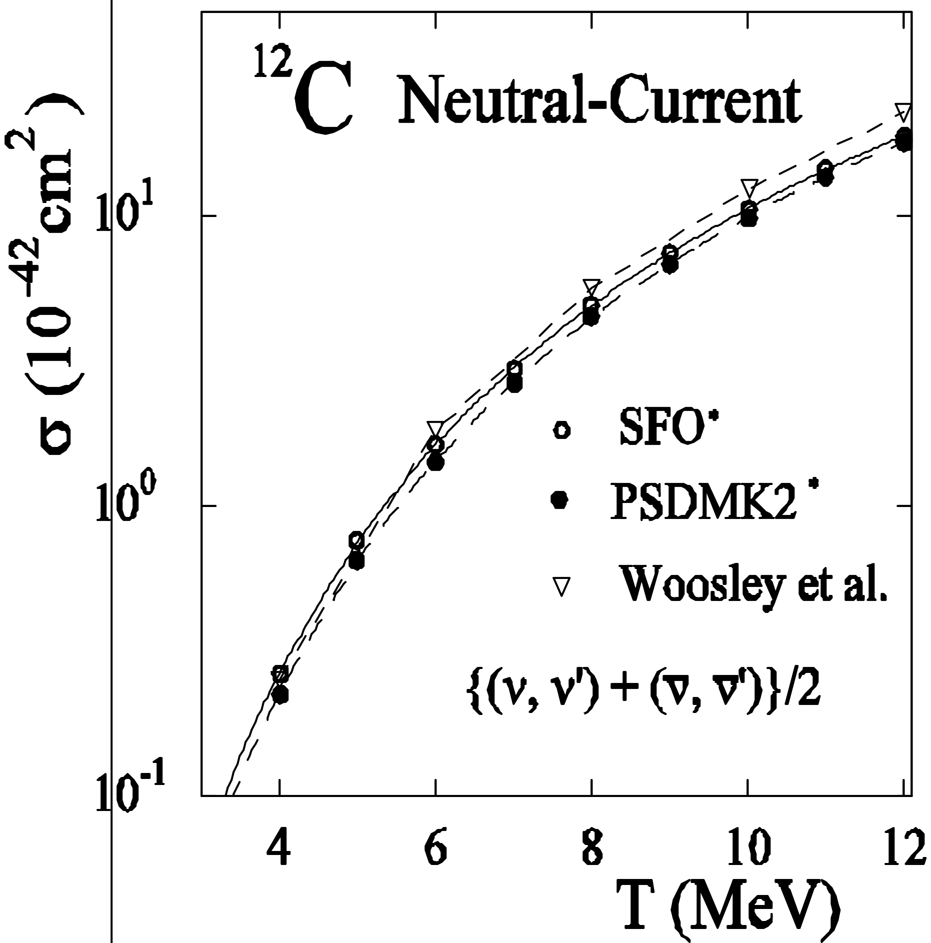
Charge-exchange

SFO* PSDMK2*

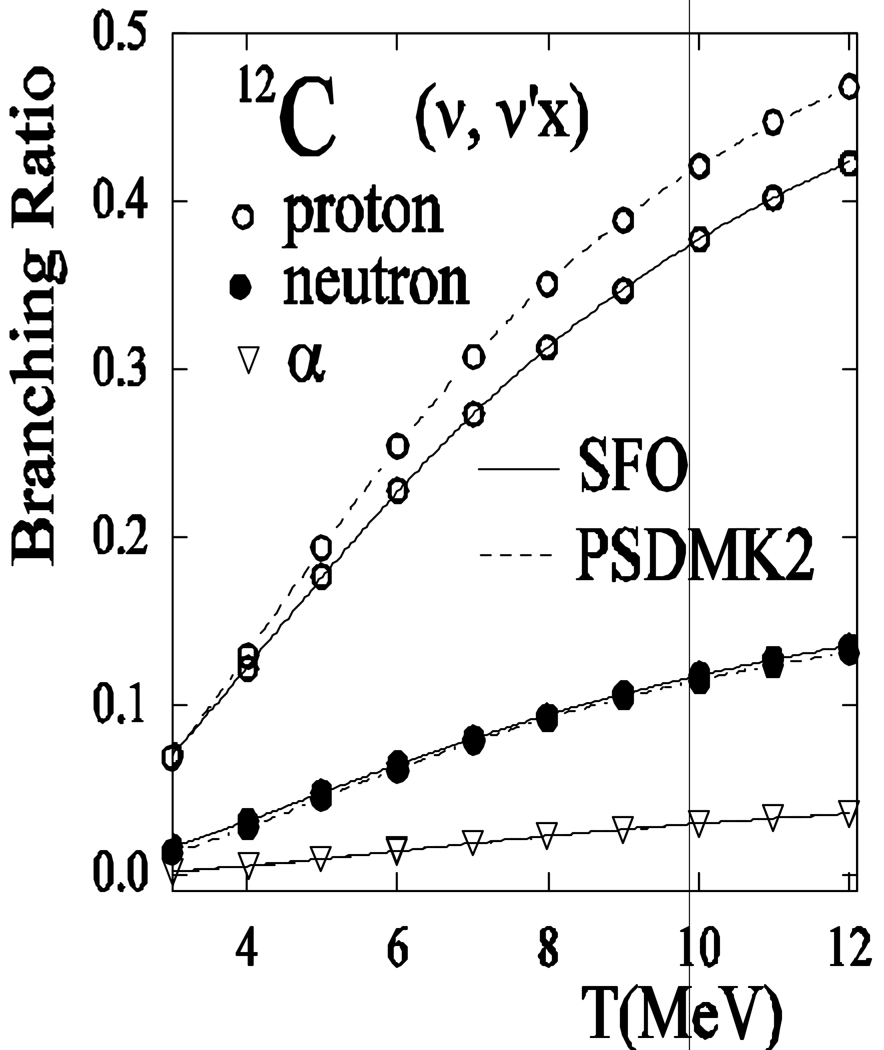


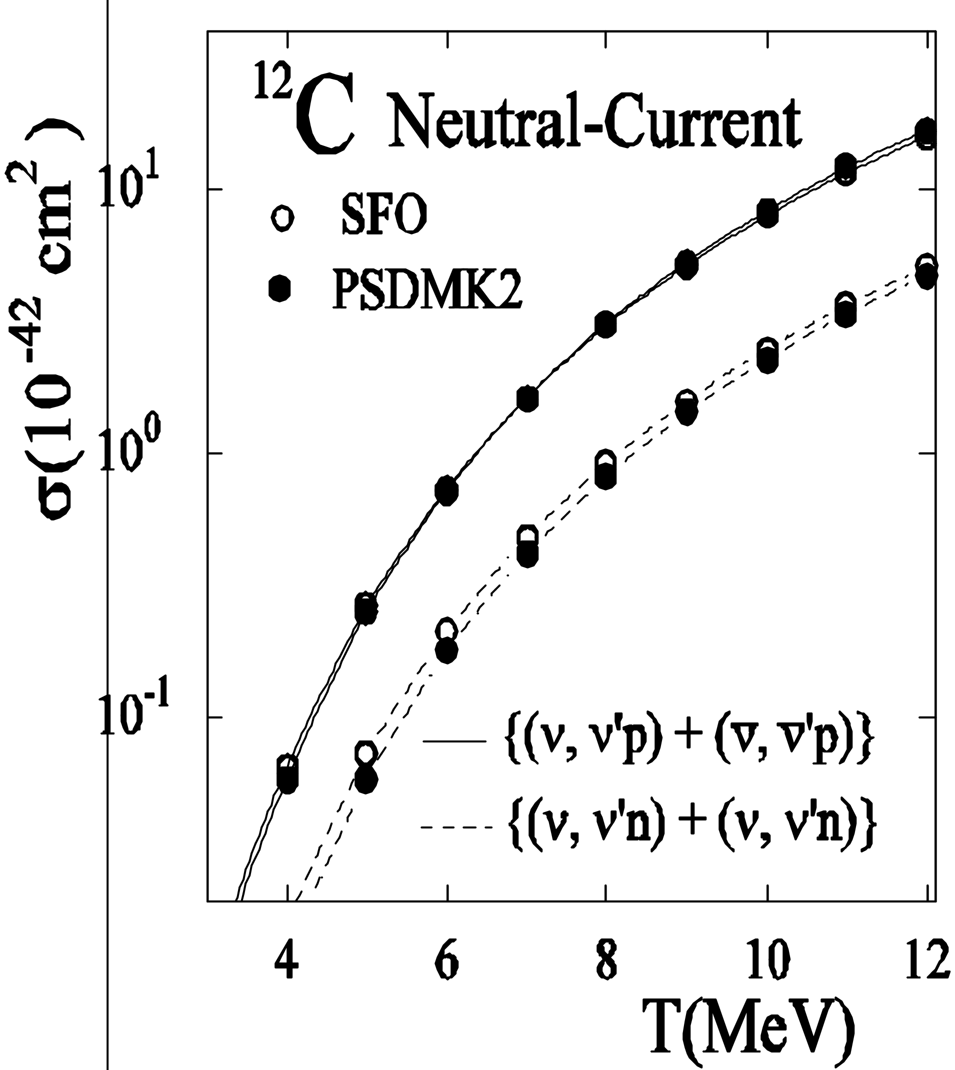
Neutral-Current

SFO* PSDMK2*

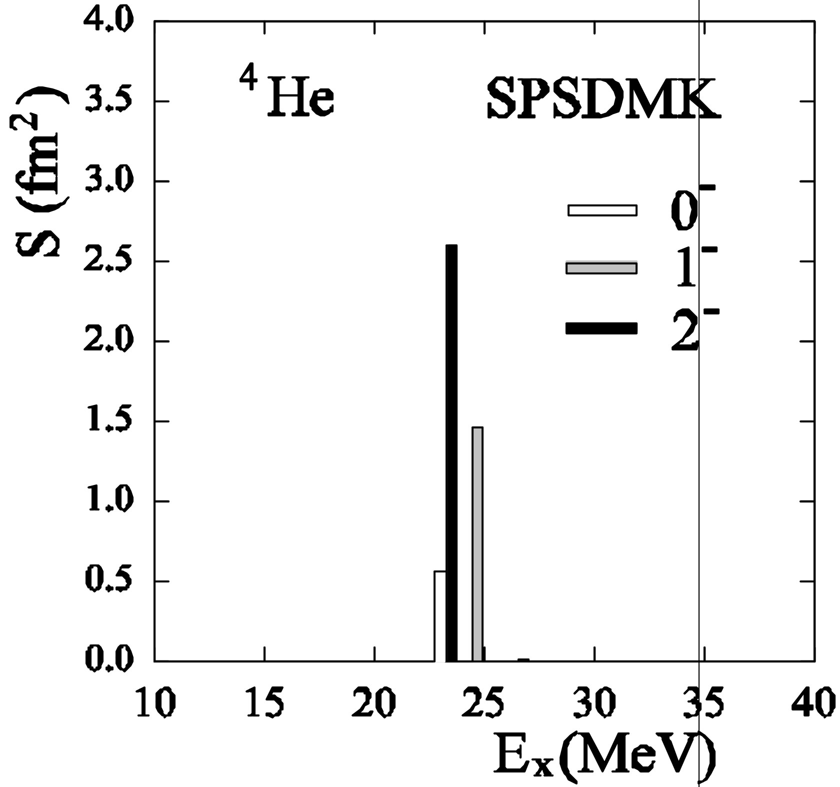


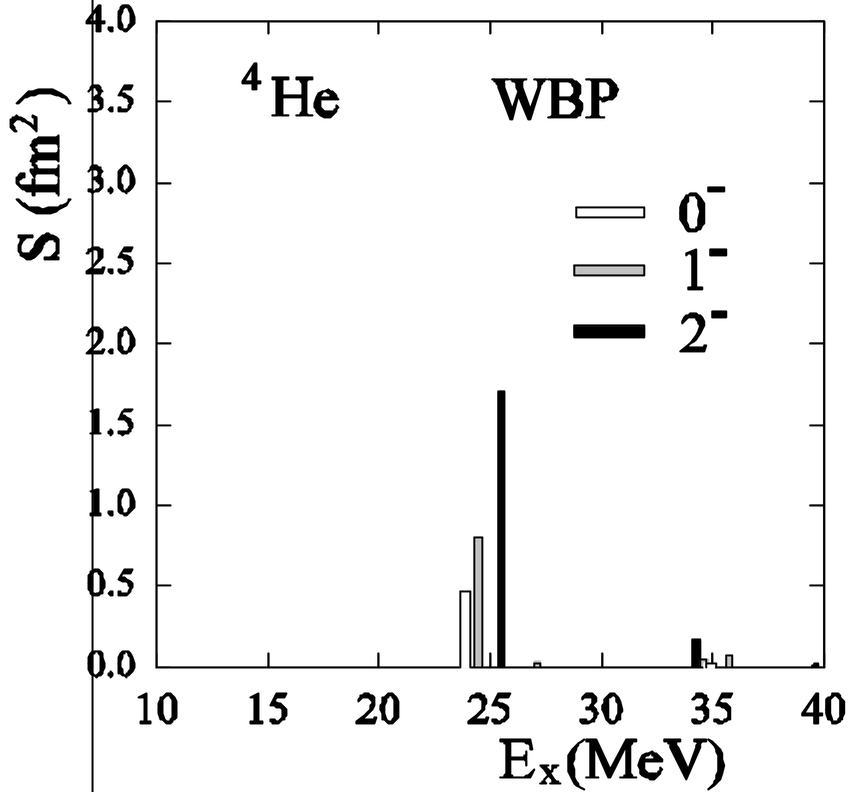
Proton and eutron emissions
BR: Hauser-Feshbach model





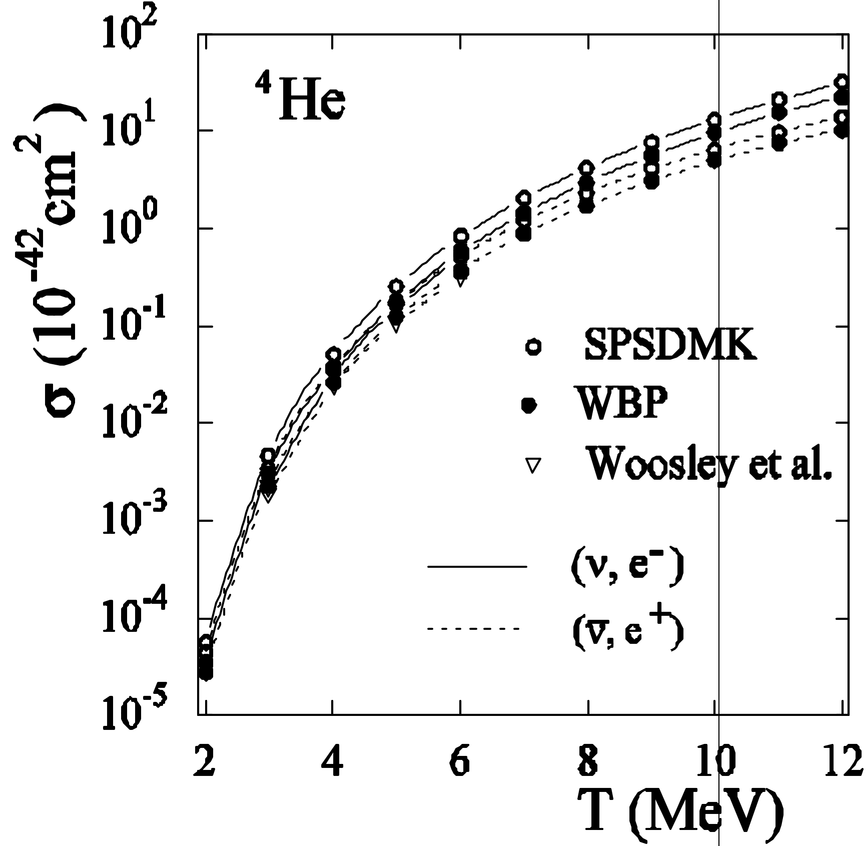
Spin-dipole strength in ^4He

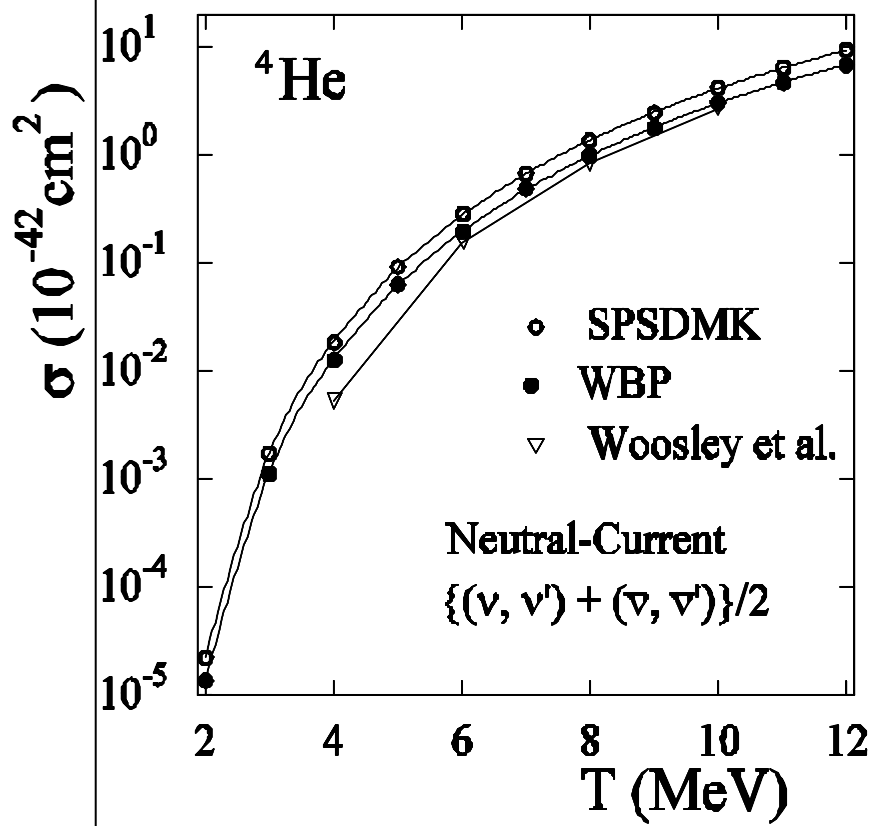




Charge-exchange

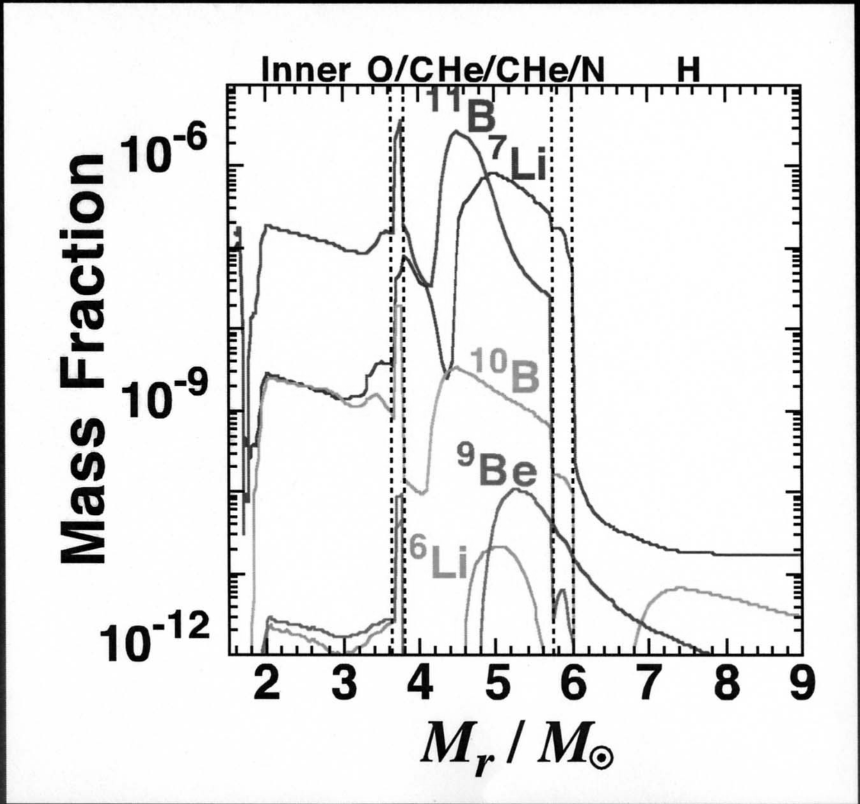
Neutral-Current



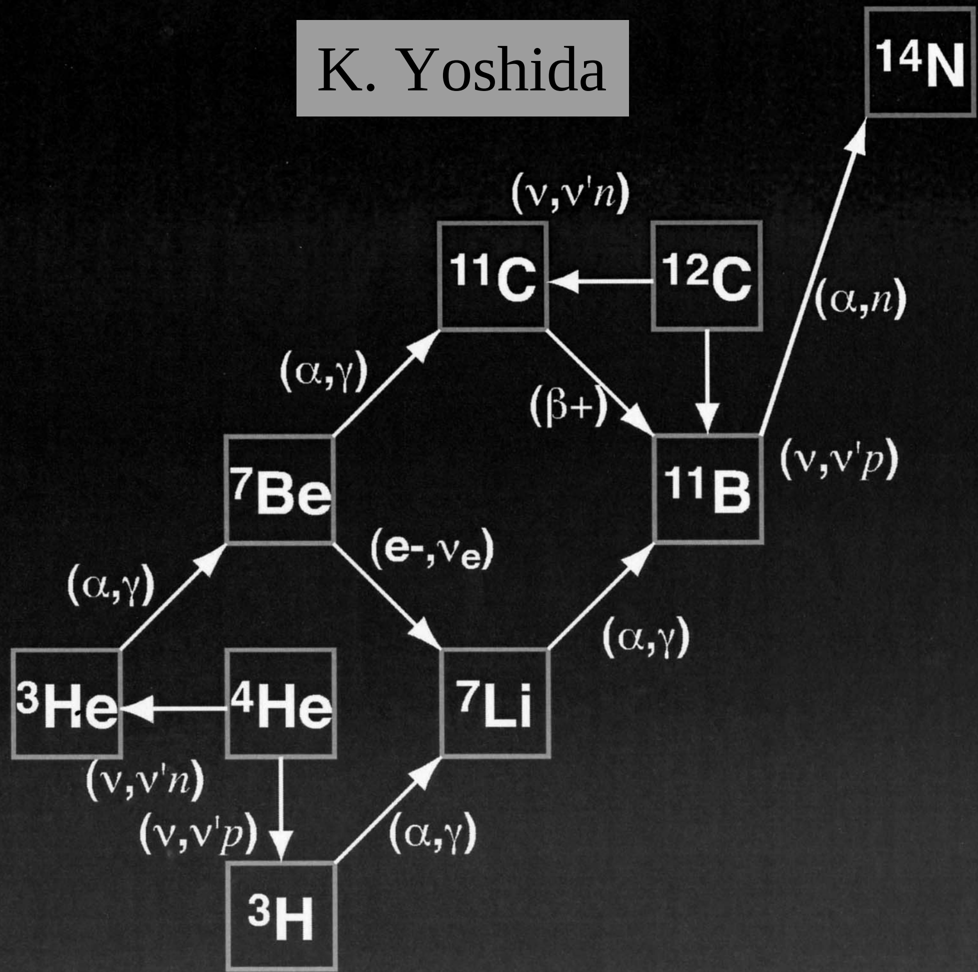


軽元素の質量比分布と合成過程

K. Yoshida



E_ν=300 foe, τ_ν = 3 s, $T_{\nu\mu,\tau}$= 8 MeV



^{7}Li & ^{11}B production in He/C layer

^{4}He$(\nu,\nu' p)^{3}$H, ^{4}He$(\nu,\nu' n)^{3}$He, ^{12}C$(\nu,\nu' p)^{11}$B

^{4}He$(\bar{\nu}_e,e^{+}n)^{3}$H, ^{4}He$(\nu_e,e^{-}p)^{3}$He

Neutrino Nucleus Reactions on Fe and Ni Isotopes

Charge-exchange reactions; (ν_e, e^-), $(\bar{\nu}_e, e^+)$

- Gamow-Teller transitions

  GT strength: shell model calculation by Honma

- Emissions of proton, neutron, α, γ

  $(\nu_e, e^- p)$, $(\nu_e, e^- n)$, $(\nu_e, e^- \alpha)$, $(\nu_e, e^- \gamma)$, $(\nu_e, e^- pn)$,

  $(\nu_e, e^- pp)$, $(\nu_e, e^- \alpha p)$, $(\bar{\nu}_e, e^+ n)$

New features in GXPF1 by Honma et al.

KB3G   A = 47-52

KB + monopole corrections

G: improved gap,   3: fine tuning in V_{fr} (A = 50 -52)

GXPF1   A = 47-66

○ More attraction for T=0 m.e. than G-matrix

$E(1p_{3/2}) - E(0f_{7/2}) \sim 3$ MeV   cf. ~ 2 MeV for KB3, FPD6

New magic number at N = 34   cf.   N = 32 for KB3, FPD6

○ r.m.s deviations from observed values   GXPF1 vs KB3G

Z, N <28; Z<28, N>28: similar

Z or N =28 (^{56}Ni, ^{55}Co, ^{57}Ni); Z, N>28: smaller for GXPF1

Core excitations are not well described by KB3G

○ Monopoles   GXPF1 vs KB3G

1p-1p part differ

GXPF1: not a constant shift (J-dependence)

○ Systematic description of 2_1^+ energies in Ni, Ca, Ti, Cr, Fe isotopes

cf. KB3G ^{56}Ni : $E_{cal} - E_{exp} \sim 2$ MeV

○ ^{56}Ni-core

$(f_{7/2})^{16}$:   69% (GXPF1), 49% (FPD6)

$B(GT_+)$: 11.3 (GXPF1), 10.1 (KB3), 13.7 (closed core)

Cross Sections for GT (J=1$^+$) transitions

$$\left(\frac{ds}{d\Omega}\right)_{(n\,,e^-)/(\bar{n}\,,e^+)} = \frac{G_F^2\cos^2 q_C}{2p^2} E_e p_e F(Z_f\,,E_f)\frac{4p}{2J_i+1}\cos^2\frac{q}{2}$$

$$\{K_T(q,w)[|< J_f\,||T_J^{mag}||\,J_i>|^2 + |< J_f\,||T_J^{el,5}||\,J_i>|^2] \mp K_{TI}(q,w)$$

$$2\,\mathrm{Re}[< J_f\,||T_J^{mag}||\,J_i>< J_f\,||T_J^{el,5}||\,J_i>^*]\}$$

$$< J_f\,||T_J^{el,5}||\,J_i> \cong i g_A\sqrt{\frac{2}{3}}\frac{1}{\sqrt{4p}}< J_f\,||s\;j_0(qr)||\,J_i>$$

$$< J_f\,||T_J^{mag}||\,J_i> \approx -\frac{q}{2M}g^{IV}\sqrt{\frac{2}{3}}\frac{1}{\sqrt{4p}}< J_f\,||s\;j_0(qr)||\,J_i>$$

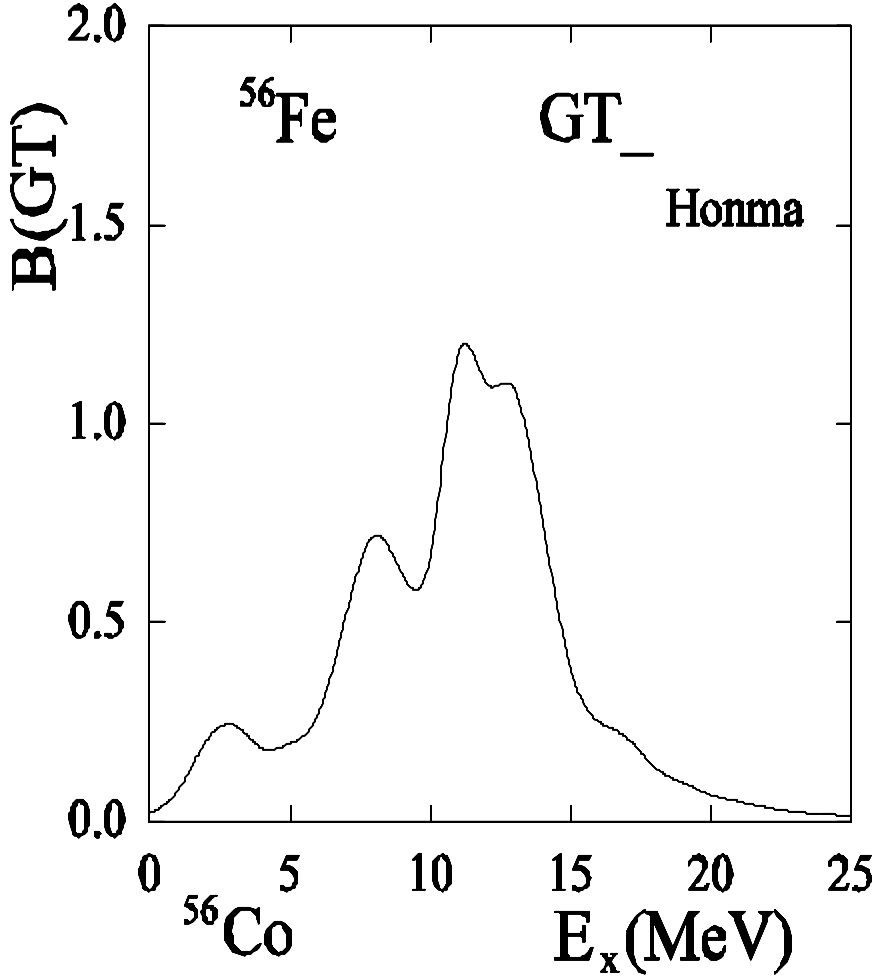
$$< J_f\,||s\;j_0(qr)||\,J_i> \square < J_f\,||s\;||\,J_i>\;j_0(qR)$$

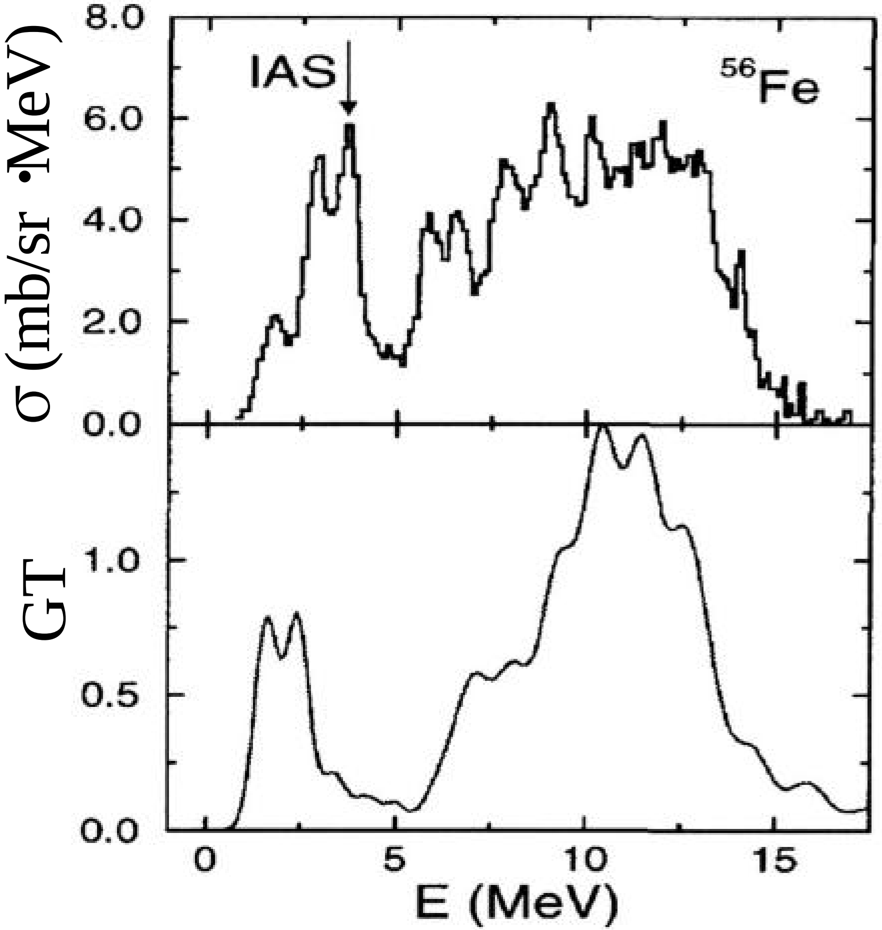
$$cf.\quad B(GT) = \frac{1}{2J_i+1}|< J_f\,||s\;||\,J_i>|^2$$

$$K_T(q,w) = \frac{q^2-w^2}{2q^2}+\tan^2\frac{q}{2},\quad K_{TI}(q,w) = \tan\frac{q}{2}\sqrt{\frac{q^2-w^2}{2q^2}+\tan^2\frac{q}{2}}$$

$$^{56}Fe(n_e, e^-)^{56}Co$$ **GXPF1** Honma et al.

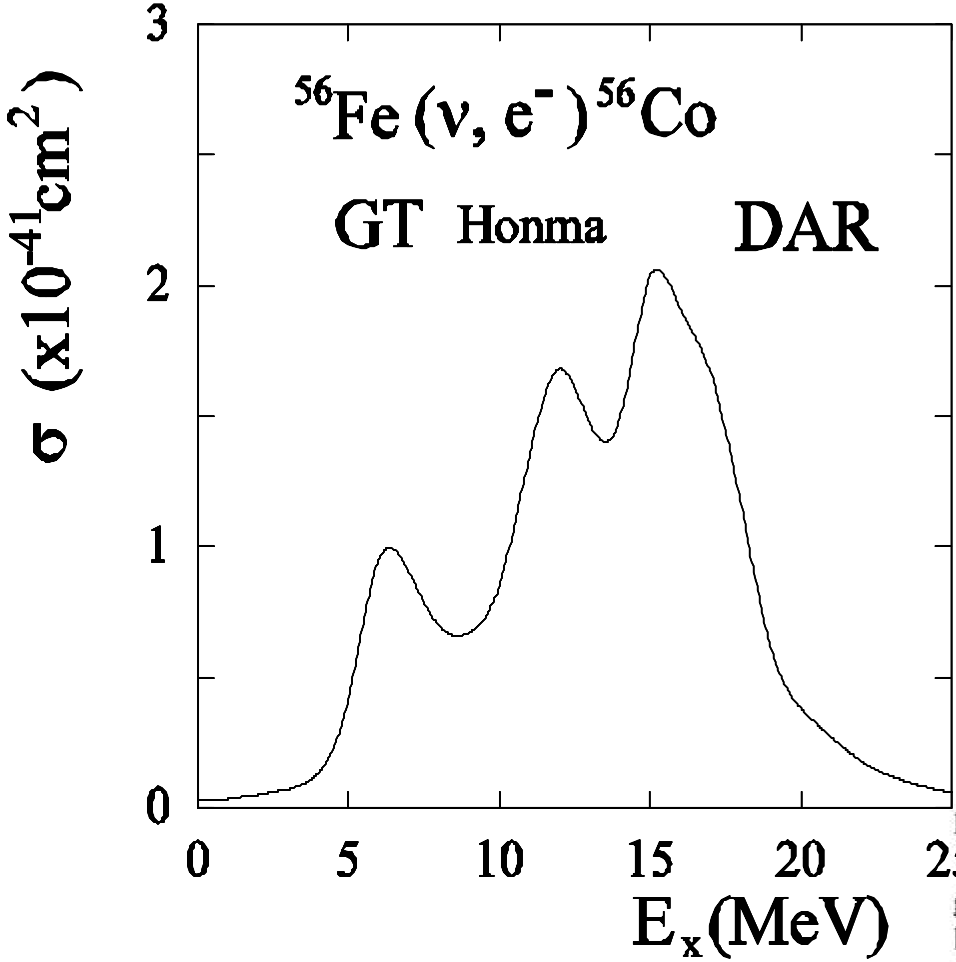
B(GT) **cf. KB3 Caurier et al.**





B(GT)=9.47 $B(GT)_{exp}$= 9.9±2.4 $B(GT)_{KB3}$=8.85

DAR GXFP1 cf. KB3 Kolb, Langanke, Martinez-Pinedo



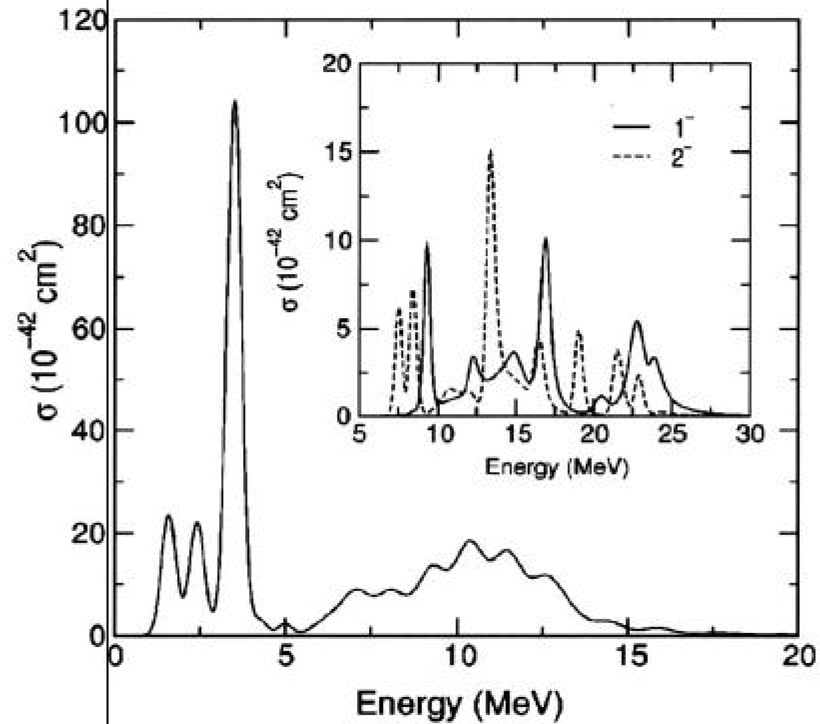


FIG. 1. Differential $^{56}Fe(\nu_e, e^-)^{56}Co$ cross section for the KARMEN neutrino spectrum as function of excitation energy in ^{56}Co. The figure shows the allowed contributions, while the inset gives the contributions of the 1^- and 2^- multipolarities. The allowed contributions have been folded with a Gaussian of 0.5 MeV full width at half maximum (FWHM) at energies below 5 MeV and with 1 MeV FWHM above 5 MeV.

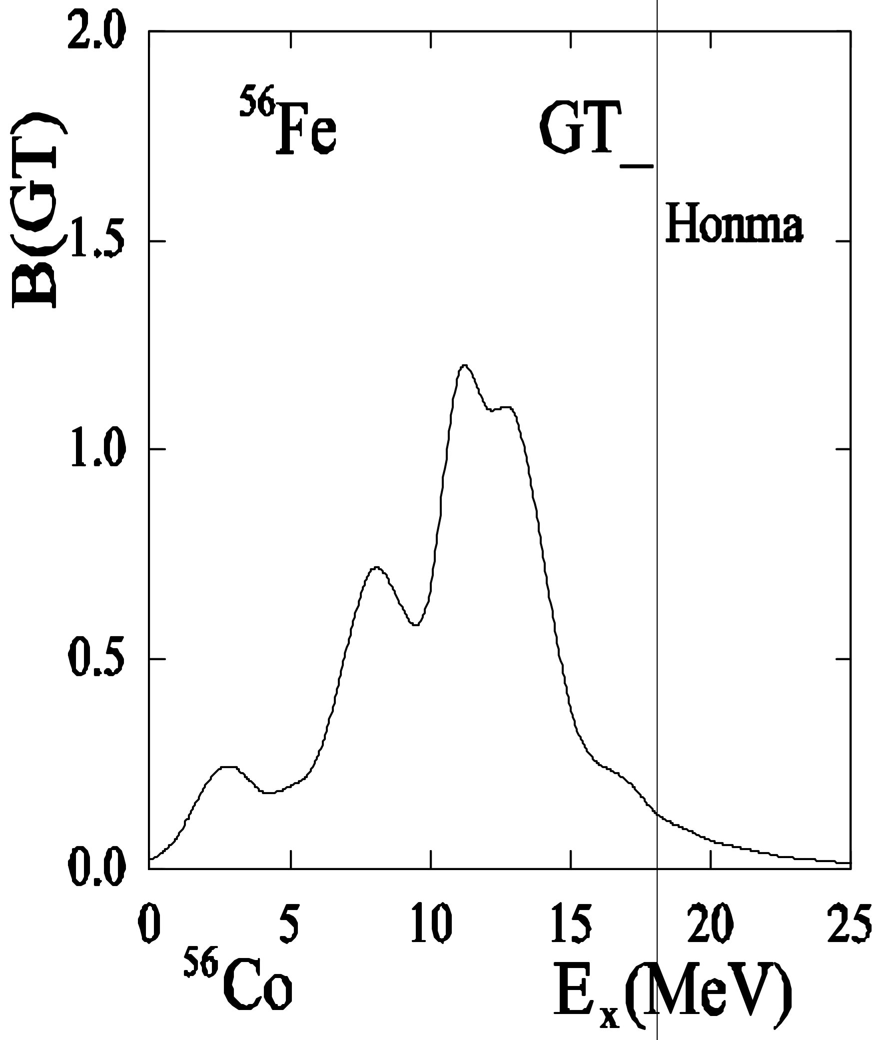
$$s = 1.99\times10^{-40} \boldsymbol{cm}^2 (\boldsymbol{GT})$$

$$s_{\exp} = 2.56 \pm 1.08 \pm 0.43 \boldsymbol{cm}^2 \qquad s = 1.12\times10^{-40} \boldsymbol{cm}^2 (\boldsymbol{GT})$$

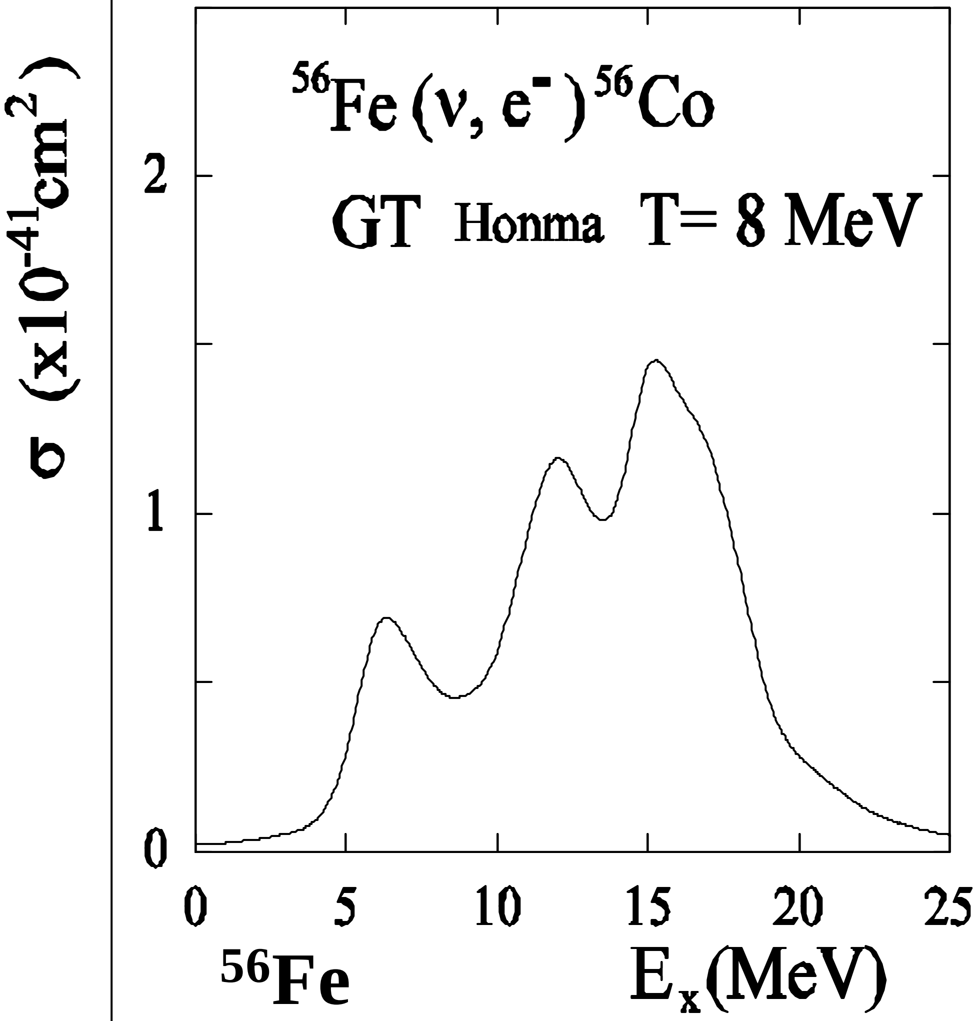
$$\boldsymbol{B}(\boldsymbol{GT}) = 9.47 \qquad \boldsymbol{B}(\boldsymbol{GT}) = 8.85$$

$^{56}Fe(\nu_e, e^-)^{56}Co$ **GXPF1** Honma et al.

B(GT)



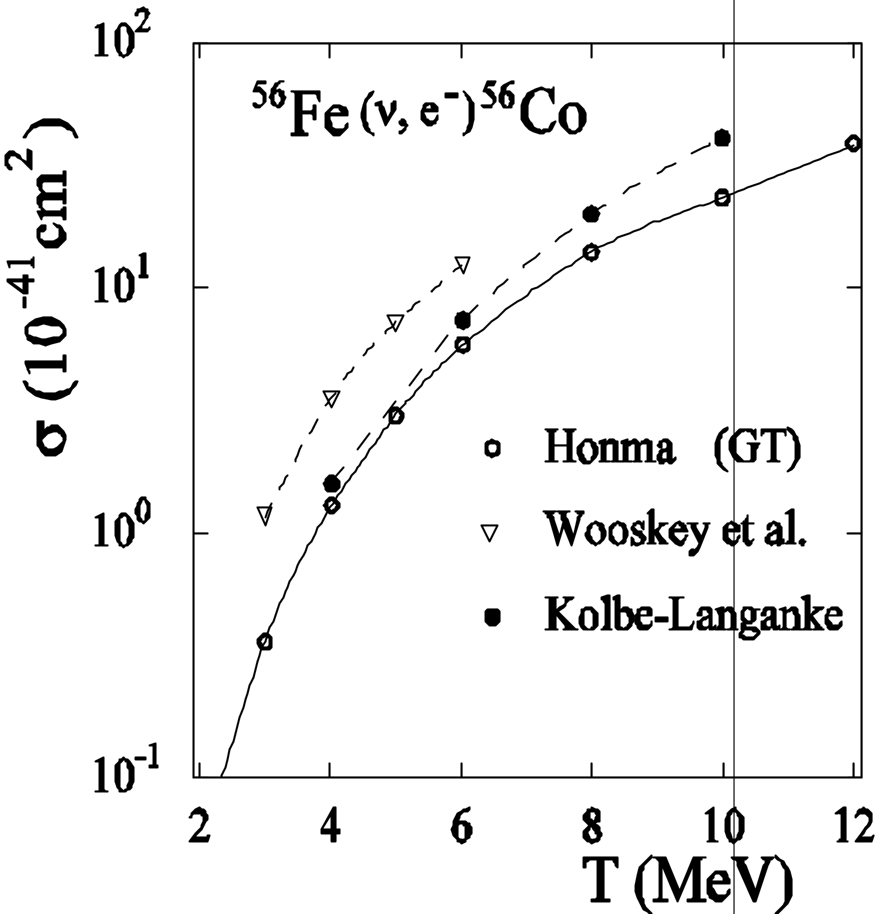
σ T=8 MeV

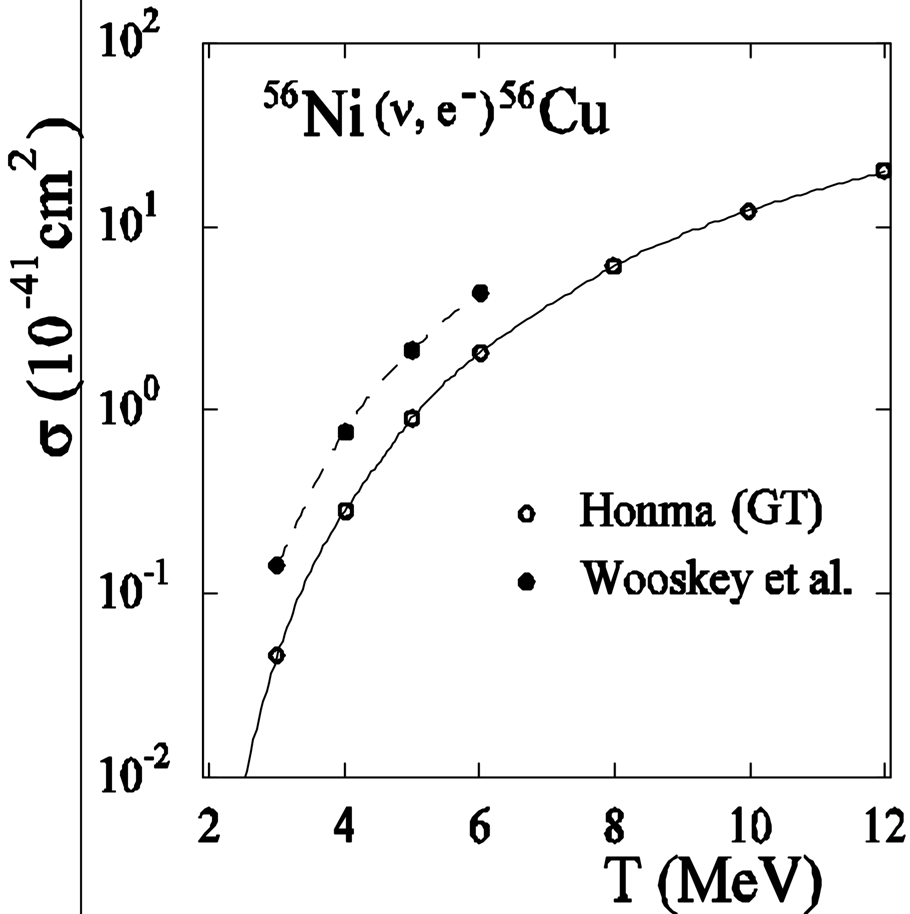


Fe, Ni Isotopes

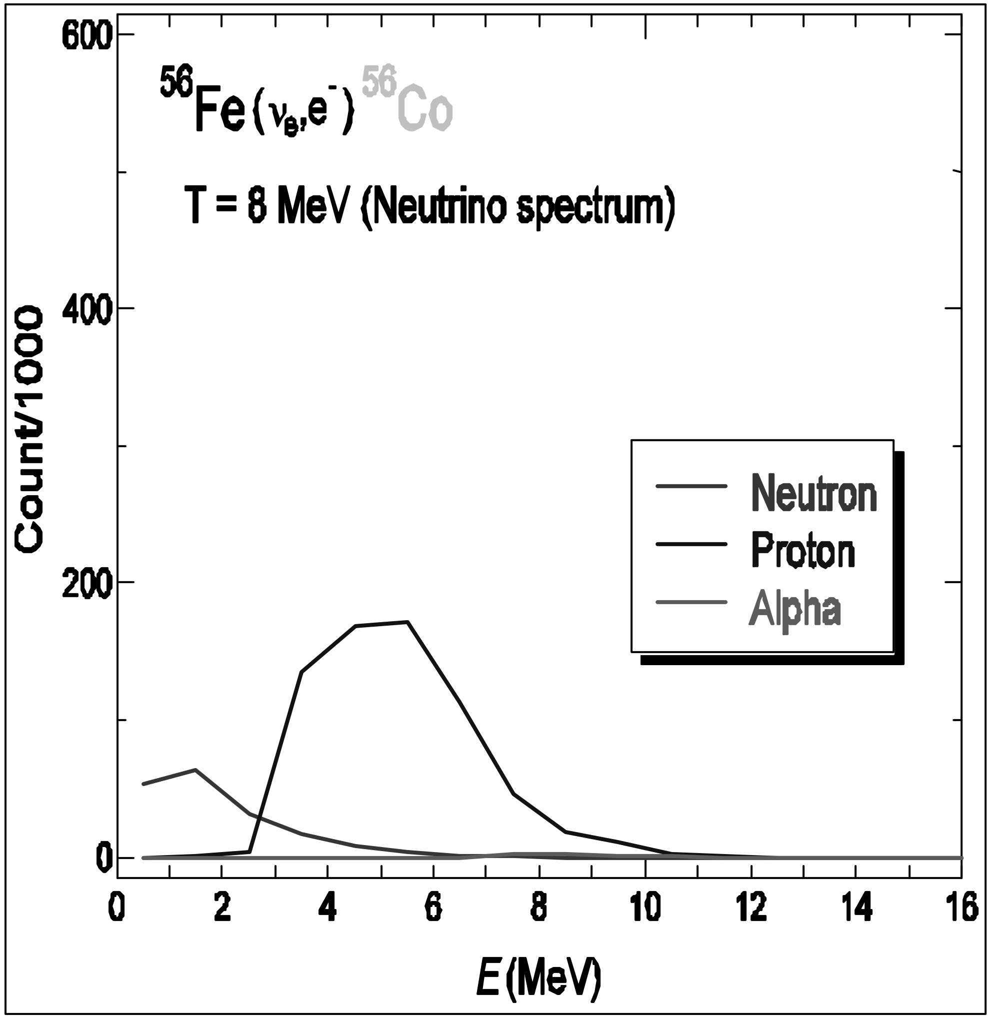
q=$(0.74)^2$ for GT (Honma)

Woosley, Kolb-Langanke: GT + $0^-,1^-,2^-,0^+,2^+$…

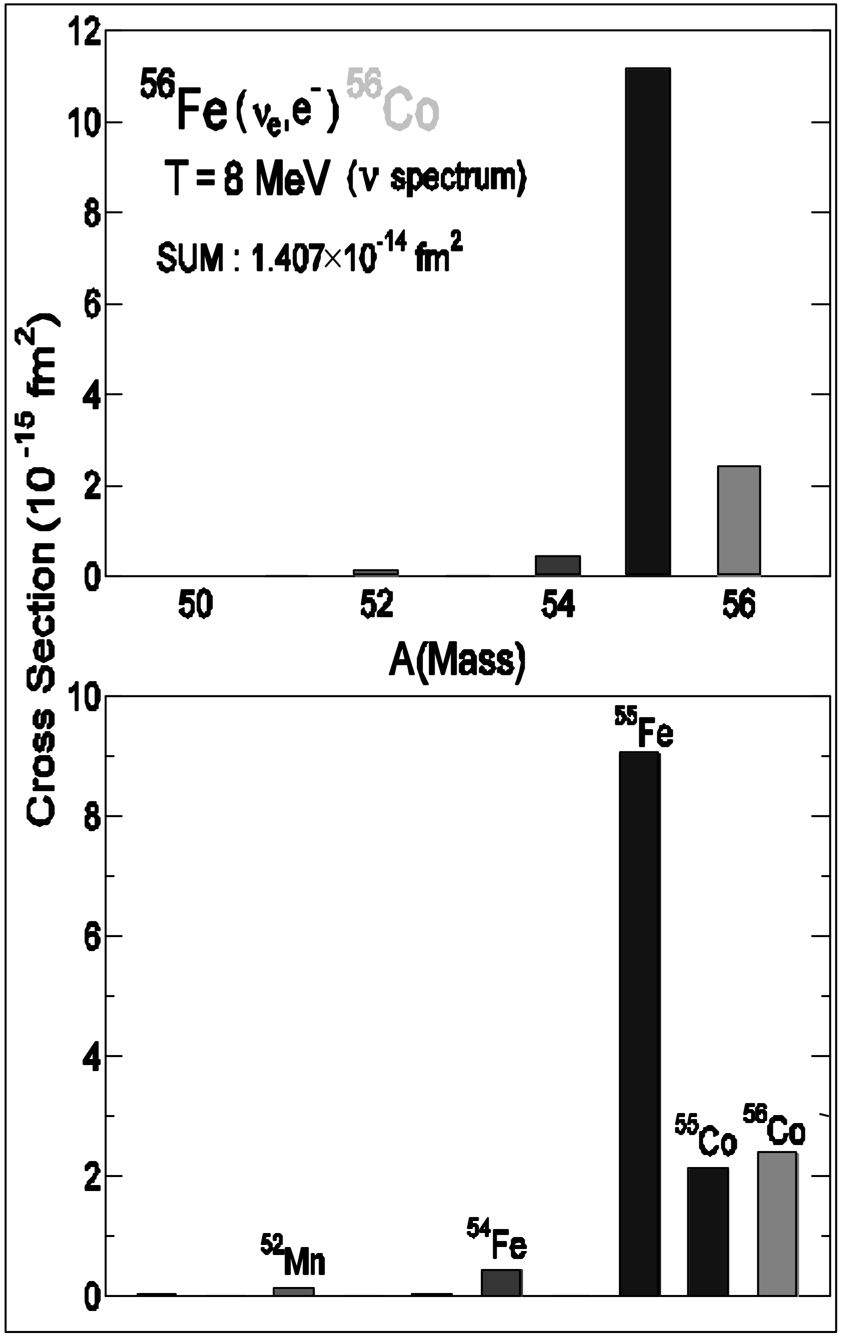




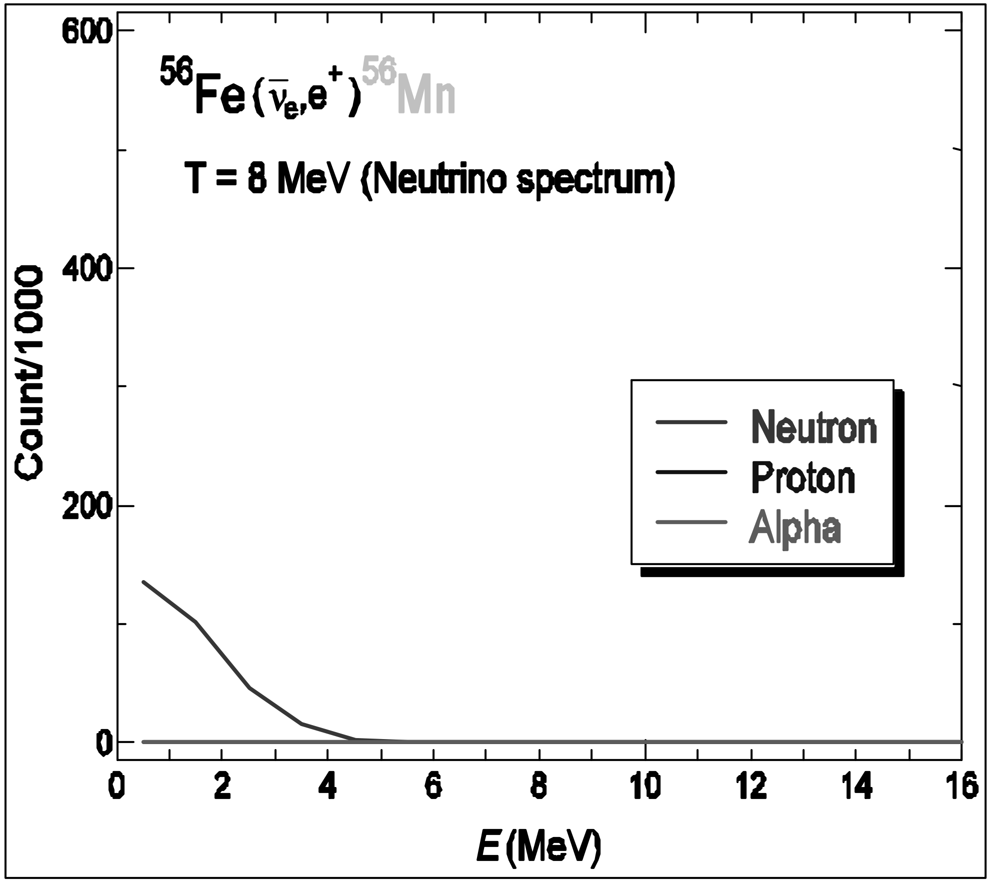
GXPF1(Honma et al.): GT only

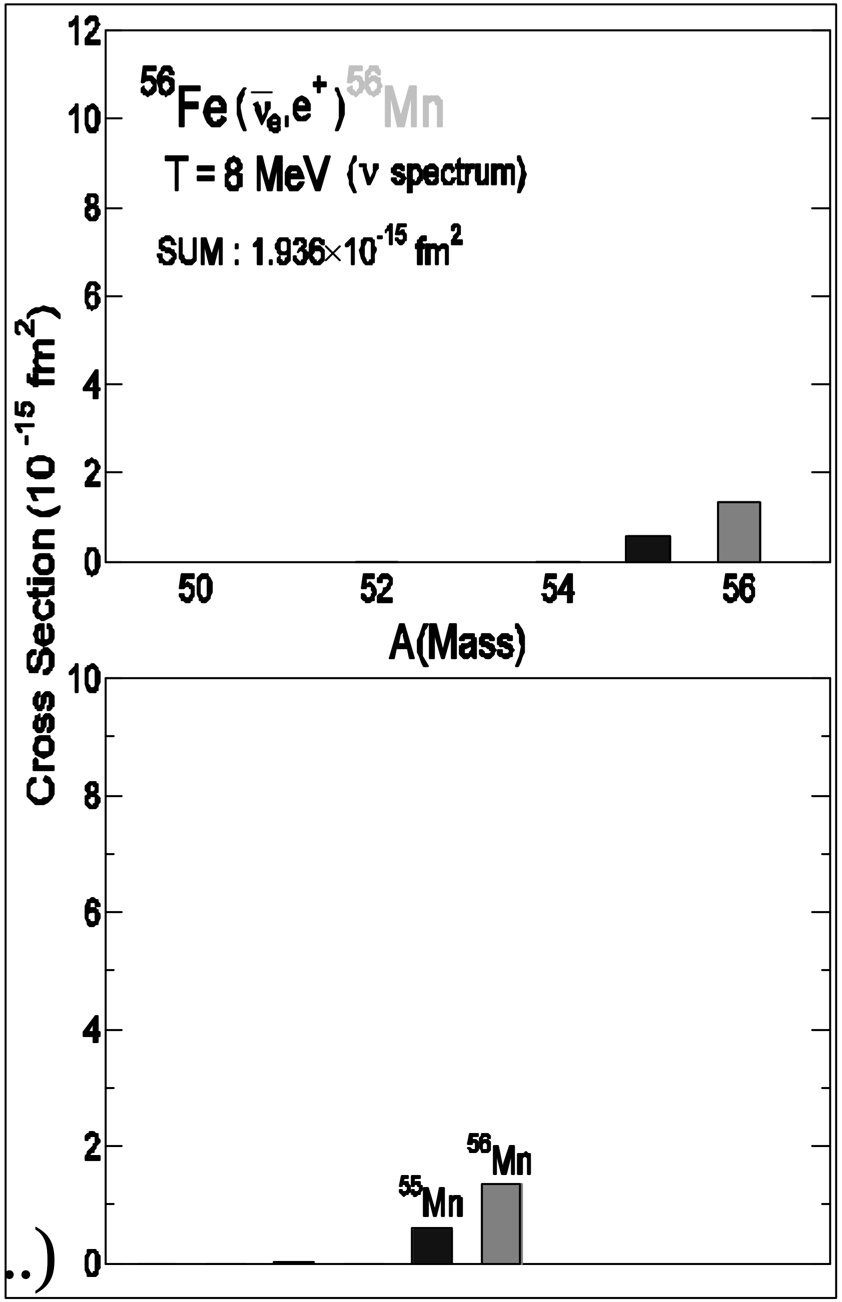


56Fe(νe,e-)56Co
T = 8 MeV (Neutrino spectrum)
Count/1000
600
400
200
0
Neutron
Proton
Alpha
0
2
4
6
8
10
12
14
16
E(MeV)



56Fe(νe,e-)56Co
T = 8 MeV (ν spectrum)
SUM : 1.407×10-14 fm2
Cross Section (10-15 fm2)
12
10
8
6
4
2
0
50
52
54
56
A(Mass)
10
8
6
4
2
0
55Fe
55Co
56Co
52Mn
54Fe





B(GT)=2.9 GXPF1

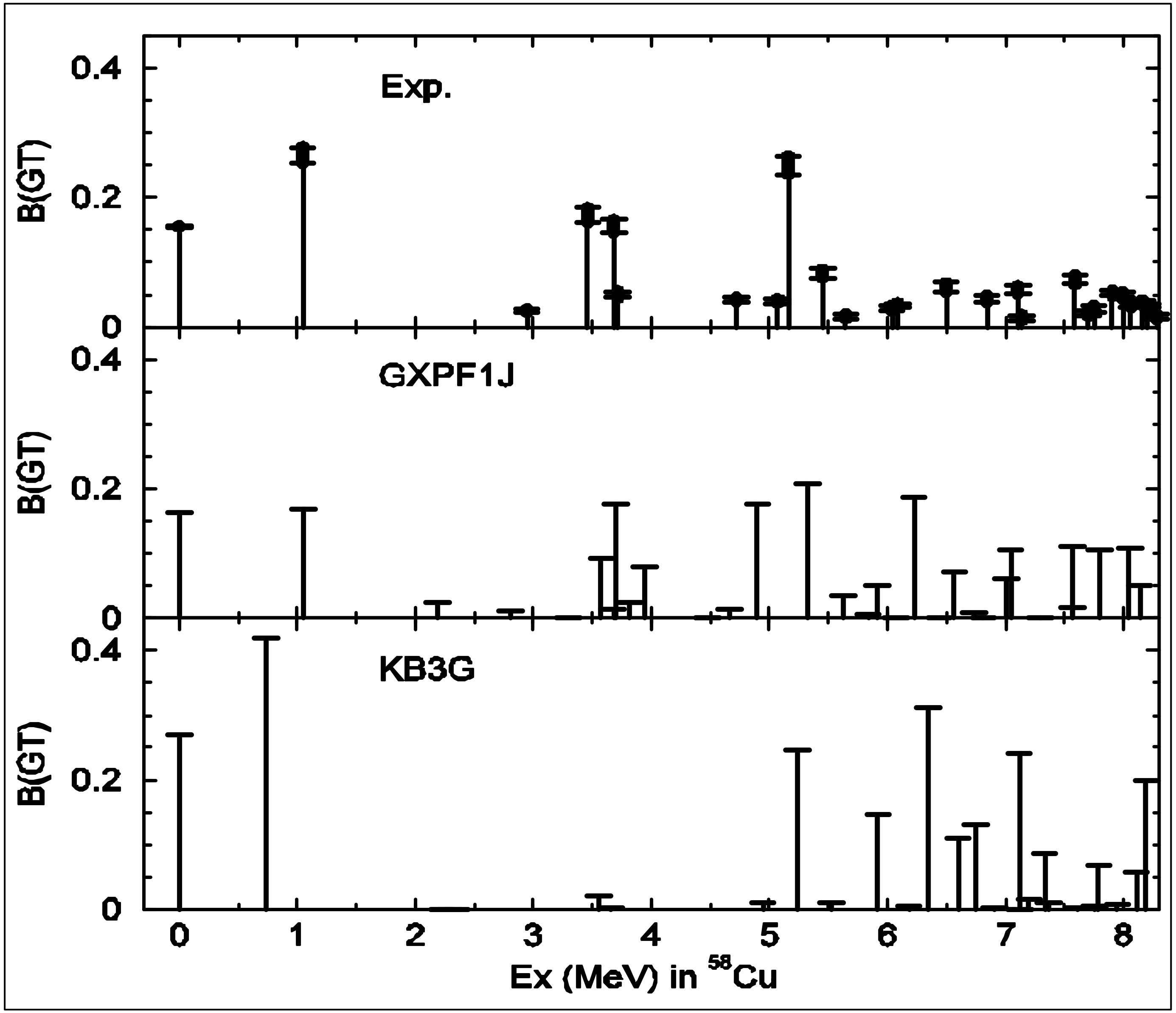
2.7 KB3

2.8±0.3 EXP

cf. $s = 3.9\times10^{-15}\ \boldsymbol{fm}^2 \quad (\boldsymbol{total};\boldsymbol{GT}+\ldots)$

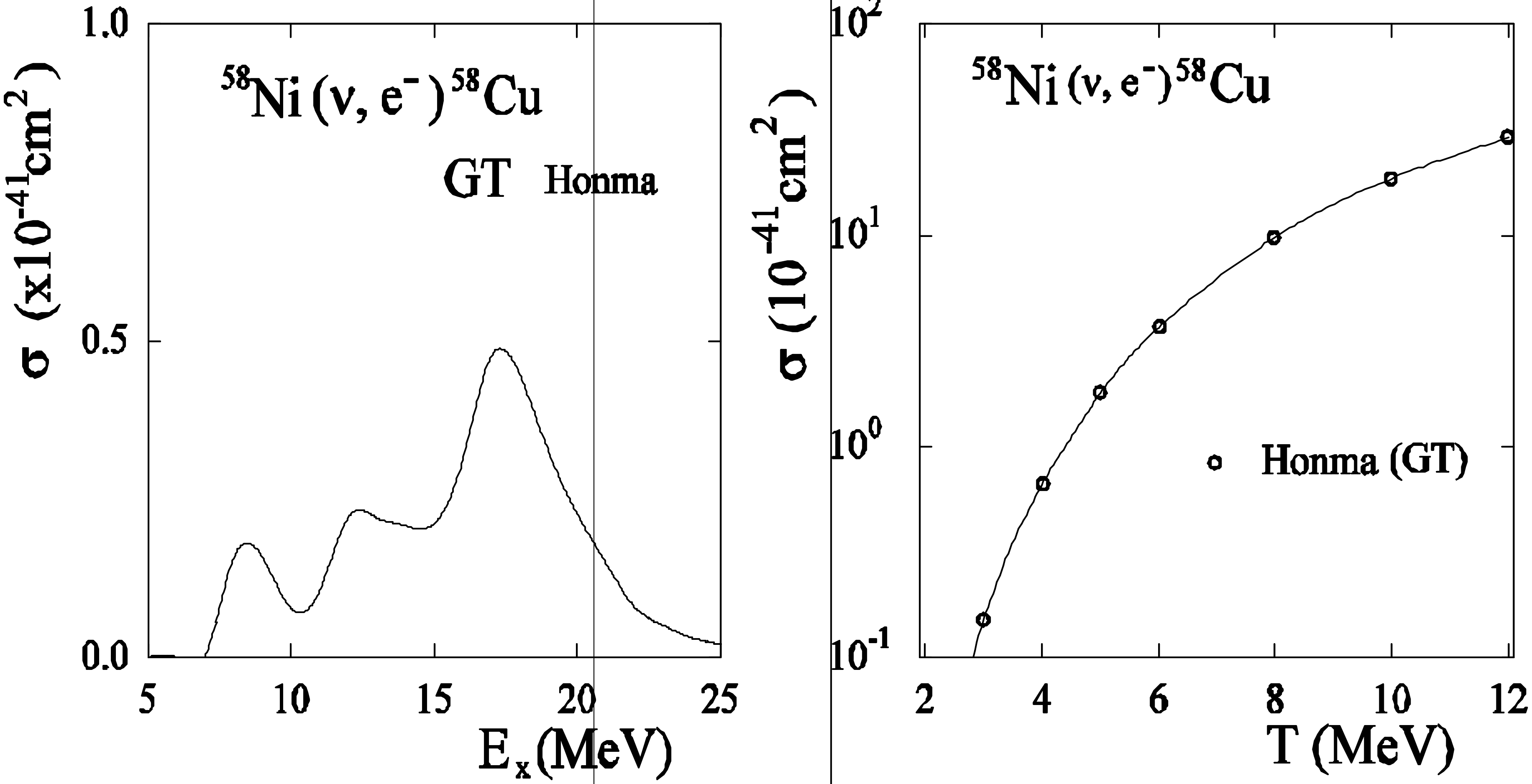
(Kolb, Langanke)

B(GT) for 58Ni

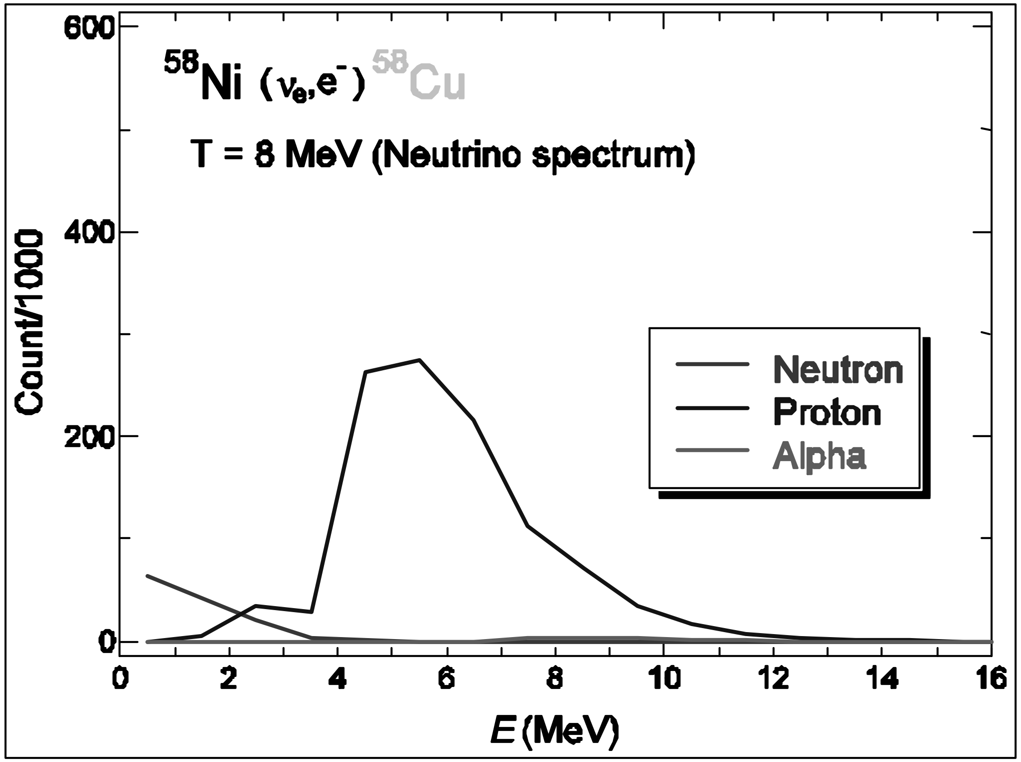


Exp.
GXPF1J
KB3G
B(GT)
B(GT)
B(GT)
0.4
0.2
0
0.4
0.2
0
0.4
0.2
0
0
1
2
3
4
5
6
7
8
Ex (MeV) in 58Cu

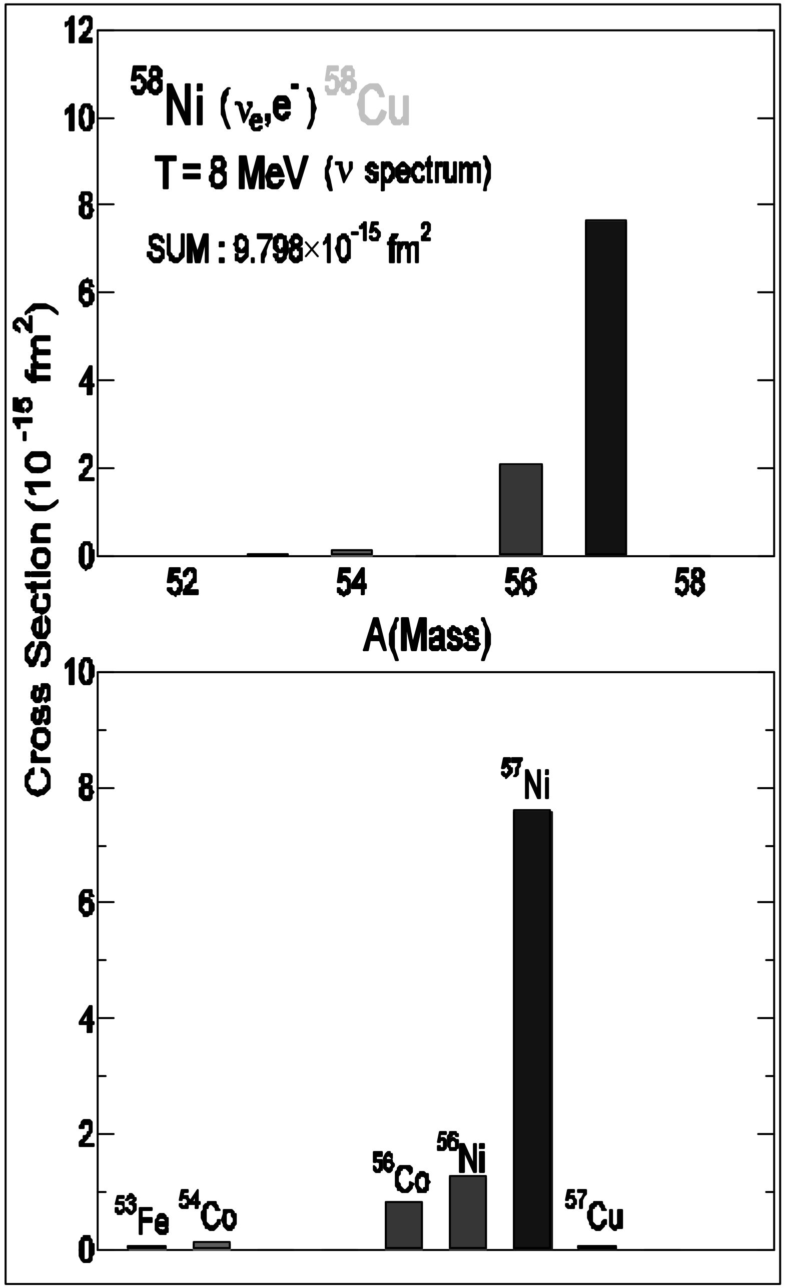
T= 6 MeV



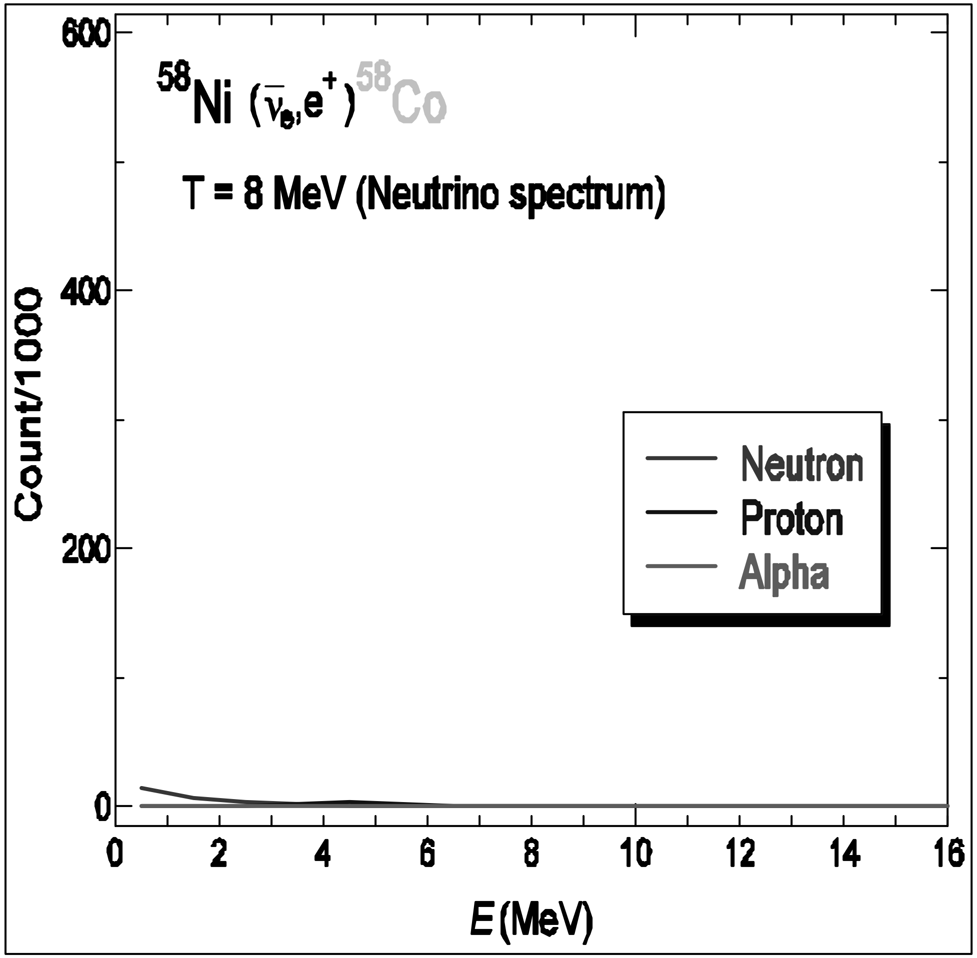
1.0
0.5
0.0
σ (x10-41cm2)
58Ni (ν, e-) 58Cu
GT Honma
5
10
15
20
25
Ex (MeV)
10^2
10^1
10^0
10^-1
σ (10-41cm2)
58Ni (ν, e-) 58Cu
Honma (GT)
2
4
6
8
10
12
T (MeV)



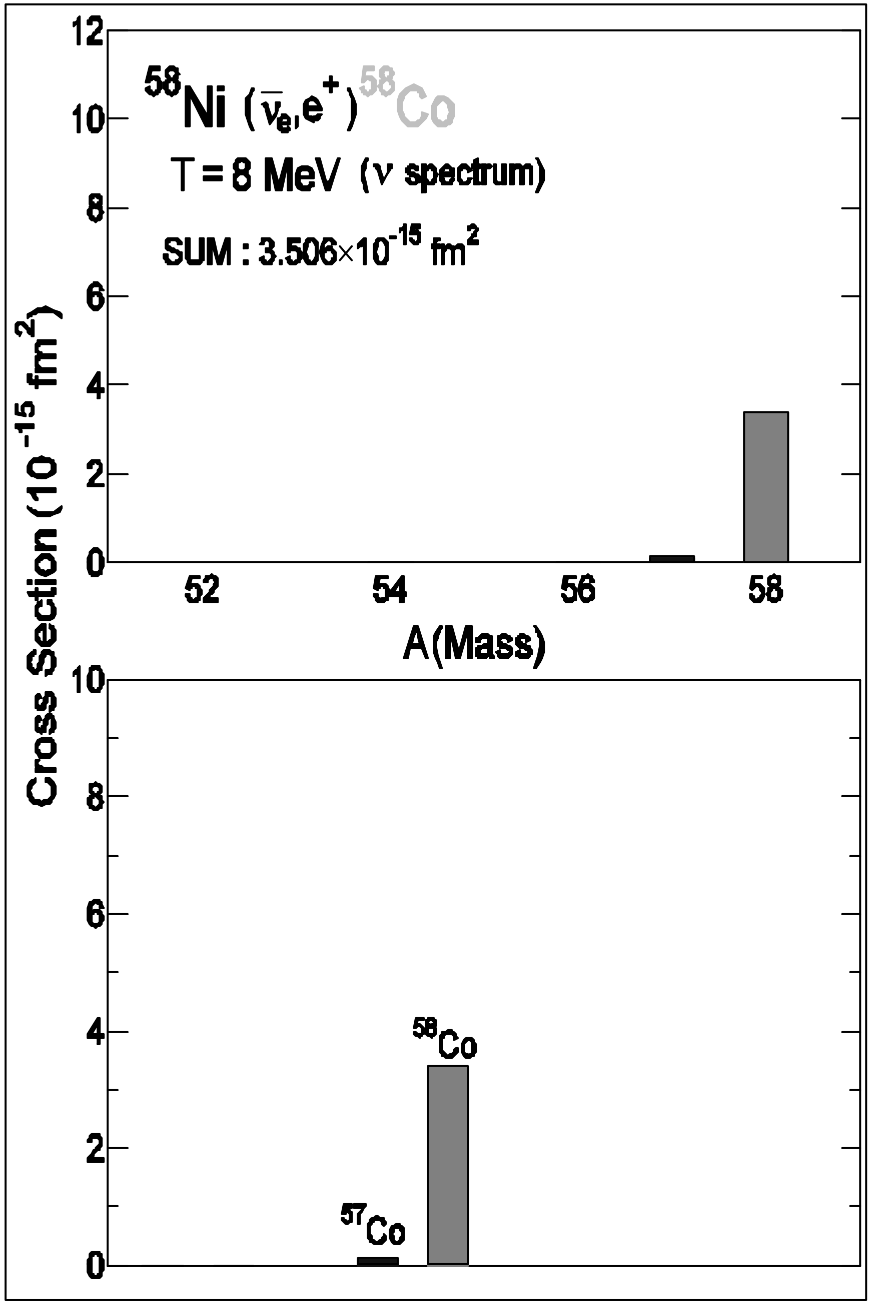
^{58}Ni (ν_e,e$^-$) ^{58}Cu
T = 8 MeV (Neutrino spectrum)
Count/1000
E (MeV)
Neutron
Proton
Alpha
0
200
400
600
0
2
4
6
8
10
12
14
16



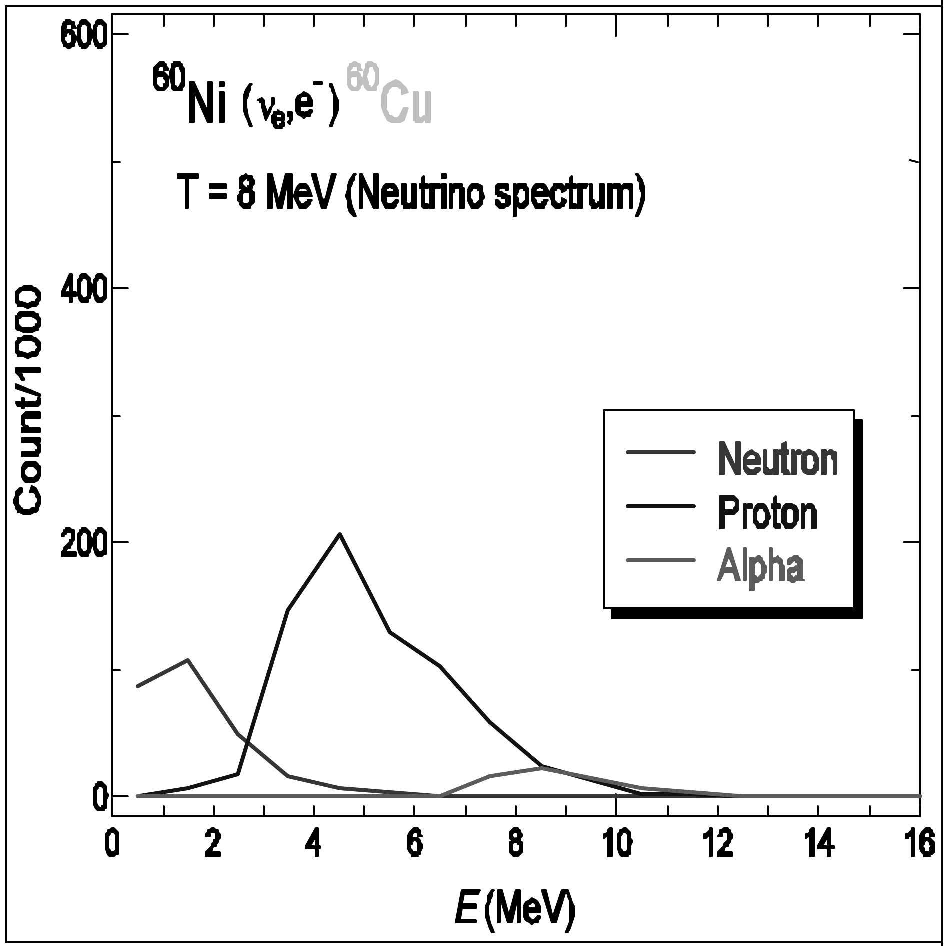
^{58}Ni (ν_e,e$^-$) ^{58}Cu
T = 8 MeV (ν spectrum)
SUM : 9.798×10^{-15} fm^2
Cross Section (10^{-15} fm^2)
A(Mass)
0
2
4
6
8
10
12
52
54
56
58
^{53}Fe
^{54}Co
^{56}Co
^{56}Ni
^{57}Ni
^{57}Cu



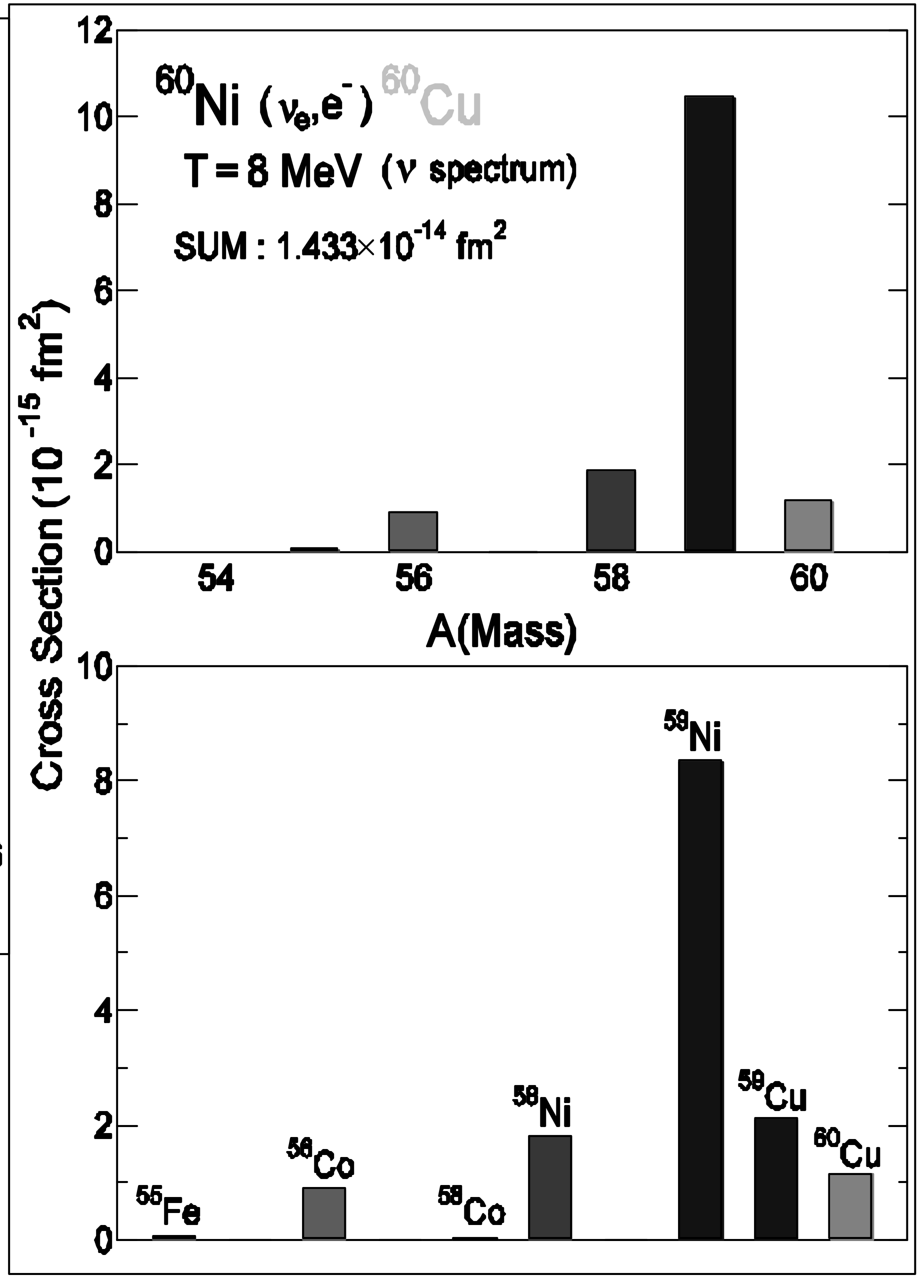
58Ni (ν̄e,e+) 58Co
T = 8 MeV (Neutrino spectrum)
Count/1000
600
400
200
0
Neutron
Proton
Alpha
0
2
4
6
8
10
12
14
16
E (MeV)



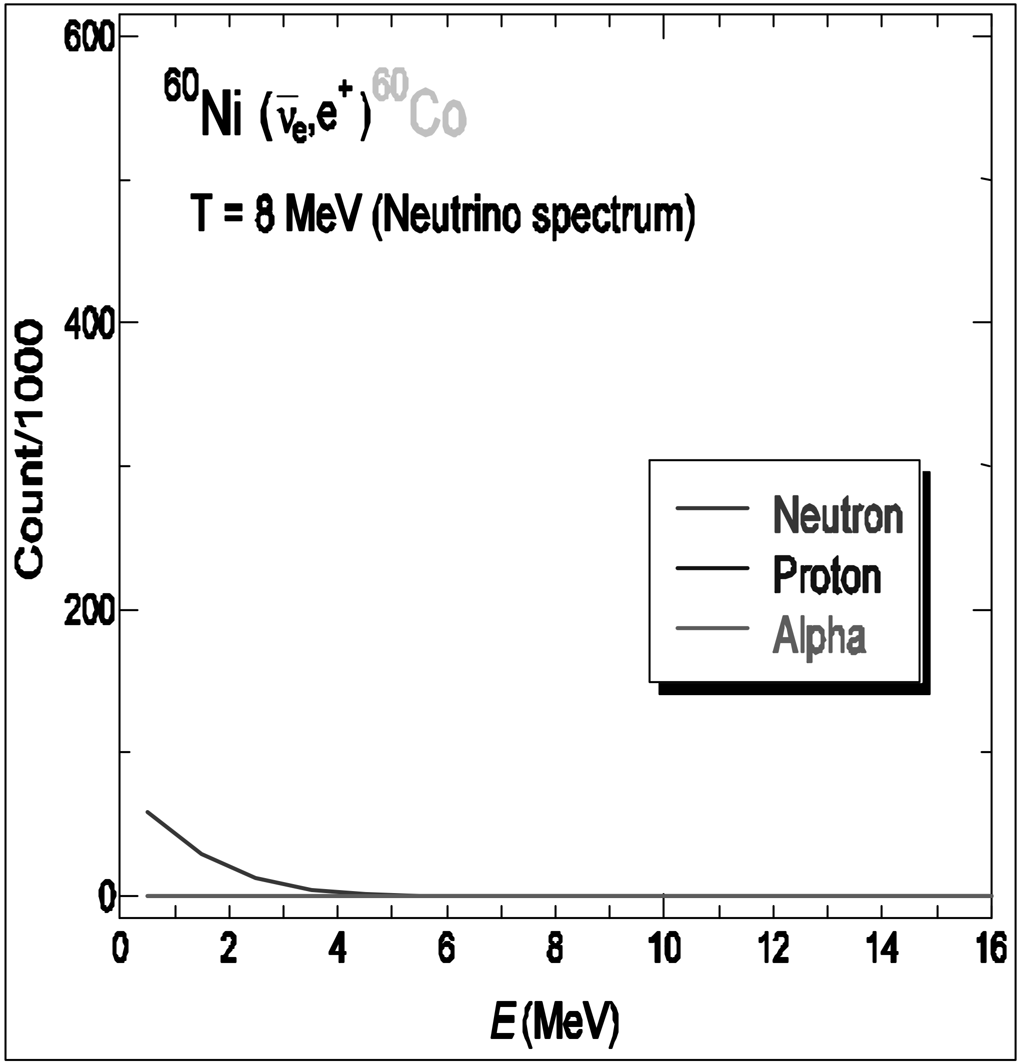
58Ni (ν̄e,e+) 58Co
T = 8 MeV (ν spectrum)
SUM : 3.506×10-15 fm2
Cross Section (10-15 fm2)
12
10
8
6
4
2
0
52
54
56
58
A(Mass)
57Co
58Co



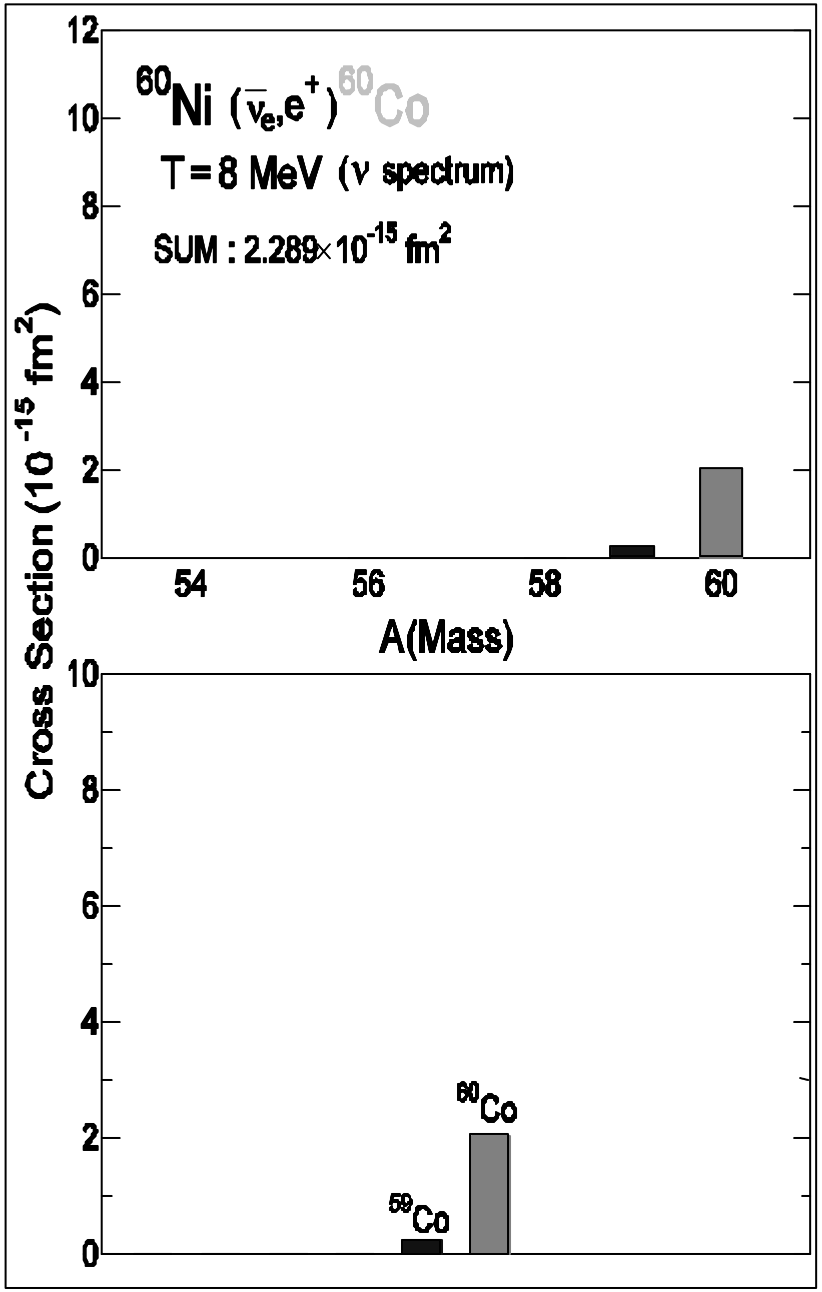
^{60}Ni (ν_e,e$^-$) ^{60}Cu
T = 8 MeV (Neutrino spectrum)
Count/1000
Neutron
Proton
Alpha
E (MeV)
0
200
400
600
0
2
4
6
8
10
12
14
16



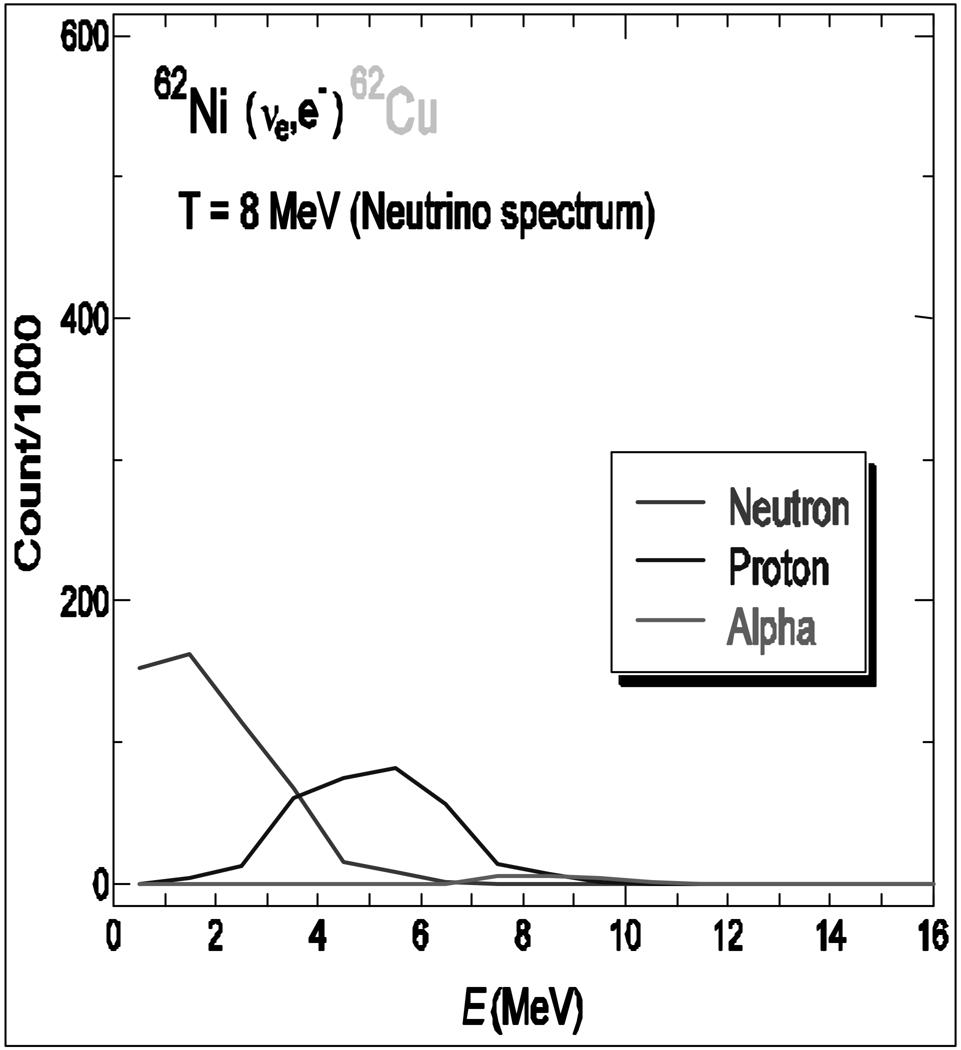
^{60}Ni (ν_e,e$^-$) ^{60}Cu
T = 8 MeV (ν spectrum)
SUM : 1.433×10^{-14} fm^2
Cross Section (10^{-15} fm^2)
A(Mass)
0
2
4
6
8
10
12
54
56
58
60
^{55}Fe
^{56}Co
^{58}Co
^{58}Ni
^{59}Ni
^{59}Cu
^{60}Cu



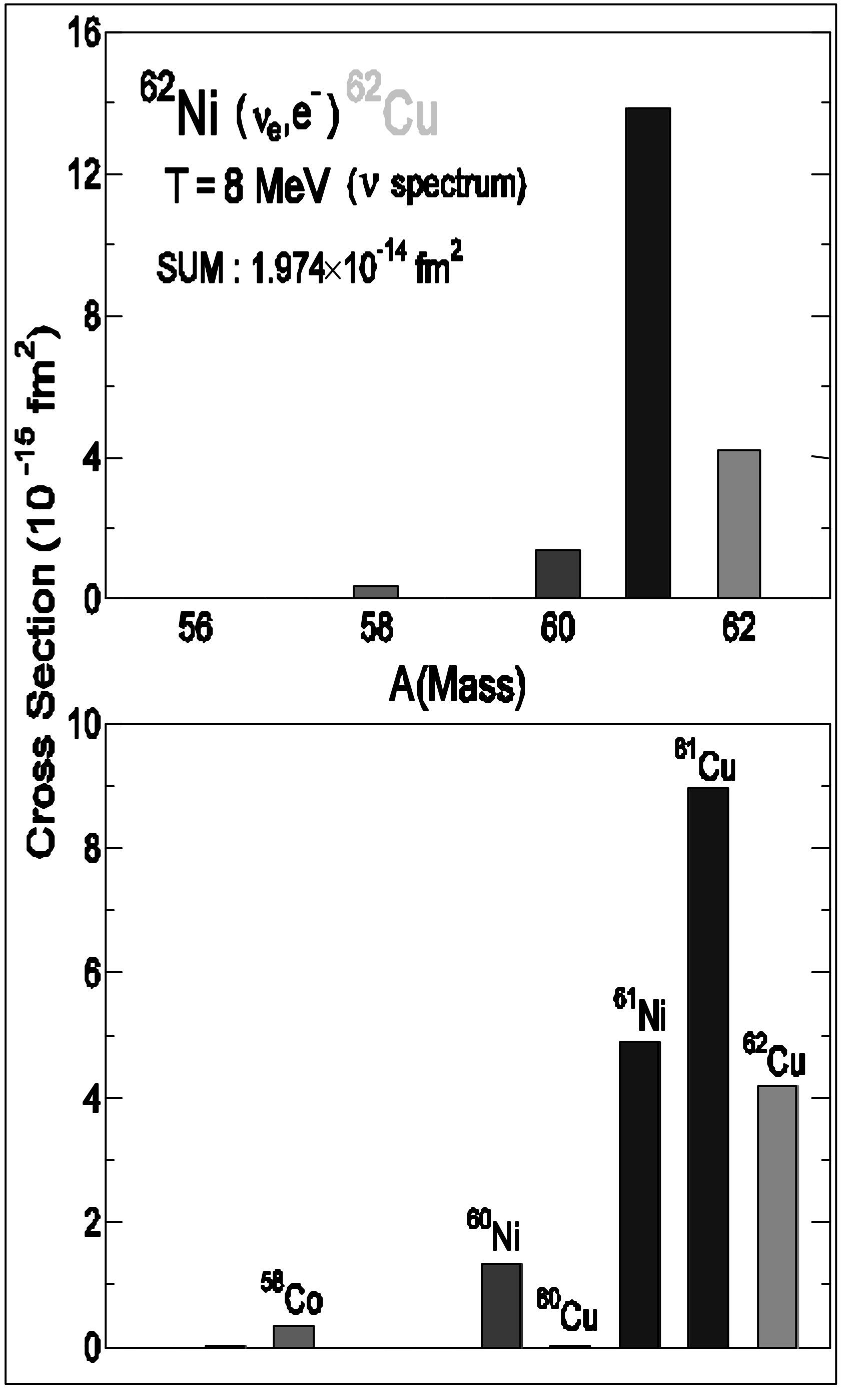
⁶⁰Ni ($\bar{\nu}_e$,e⁺)⁶⁰Co
T = 8 MeV (Neutrino spectrum)
Neutron
Proton
Alpha
Count/1000
E (MeV)
0
200
400
600
0
2
4
6
8
10
12
14
16



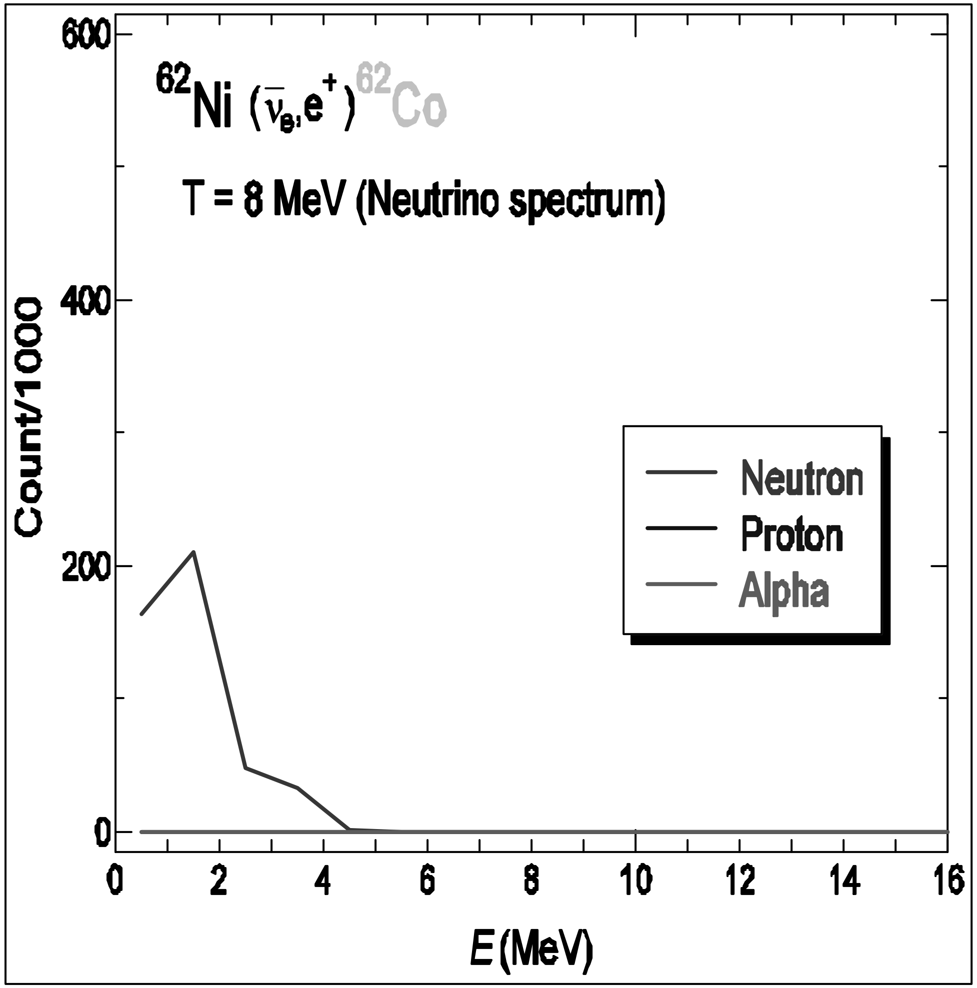
⁶⁰Ni ($\bar{\nu}_e$,e⁺)⁶⁰Co
T = 8 MeV (ν spectrum)
SUM : 2.289×10⁻¹⁵ fm²
Cross Section (10⁻¹⁵ fm²)
A(Mass)
54
56
58
60
0
2
4
6
8
10
12
⁵⁹Co
⁶⁰Co



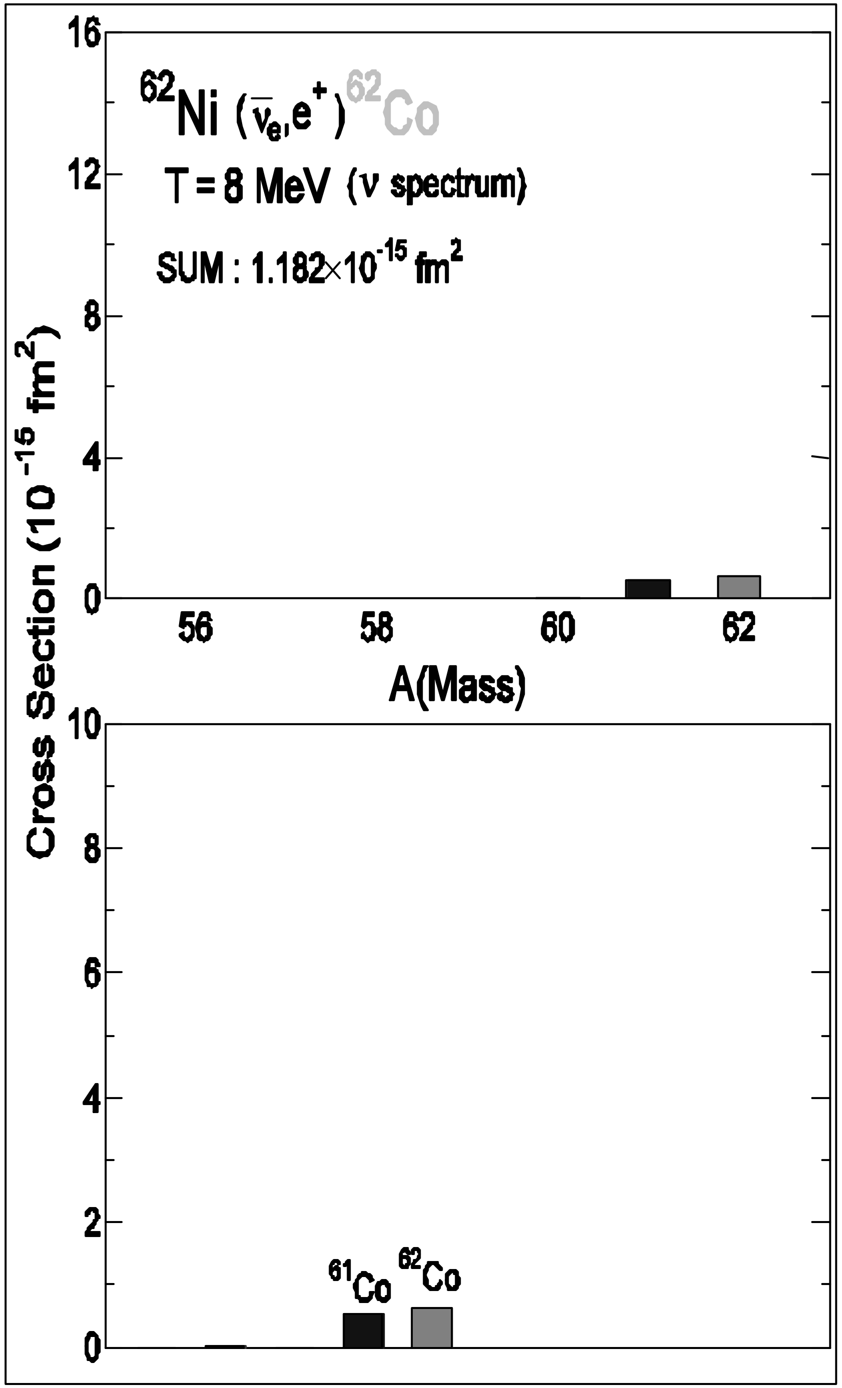
62Ni (νe,e-) 62Cu
T = 8 MeV (Neutrino spectrum)
Count/1000
Neutron
Proton
Alpha
E(MeV)
0
200
400
600
0
2
4
6
8
10
12
14
16



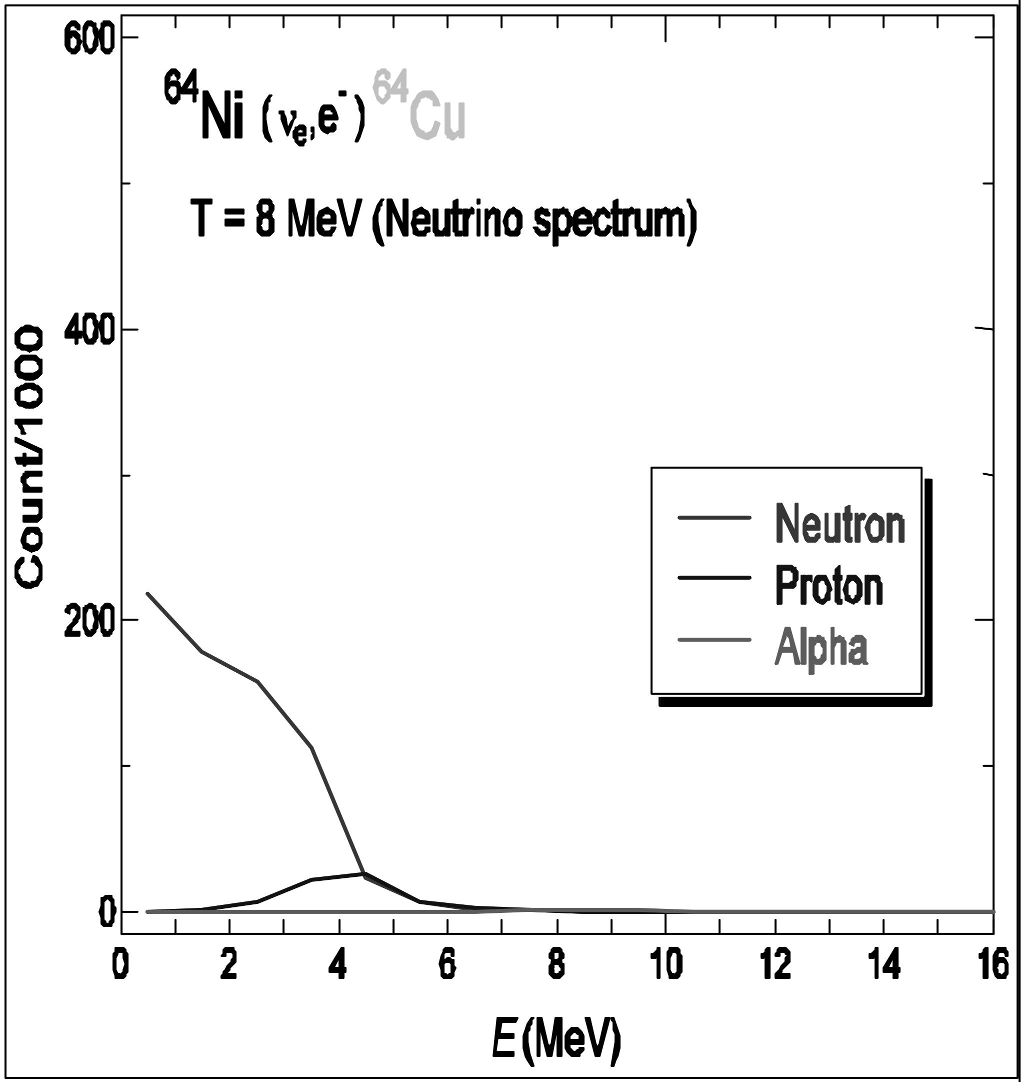
62Ni (νe,e-) 62Cu
T = 8 MeV (ν spectrum)
SUM : 1.974×10-14 fm2
Cross Section (10-15 fm2)
A(Mass)
56
58
60
62
0
4
8
12
16
58Co
60Ni
60Cu
61Ni
61Cu
62Cu
0
2
4
6
8
10



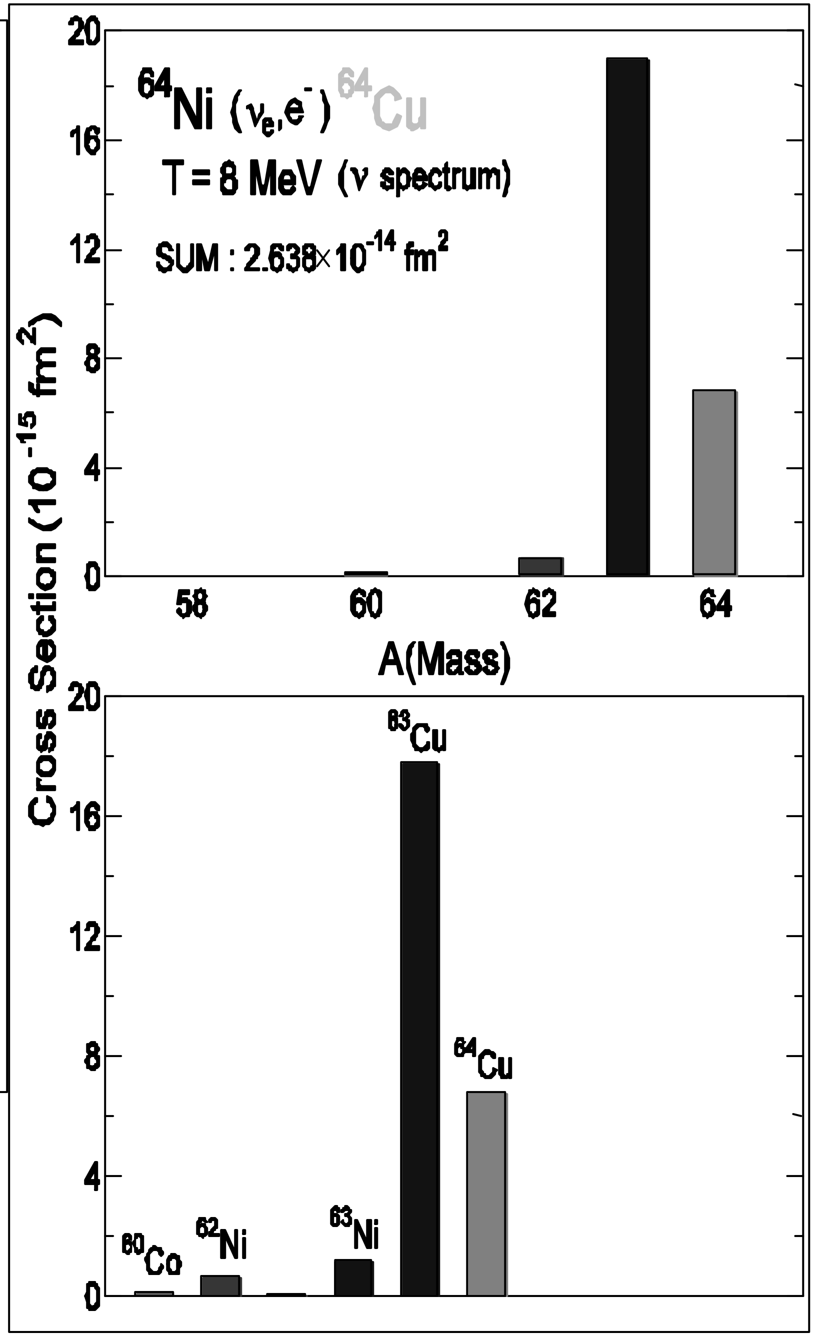
$^{62}Ni\ (\bar{\nu}_e, e^+)\ ^{62}Co$
T = 8 MeV (Neutrino spectrum)
Count/1000
Neutron
Proton
Alpha
E (MeV)
0
200
400
600
0
2
4
6
8
10
12
14
16



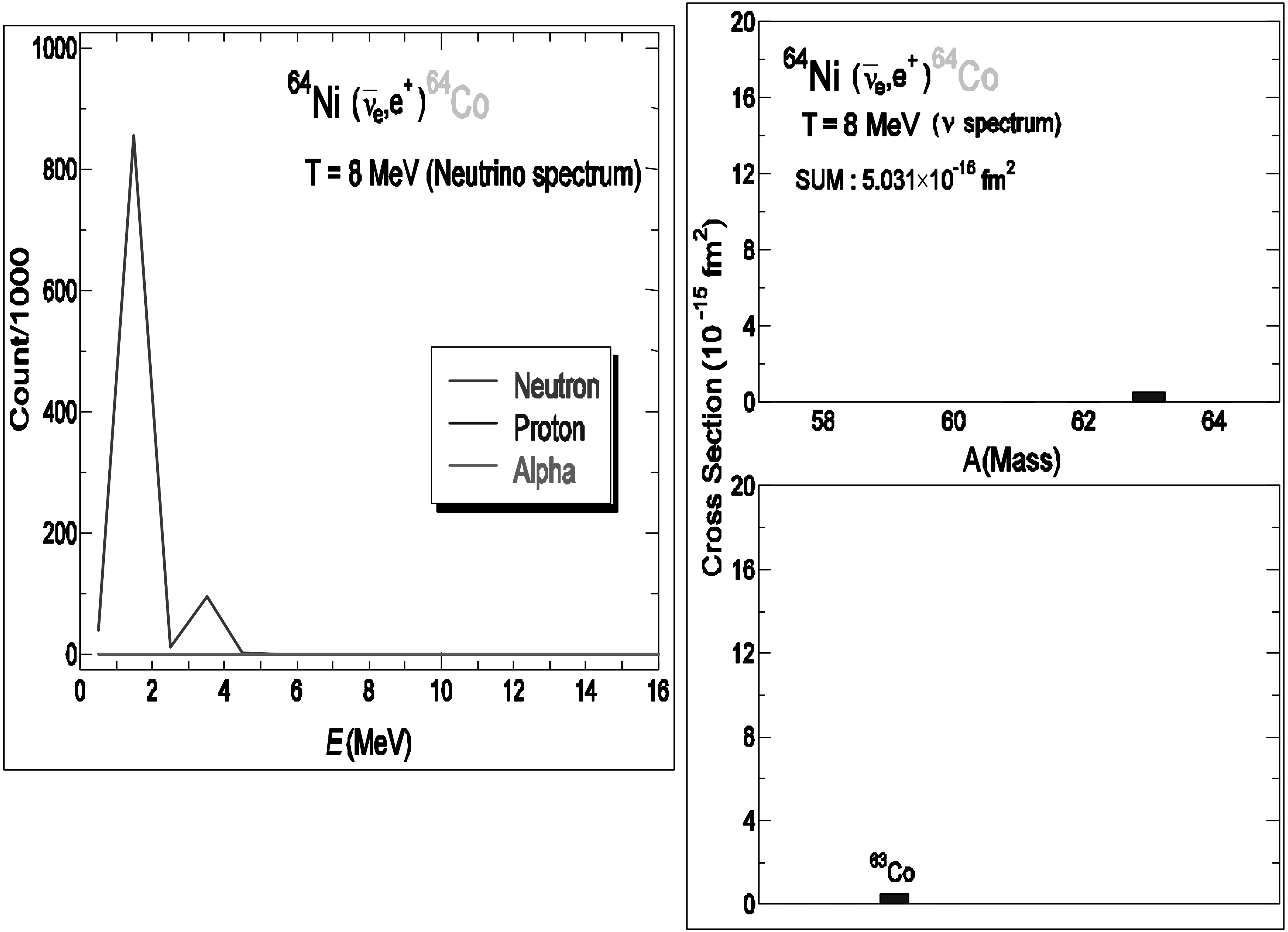
$^{62}Ni\ (\bar{\nu}_e, e^+)\ ^{62}Co$
T = 8 MeV (ν spectrum)
SUM : 1.182×10^{-15} fm^2
Cross Section (10^{-15} fm^2)
A(Mass)
56
58
60
62
^{61}Co
^{62}Co



^{64}Ni (ν_e,e$^-$) ^{64}Cu
T = 8 MeV (Neutrino spectrum)
Count/1000
600
400
200
0
Neutron
Proton
Alpha
0
2
4
6
8
10
12
14
16
E (MeV)



^{64}Ni (ν_e,e$^-$) ^{64}Cu
T = 8 MeV (ν spectrum)
SUM : 2.638×10^{-14} fm^2
Cross Section (10^{-15} fm^2)
20
16
12
8
4
0
58
60
62
64
A(Mass)
^{63}Cu
^{64}Cu
^{60}Co
^{62}Ni
^{63}Ni



^{64}Ni ($\bar{\nu}_e$,e$^+$)^{64}Co
T = 8 MeV (Neutrino spectrum)
Neutron
Proton
Alpha
Count/1000
E(MeV)
^{64}Ni ($\bar{\nu}_e$,e$^+$)^{64}Co
T = 8 MeV (ν spectrum)
SUM : 5.031×10^{-16} fm^2
Cross Section (10^{-15} fm^2)
A(Mass)
^{63}Co

Summary

1. P-shell SFO

   $\boldsymbol{B(GT)} \uparrow \;\; \Rightarrow \;\; \boldsymbol{s}\,(n, \boldsymbol{e}) \uparrow$

   $(n, n'\boldsymbol{n}) \uparrow$

2. fp-shell GXPF1

   $\boldsymbol{B(GT)} \uparrow$, ***more fragmented***, $\boldsymbol{s}\,(n, \boldsymbol{e}) \uparrow$

   e-capture and β -decay rates $\Leftrightarrow$ steller core collapse and supernovae explosion mechanism

Remaning issues:

Inclusion of spin-dipole contributions

Study of effects of n from $(n, \boldsymbol{en})$

(n, γ) in r-process in stars