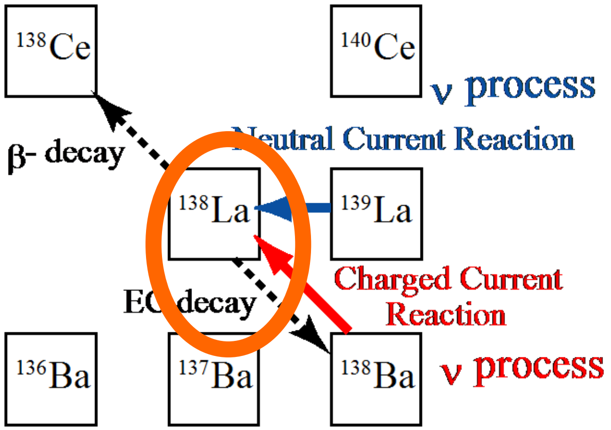
Charge Exchange Reactions and Applications to Nuclear-Astrophysics

Myung-Ki Cheoun

Soongsil University, Seoul, Korea

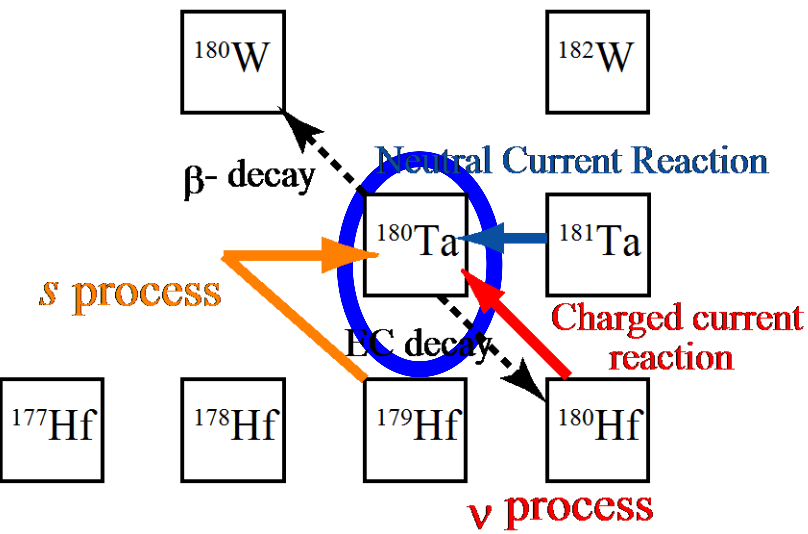
K. S. Kim, E. Ha, C. Ryu…
G. Mathews,
T. Kajino, T. Hayakawa, T. Maruyama …
F. Simkovic, A. Faessler…

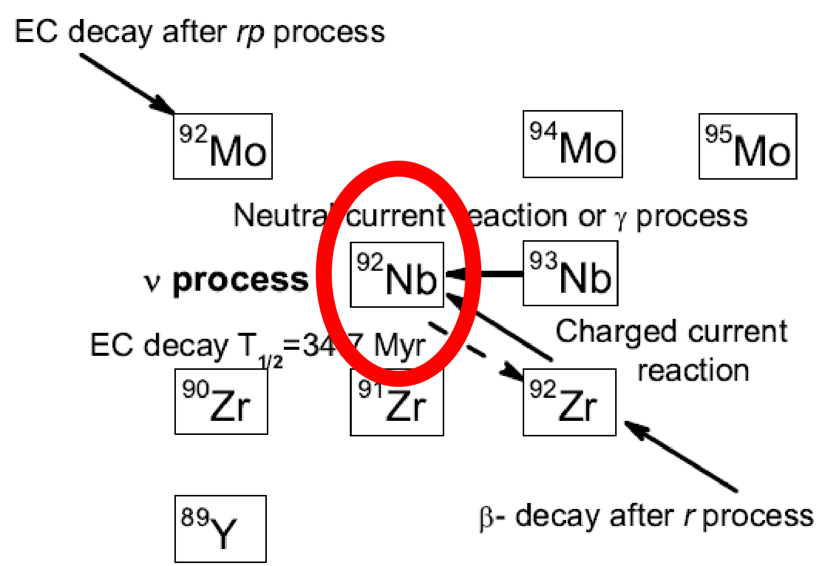
Contents

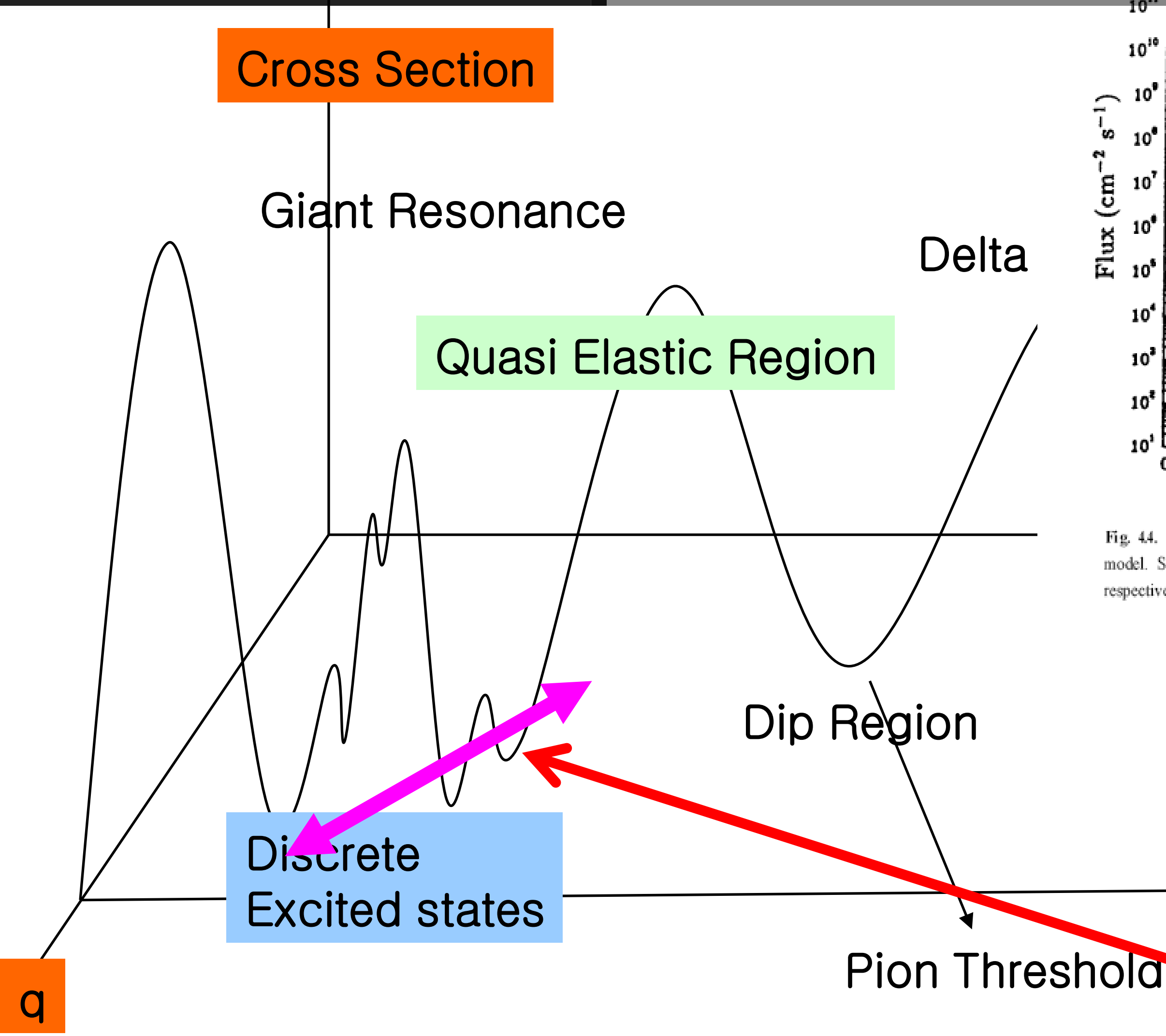


- Isotopic ratios:
- Solar:

Isotopic ratios			Solar
$^{92}Nb/^{93}Nb$ =		>>	10^{-3} - 10^{-5}
$^{138}La/^{139}La$ =		>	0.001
$^{180}Ta/^{181}Ta$ =		>	0.0001







Typical cross section by incident electron

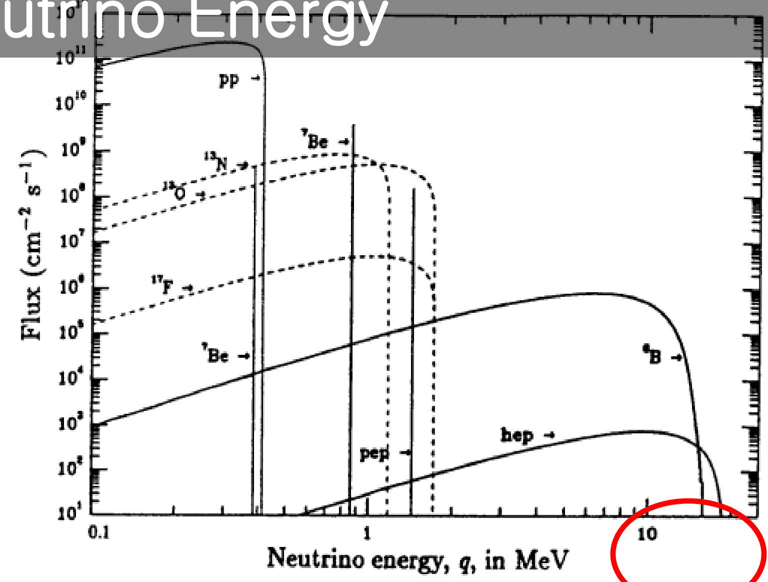
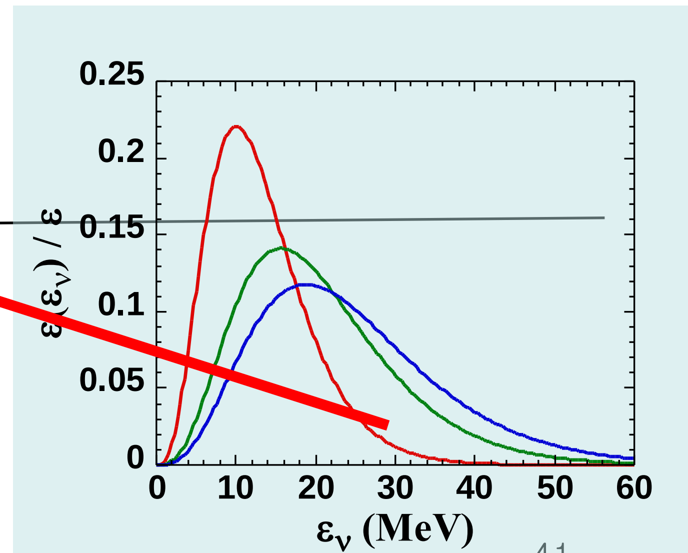


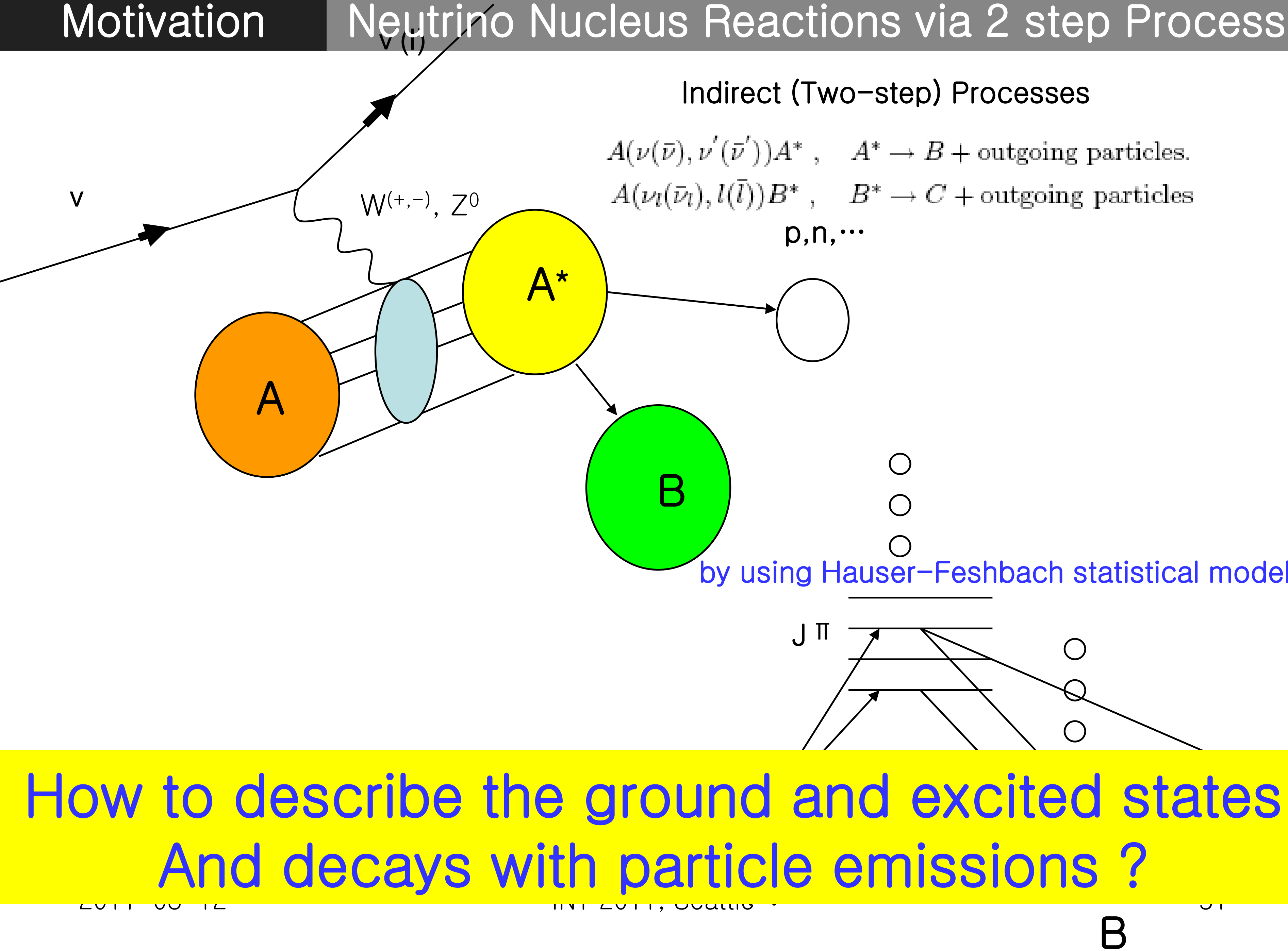
Fig. 4.4. Solar neutrino spectrum. Energy spectrum of solar neutrinos, as predicted by the standard solar model. Solid and dashed curves distinguish between neutrinos produced in the pp-chains and the CNO cycle, respectively. (From 49.)



$T(\nu_e) = 3.2$ MeV $< T(\overline{\nu_e}) = 5.0$ MeV $< T(\nu_{\mu,\tau}) = T(\overline{\nu_{\mu,\tau}}) = 6.0$ MeV

Indirect (Two-step) Processes

$$A(\nu(\bar{\nu}), \nu'(\bar{\nu}'))A^* \ , \quad A^* \rightarrow B + \text{outgoing particles.}$$
$$A(\nu_l(\bar{\nu}_l), l(\bar{l}))B^* \ , \quad B^* \rightarrow C + \text{outgoing particles}$$



by using Hauser−Feshbach statistical model

How to describe the ground and excited states And decays with particle emissions ?

Pairing of Like and Unlike nucleons

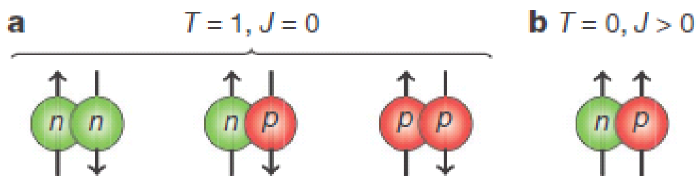
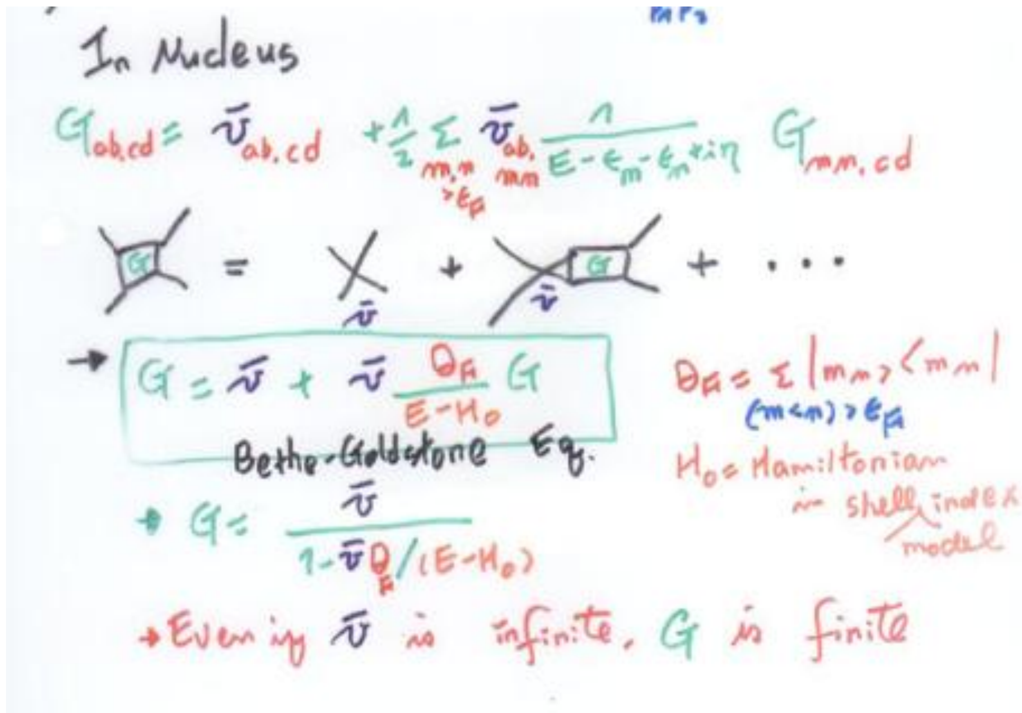


Figure 1 | Schematic illustration of the two possible pairing schemes in nuclei. **a**, The normal isospin $T = 1$ triplet. The two like-particle pairing components are responsible for most known effects of nuclear superfluidity. Within a given shell these isovector components are restricted to spin zero owing to the Pauli principle. **b**, Isoscalar $T = 0$ neutron–proton pairing. Here the Pauli principle allows only non-zero components of angular momentum.

- neutron-neutron, proton-proton (T= 1)
- neutron-proton (T=1 and 0) couples J=L-1 and J=L+1 by tensor force. For example, $^3S_1$ and $^3D_1$ states play roles
- The np pairing is vital for the exotic nuclei in the nucleo-synthesis with the deformations

(iii) *Nucleon–nucleon interaction*. In the $0\nu\beta\beta$-decay calculations both schematic zero-range [40] and realistic interactions were considered. In Ref. [41] G-matrix of the Paris potential approximated by a sum of Yukawa terms was used. The interaction employed by the Tuebingen group has been the Brueckner G matrix that is a solution of the Bethe–Goldstone equation with Bonn (Bonn CD, Argonne, Nijmegen) one boson exchange potential. The results do not depend significantly on the choice of the NN interaction [19].



$$\left(\frac{d\sigma_\nu}{d\Omega}\right)_{(\nu/\bar{\nu})} = \frac{G_F^2 \epsilon k}{\pi\ (2J_i+1)}\ \Big[\ \sum_{J=0} (1+\vec{\nu}\cdot\vec{\beta})| < J_f||\hat{\mathcal{M}}_J||J_i > |^2$$

$$+(1-\vec{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\hat{q}\cdot\vec{\beta}))| < J_f||\hat{\mathcal{L}}_J||J_i > |^2 -$$

$$\hat{q}\cdot(\hat{\nu}+\vec{\beta})2Re < J_f||\hat{\mathcal{L}}_J||J_i > < J_f||\hat{\mathcal{M}}_J||J_i >^*$$

$$+\sum_{J=1}(1-(\hat{\nu}\cdot\hat{q})(\hat{q}\cdot\vec{\beta}))(| < J_f||\hat{\mathcal{T}}_J^{el}||J_i > |^2 + | < J_f||\hat{\mathcal{T}}_J^{mag}||J_i > |^2)$$

$$\pm \sum \hat{q}\cdot(\hat{\nu}-\vec{\beta})2Re[< J_f||\hat{\mathcal{T}}_J^{mag}||J_i > < J_f||\hat{\mathcal{T}}_J^{el}||J_i >^*]\Big]\ ,$$

$$\sigma(E_\nu) = \frac{G_F^2 cos^2\theta_c}{\pi\hbar^4 c^3}\sum_i k_i\epsilon_i F(Z,\epsilon_i)[B_i(GT)+B_i(F)]\ , \qquad (8)$$

where k_i and ϵ_i refer to the momentum and total energy of the outgoing electron and $F(Z,\epsilon_i)$

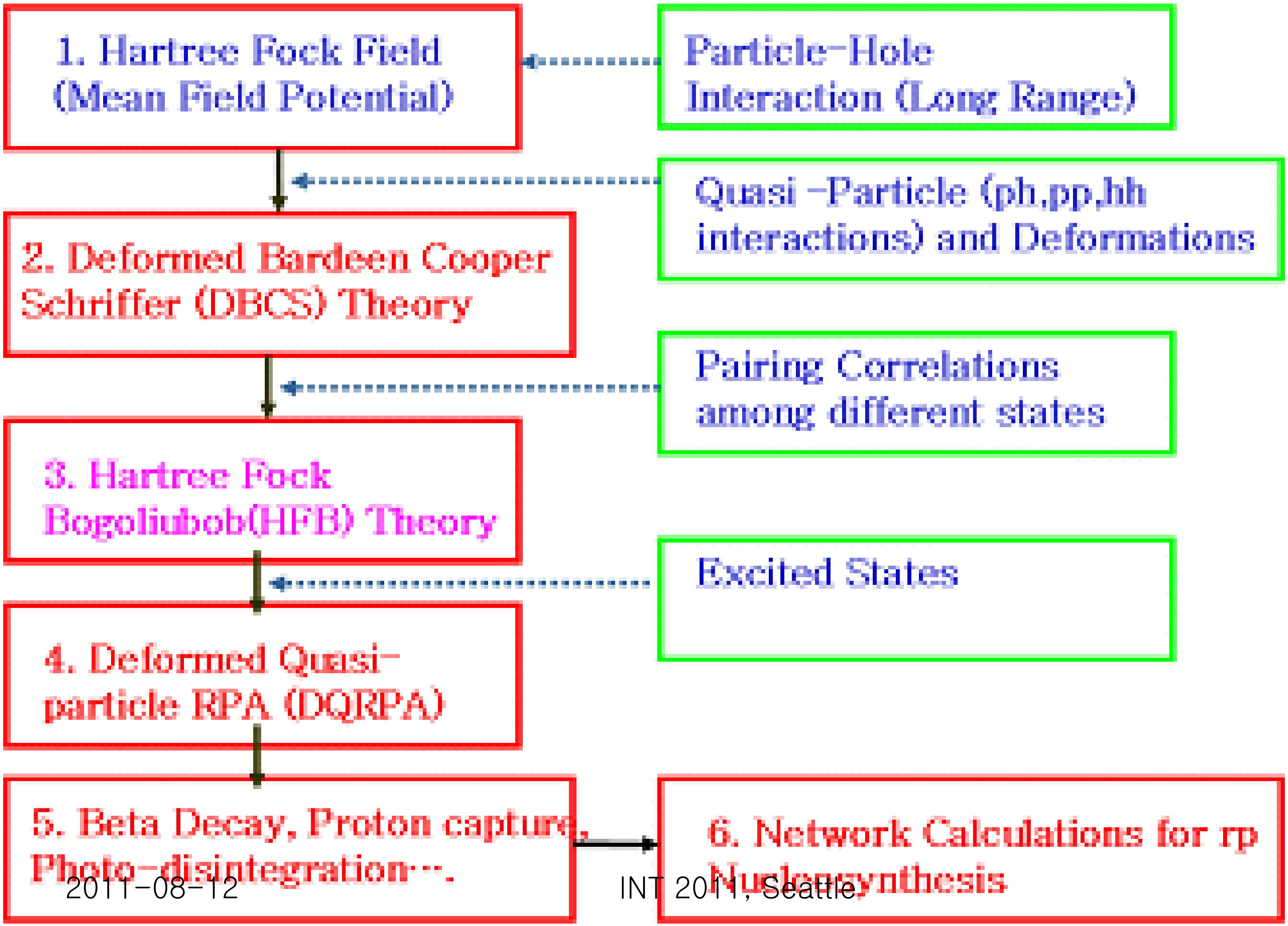
$$R_{CL}(\mathbf{q},\omega) = \Sigma_{J=0}| < J_f||\hat{\mathcal{M}}_J(\mathbf{q}) + \frac{\omega}{\mathbf{q}}\hat{\mathcal{L}}_J(\mathbf{q})||J_i > |^2\ ,$$

$$R_T(\mathbf{q},\omega) = \Sigma_{J=0}| < J_f||\hat{\mathcal{T}}_J^{el}(\mathbf{q})||J_i > |^2 + | < J_f||\hat{\mathcal{T}}_J^{mag}(\mathbf{q})||J_i > |^2\ ,$$

$$R_I(\mathbf{q},\omega) = \Sigma_{J=0}2Re < J_f||\hat{\mathcal{T}}_J^{el}(\mathbf{q})||J_i >< J_f||\hat{\mathcal{T}}_J^{mag}(\mathbf{q})||J_i >\ ,$$

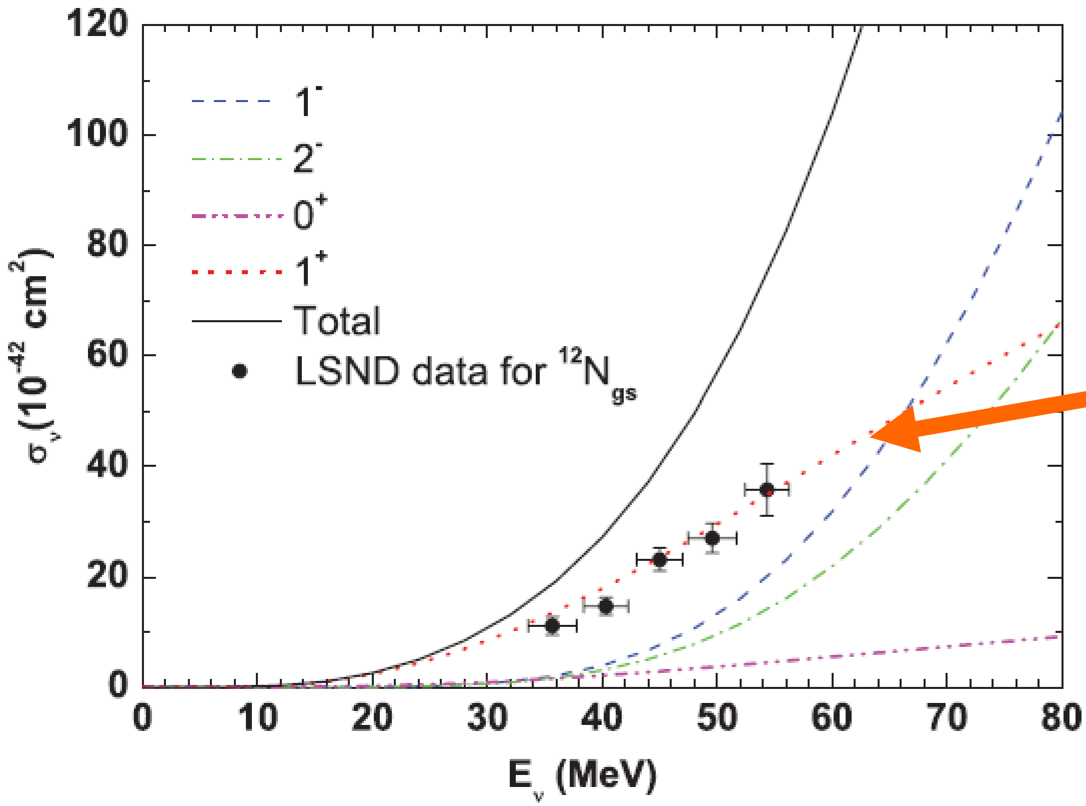
$$\left(\frac{d\sigma_\nu}{d\mathbf{q}^2}\right)^{ERL}_{\nu/\bar{\nu}} = \frac{2G_F^2\epsilon cos^2(\frac{\theta}{2})}{\nu\ 2(J_i+1)}\ [\ R_{CL}(\mathbf{q},\omega) + C(\theta,\mathbf{q})R_T(\mathbf{q},\omega) \mp tan(\frac{\theta}{2})C(\theta,\mathbf{q})R_I(\mathbf{q},\omega)]$$

FLOW of Computer Program



Results : Neutrino Reactions for ^{12}C, ^{56}Fe, ^{92}Nb, ^{138}La and ^{180}Ta, ^{40}Ar.

LSND : ν_e ^{12}C -> e− + ^{12}N



1+

O.K. !!

PHYSICAL REVIEW C **81**, 028501 (2010)

Neutrino reactions on ^{12}C by the quasiparticle random-phase approximation (QRPA)

Myung-Ki Cheoun,[1,4,*] Eunja Ha,[1] Su Youn Lee,[1] K. S. Kim,[2] W. Y. So,[3] and Toshitaka Kajino[4,5]

Results for 12 C

J. Phys. G: Nucl. Part. Phys. 37 (2010) 055101 M-K Cheoun *et al*

Table 1. Comparison of calculated and measured flux averaged cross sections for the ν–^{12}C reaction in units of 10^{-42} cm^2, and half life time of neighboring nuclei. The cross sections are folded by the corresponding DAR neutrino spectra, where the Michel spectrum is used for the energies ν_e and ν_μ is fixed at 29.8 MeV. 'K' and 'L' mean Karmen and LSND groups results, respectively. Shell model (SM) and continuum RPA (CRPA) results are cited from [3] and [9], respectively. (9.834*) is a result with no Coulomb correction.

	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	$^{12}C(\nu_e, e^-)^{12}N^*$	$\beta^{(-)}: (^{12}B(1^+) \to {}^{12}C)$
Experimental data	$8.9 \pm 0.3 \pm 0.9$ [12]'L' $9.1 \pm 0.5 \pm 0.8$ [13]'K'	$4.3 \pm 0.4 \pm 0.6$ [12]'L' $5.1 \pm 0.6 \pm 0.5$ [14]'K'	23.6 ms
Ours	11.53 (9.834*)	6.1	21.33 ms
SM	9.06–8.48	5.22–4.87	
CRPA	8.9	5.4	
	$^{12}C[(\nu_e, \nu_e') + (\bar{\nu}_\mu, \bar{\nu}_\mu')]^{12}N_{g.s.}$	$^{12}C[(\nu_\mu, \nu_\mu')]^{12}C^*$	$\beta^{(+)}(EC): (^{12}N(1^+) \to {}^{12}C)$
Experimental data	$10.4 \pm 1.0 \pm 0.9$ [13]'K'	$3.2 \pm 0.5 \pm 0.4$ [15]'K'	11.0 ms
Ours	9.92	3.60	10.34 ms
SM	9.76–8.27	2.68–2.26	
CRPA	10.5		

Cross sections averaged by incident neutrino flux $\langle\sigma\rangle = \int dE_\nu f(E_\nu)\sigma(E_\nu)/\int dE_\nu f(E_\nu)$ for exclusive and inclusive reactions via charged and neutral currents are tabulated

Results for 56 Fe and 56 Ni

Without Fermi correction : 0.79 (−40) !!!!

Flux averaged C.S. for DAR

N. PAAR, D. VRETENAR, T. MARKETIN, AND P. RING — PHYSICAL REVIEW C **77**, 024608 (2008)

TABLE II. Flux-averaged cross sections for the ν_e reaction on ^{16}O, ^{56}Fe, and ^{208}Pb target nuclei.

	$^{16}O(\nu_e, e^-)^{16}F$ $\langle\sigma\rangle(10^{-42}\ cm^2)$	$^{56}Fe(\nu_e, e^-)^{56}Co$ $\langle\sigma\rangle(10^{-42}\ cm^2)$	$^{208}Pb(\nu_e, e^-)^{208}Bi$ $\langle\sigma\rangle(10^{-42}\ cm^2)$
SM ($0\hbar\omega \times 0.64$) [62]	10.8		
TM [65]		214	
TDA (SKIII) [66]			2954,3204
RPA [64]	14.55	277	2643
CRPA (WS+LM) [67]		240	3620
(Q)RPA (SIII,SGII)	16.90,17.20 [21]	352 [63]	4439 [23]
PN-RQRPA (DD-ME2)	13.18	140	2789
Exp. (KARMEN) [9,67]		256 ± 108 ± 43	

Our results : 1.418 (−40) : Fermi Coulomb Correction

With np pairing 1.735 (−40) !!!!

O.K. !!

Results for 56Fe and 56Ni

J. Phys. G: Nucl. Part. Phys. 37 (2010) 055101 M-K Cheoun *et al*

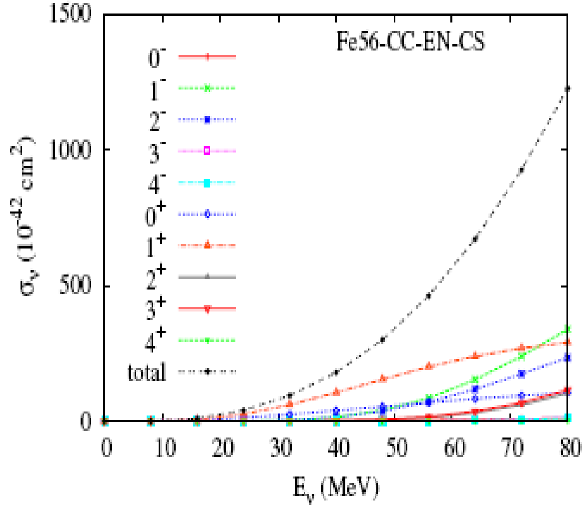
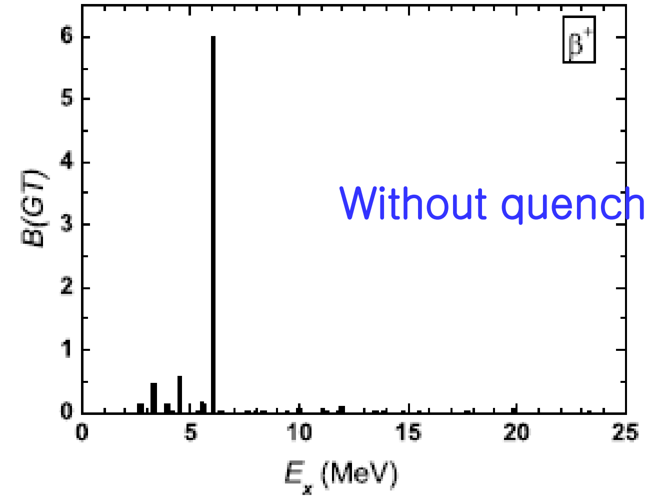
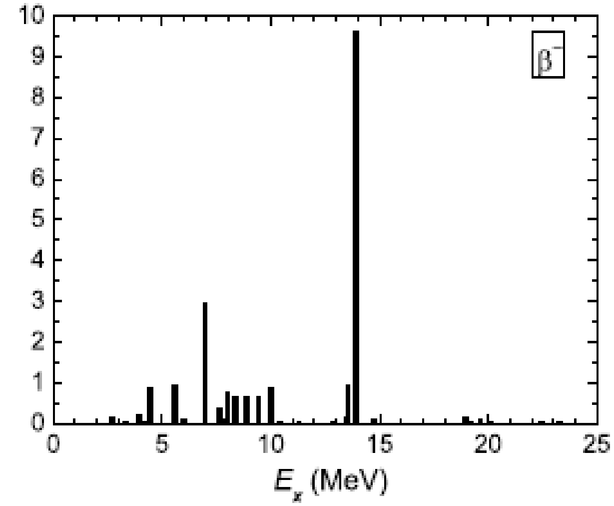


Figure 6. Cross sections of the ^{56}Fe$(\nu_e, e^-)^{56}$Co* reaction for $J_\pi = 0^\pm$–$4^\pm$ states. Each multipole state contribution and total sum are presented.



Without quenching



We need the quenching for the exp. data.

Since results of the total GT strength are also reported in [40], we take the summation of the distributions. Our results for the total GT strength with a universal quenching factor $f_q^2 = (0.74)^2$ [6, 40] are 11.38 and 4.41 for $B(GT_\mp)$, respectively. They are consistent with those of experimental data, 9.9 ± 2.4 [39] and 2.8 ± 0.3 [40], respectively. As shown in

Results of 138 La and 180Ta

We reproduce experimental (GT) strength distribution by the quenching factor !!

$^{138}Ba(^{3}He, t)^{138}La$ reaction

PRL 98, 082501 (2007) PHYSICAL REV

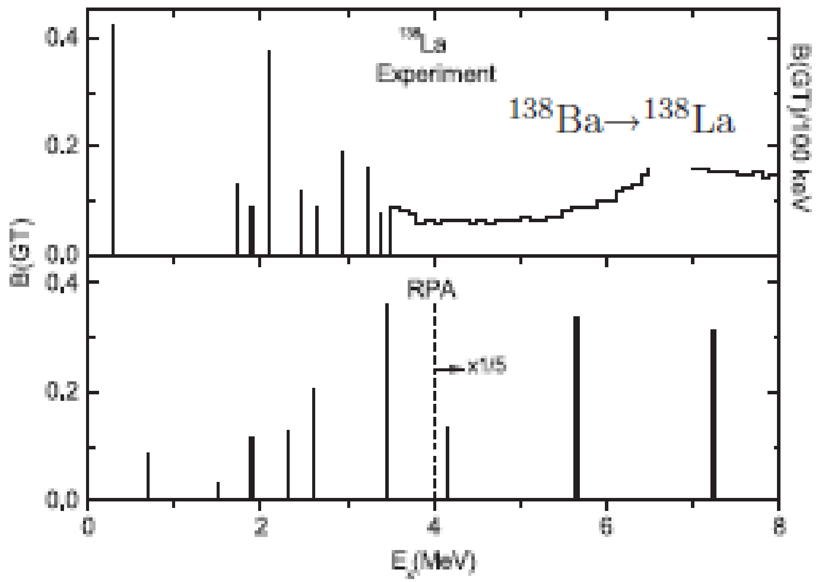
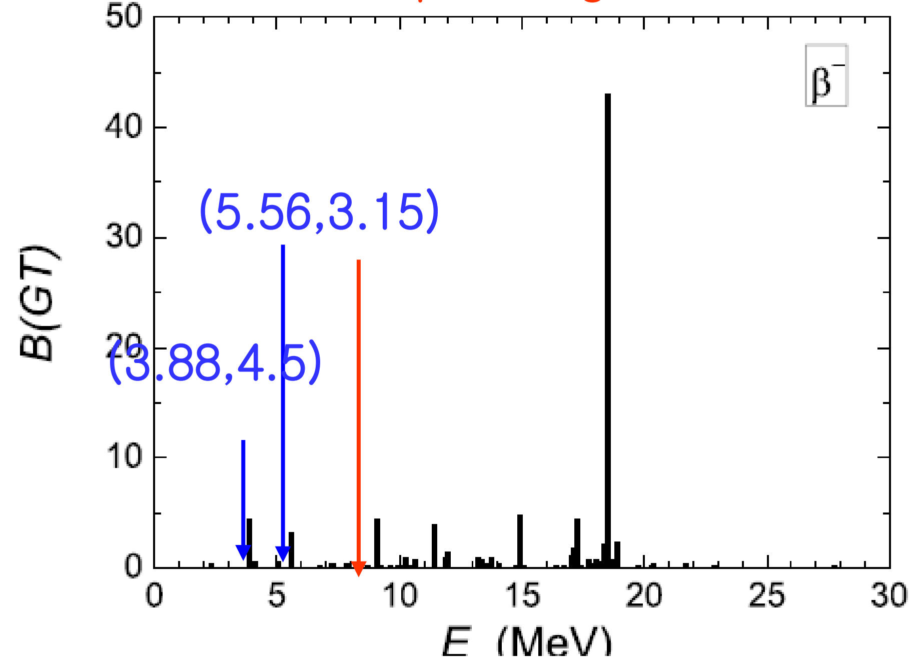
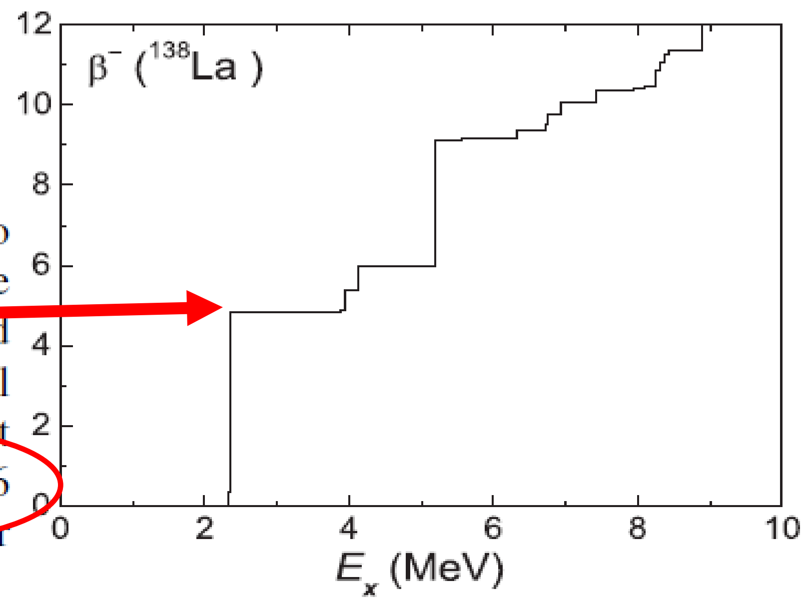


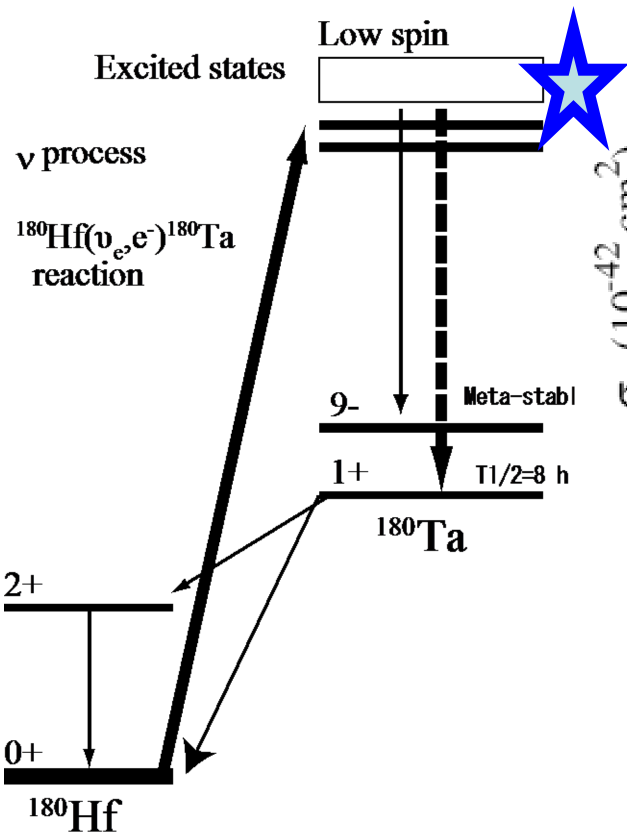
FIG. 3. GT strength distribution in [138]La. Top: present work. Bottom: RPA calculation used in Ref. [2].

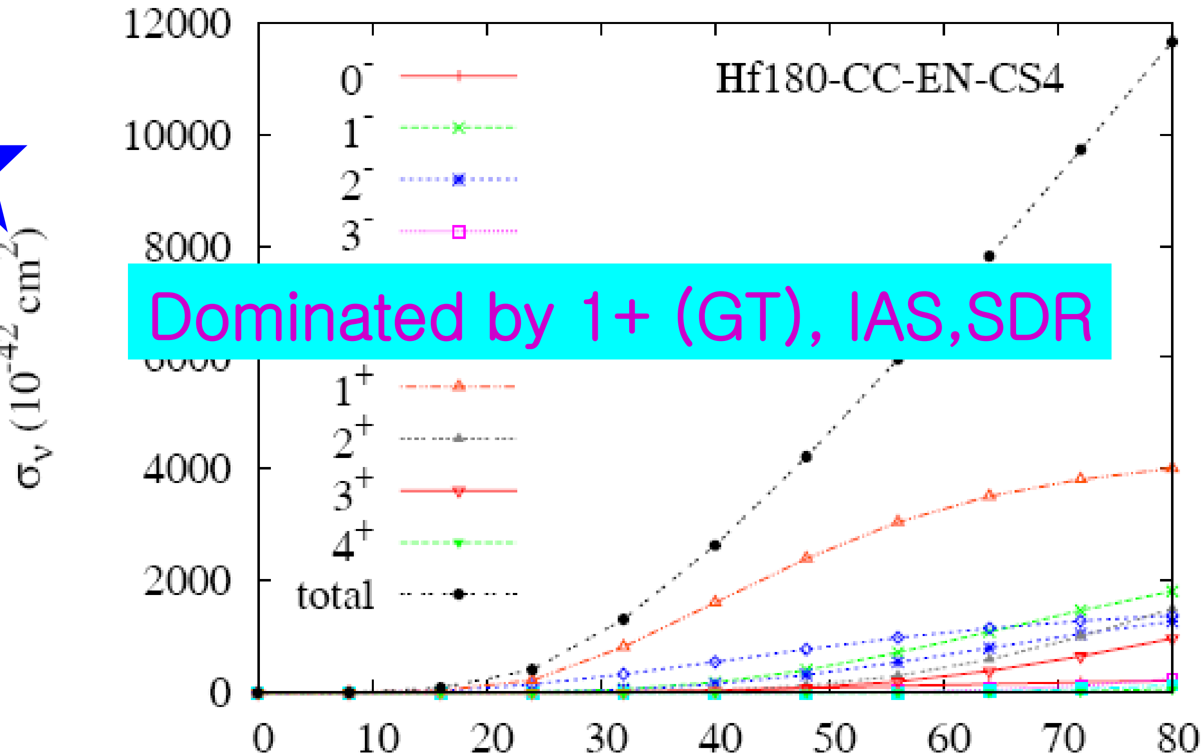


Running sums of the GT(−) strength distribution up to 10 MeV are shown in the right panels. Our results for the running sum up to 8 MeV are 5.5 and 3.8 for [138]La and [180]Ta, respectively, if we take into account the universal quenching factor $f_q = 0.74$ for the axial coupling constant g_A. They reproduce well the experimental data, 5.8 ± 1.6 and 4.4 ± 0.9, respectively, reported in Ref. [12]. For other



Results of 138 La and 180Ta

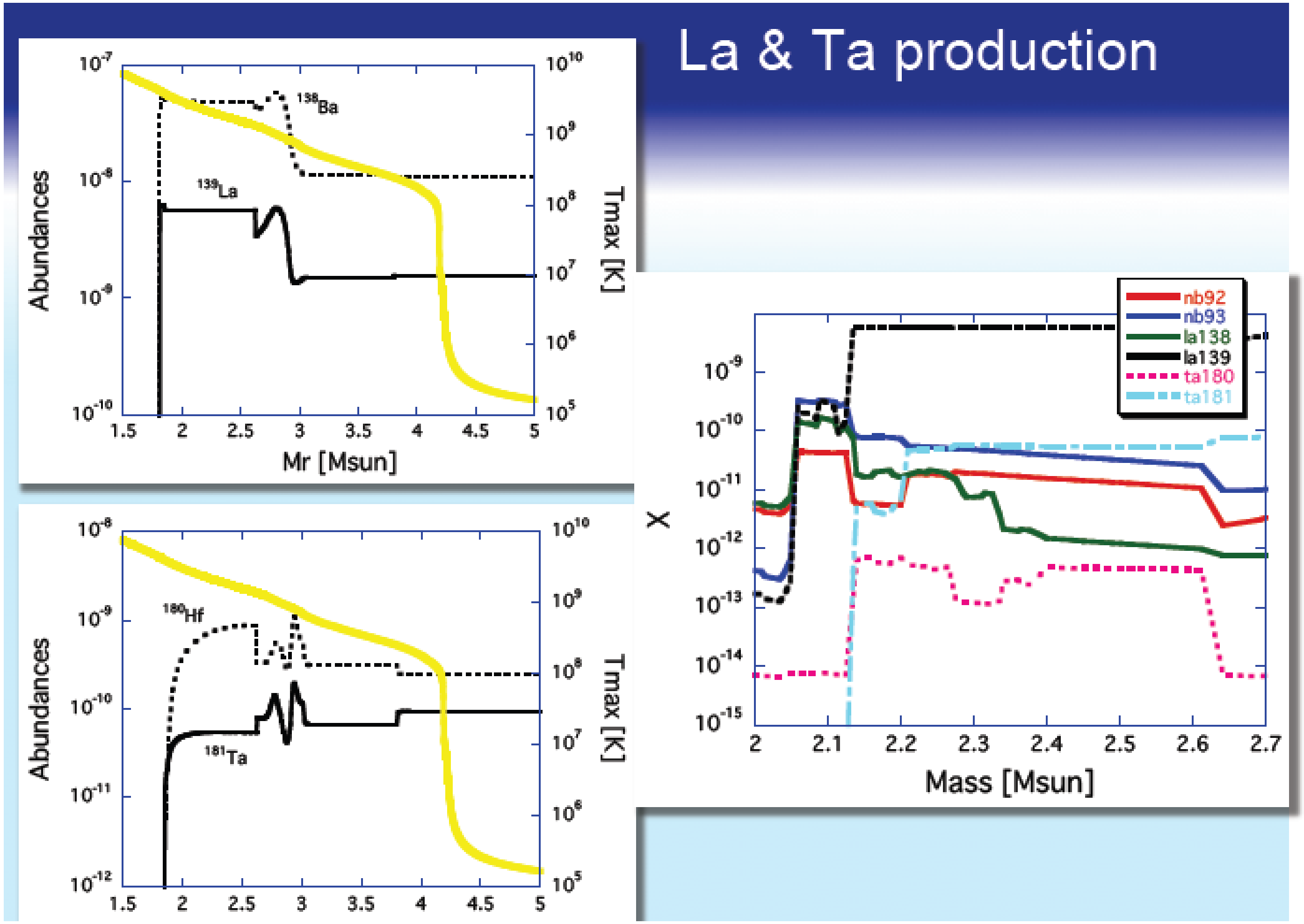




$$< \sigma_\nu >= \frac{\int dE_\nu \sigma_\nu(E_\nu) f(E_\nu)}{\int dE_\nu f(E_\nu)} ,$$

T(MeV)	^{138}La			^{180}Ta		
	Exp.	RPA	Ours	Exp.	RPA	Ours
4	74	61	68	151	115	76
6	226	156	254	399	272	316
8	435	281	554	752	485	672

Results of 138 La and 180Ta

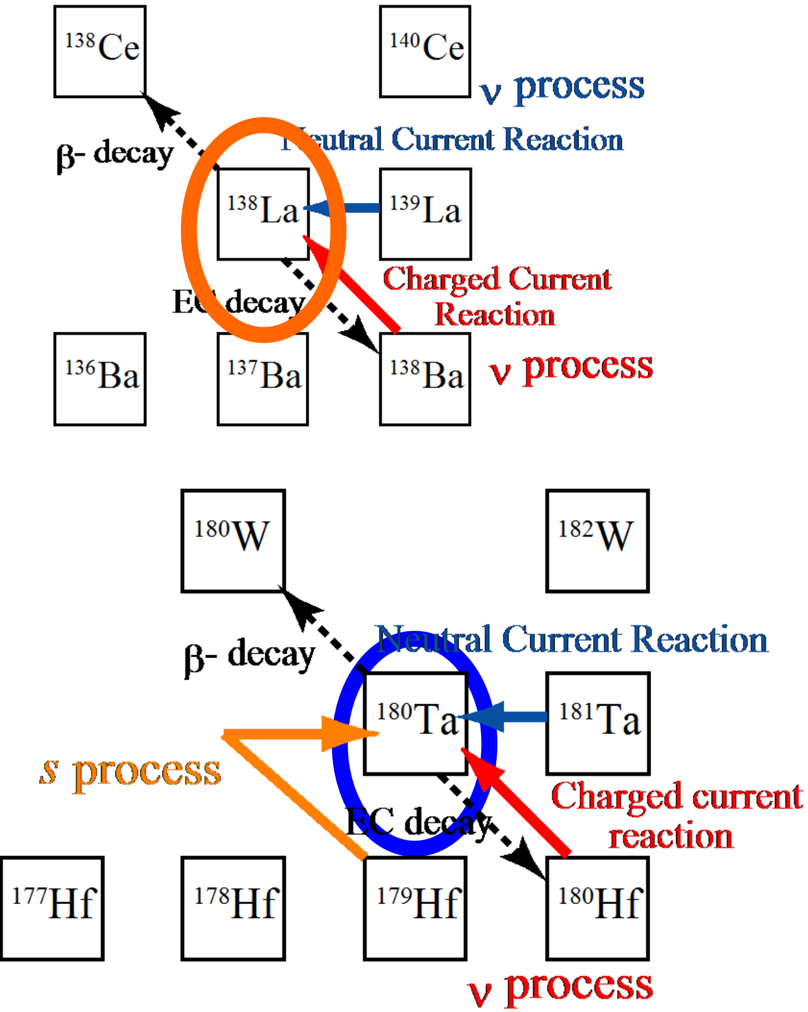


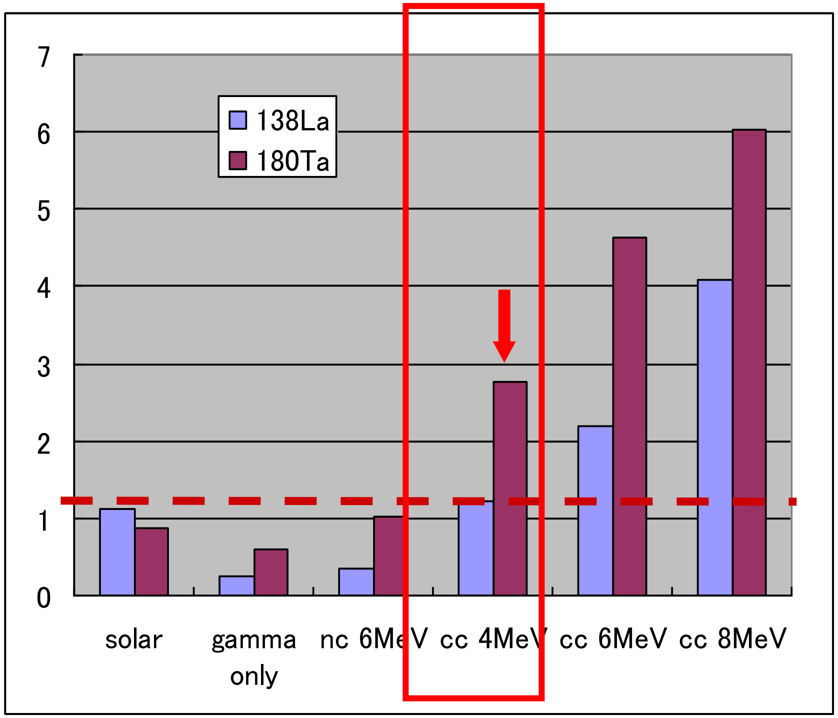
PHYSICAL REVIEW C **82**, 035504 (2010)

Neutrino reactions on ^{138}La and ^{180}Ta via charged and neutral currents by the quasiparticle random-phase approximation

Myung-Ki Cheoun,[1,*] Eunja Ha,[1] T. Hayakawa,[2] Toshitaka Kajino,[3,4] and Satoshi Chiba[5]

Results of 138 La and 180Ta





Hayakawa et.al, (2010)

Results for 40Ar

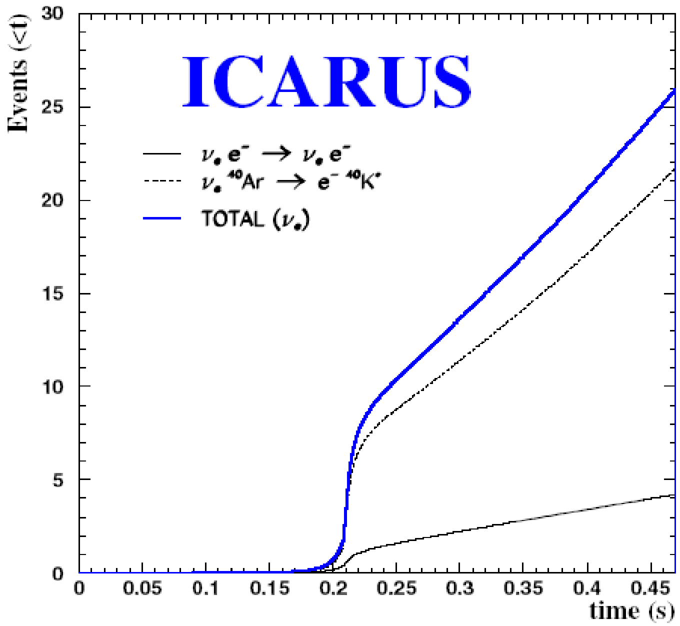
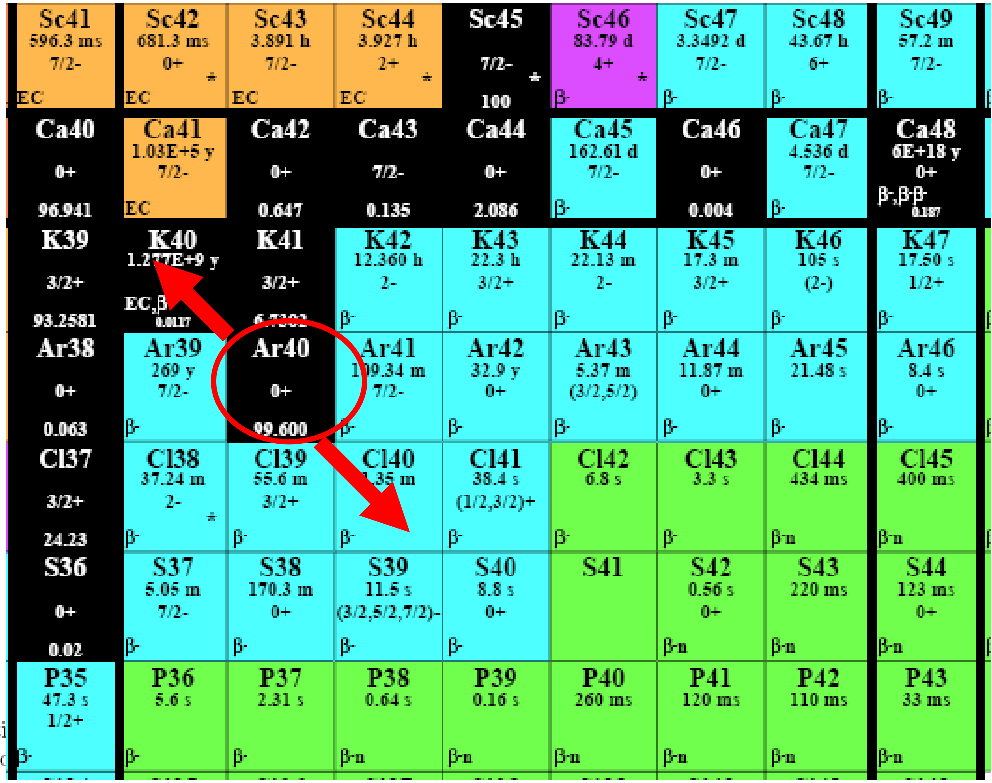


Figure 11. Integrated number of ν_e events as a function of time for the elasti
and absorption channels. The thick solid line corresponds to the total number o
events for a 3 kton detector. No oscillation effects are included.



Imaging of Cosmic and Rare Underground Sign
(ICARUS) :

1. Liquid Argon time projection chamber (LArTI
2. For solar neutrino from ^{8}B
3. For SN neutrino and oscillations

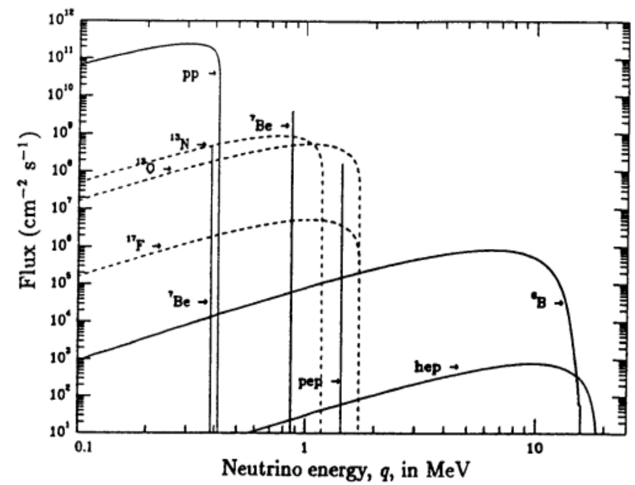
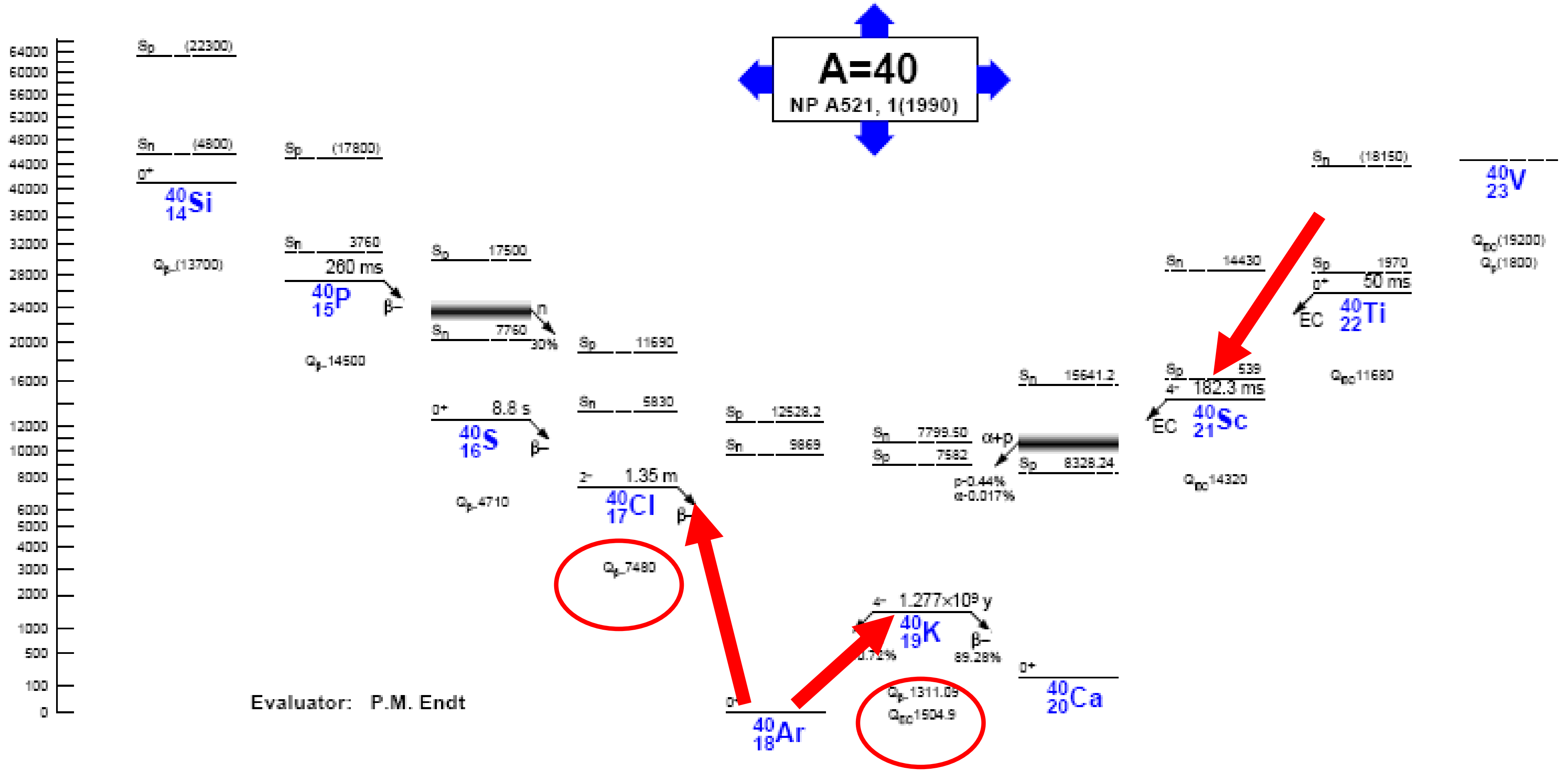


Fig. 44. Solar neutrino spectrum. Energy spectrum of solar neutrinos, as predicted by the standard solar model. Solid and dashed curves distinguish between neutrinos produced in the pp-chains and the CNO cycle, respectively. (From 49.)

Results for 40Ar



Results for 40Ar

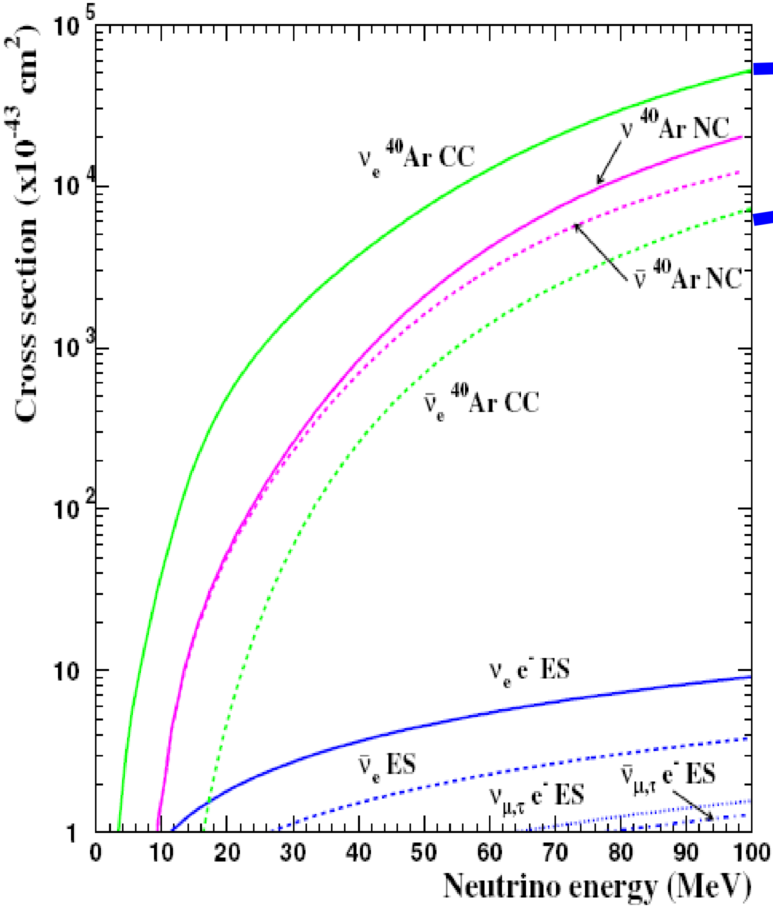
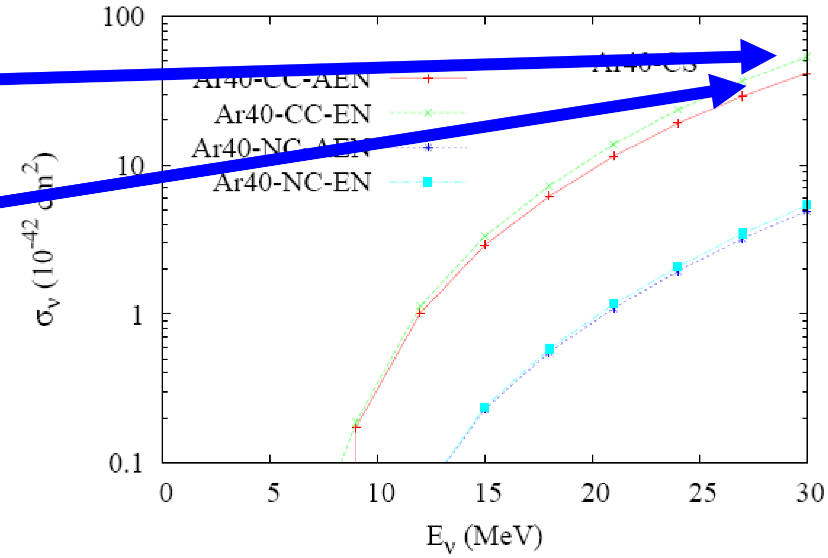
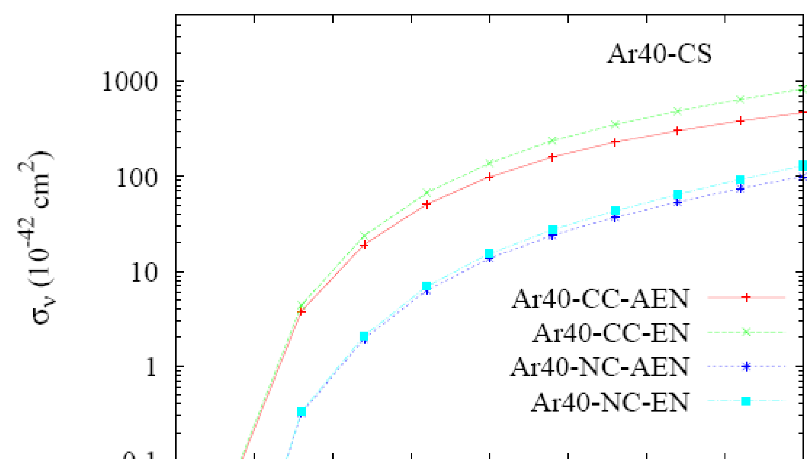


Figure 3. Neutrino cross sections relevant to the supernovae detection with a liquid argon TPC detector.





$$\sigma(E_\nu) = \frac{G_F^2 \cos^2\theta_c}{\pi \hbar^4 c^3} \sum_i k_i \epsilon_i F(Z, \epsilon_i)[B_i(GT) + B_i(F)] \ , \qquad (8)$$

where k_i and ϵ_i refer to the momentum and total energy of the outgoing electron and $F(Z, \epsilon_i)$

Results for 40Ar

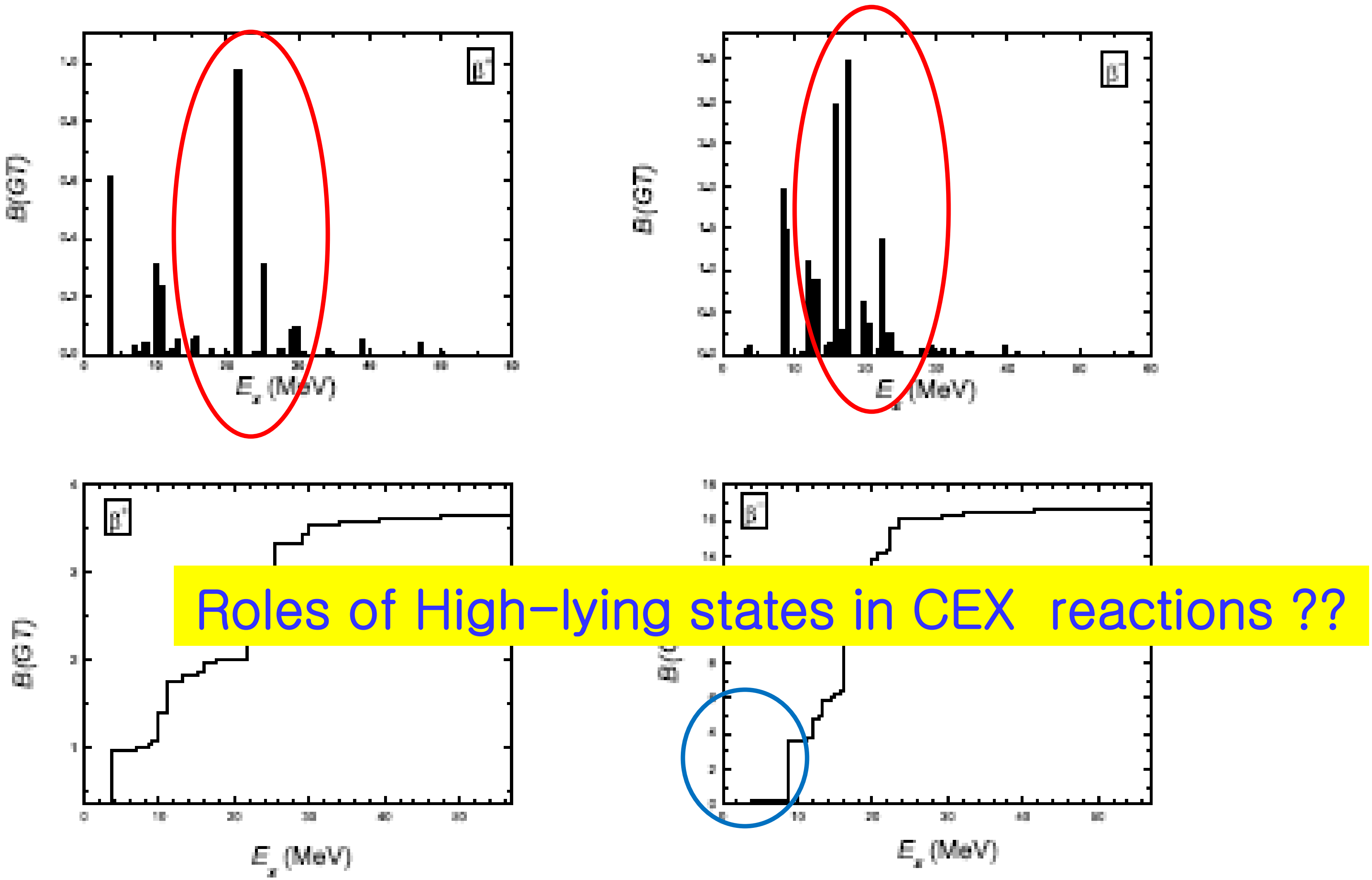
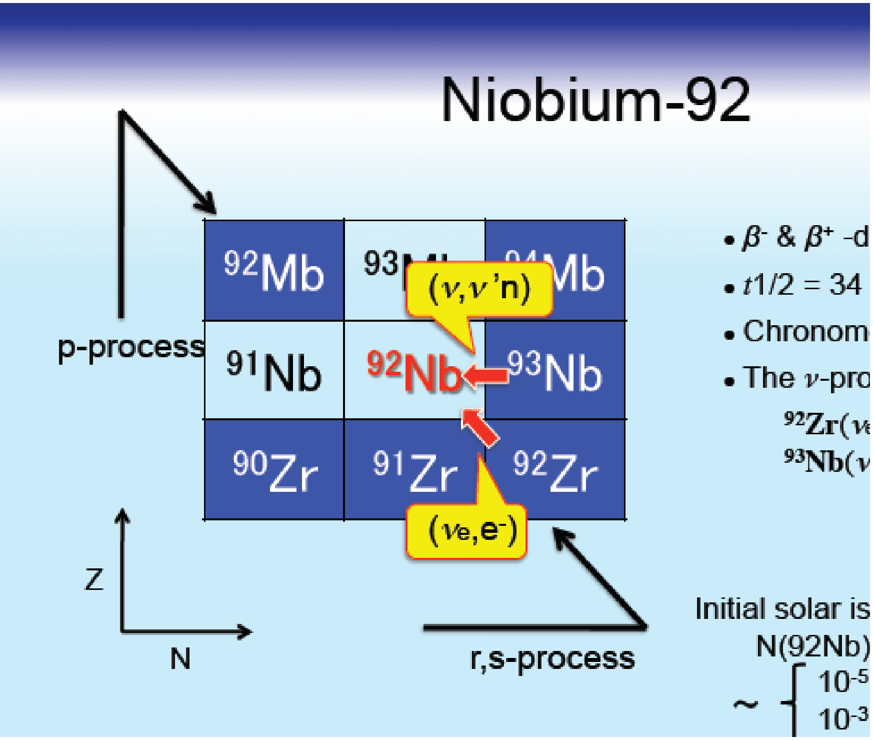
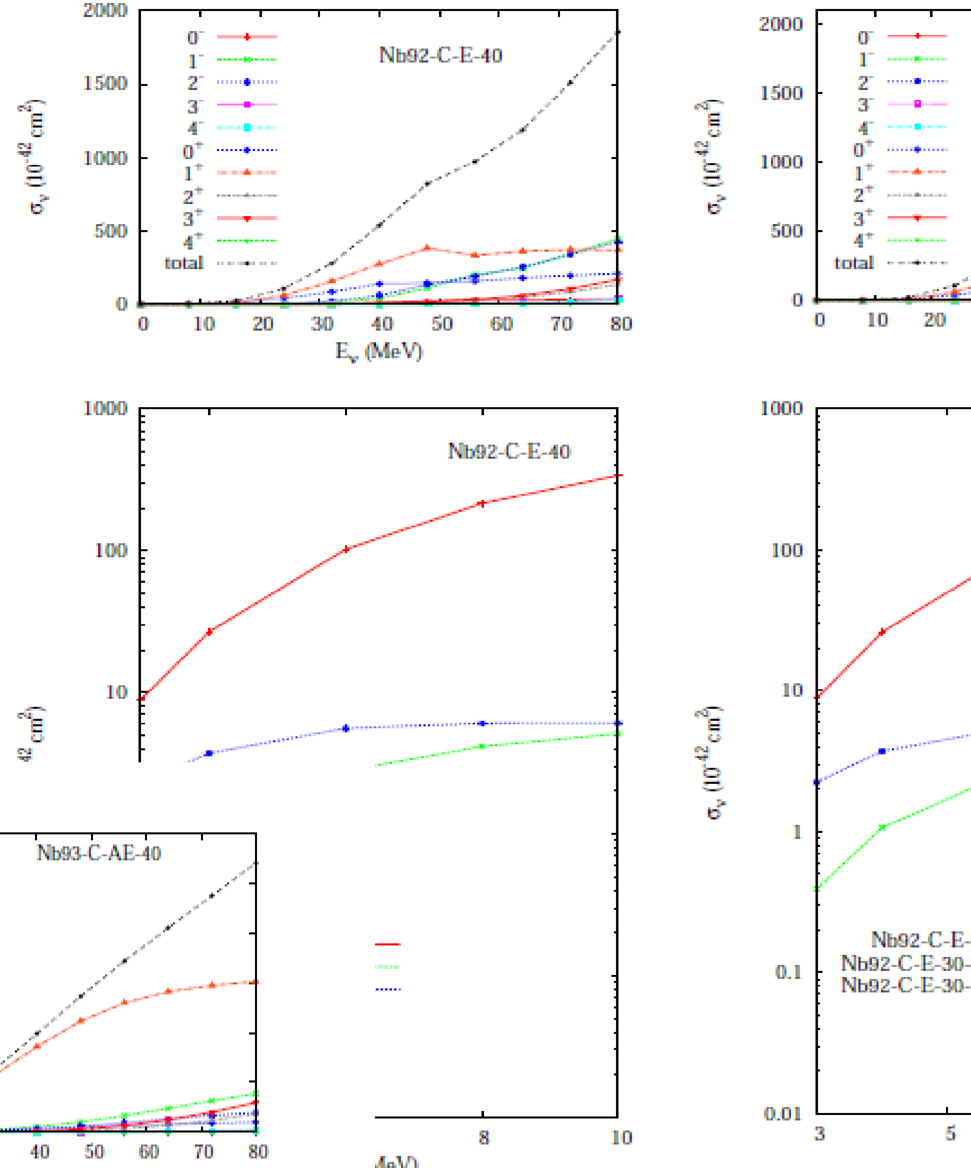


Fig. 2: The Gamow Teller strength GT(±) from ^{40}Ar and their running sums

Results for 92Nb





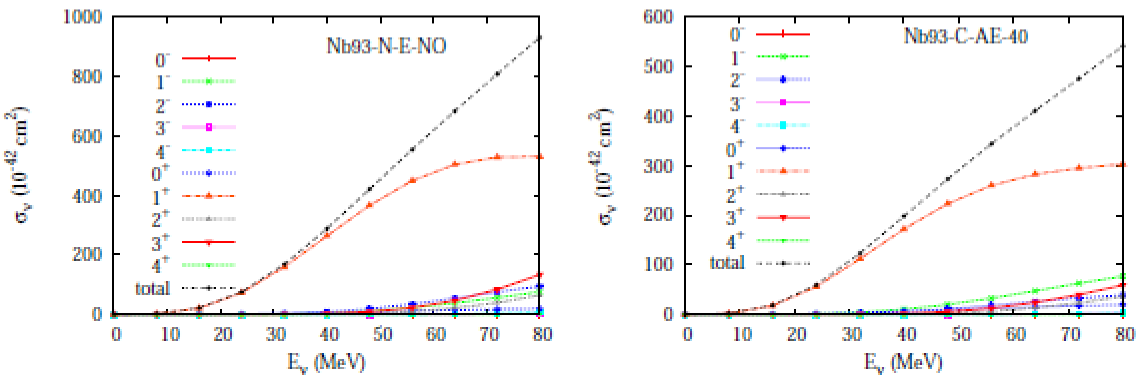


FIG. 7: Energy dependent cross sections of NC reactions for ^{92}Nb, ^{93}Nb$(\nu(\bar{\nu}),\nu'(\bar{\nu}')n)^{93}$Nb. Left is for incident ν_e and right is for $\bar{\nu}_e$.

ture dependent cross sections of CC reac ions for ^{92}Nb, ^{92}Zr$(\nu_e,e^-)^{92}$Nb. Blue and $(\nu_e,e^-p)^{91}$Zr and ^{92}Zr$(\nu_e,e^-n)^{91}$Nb.

Results for 92Nb

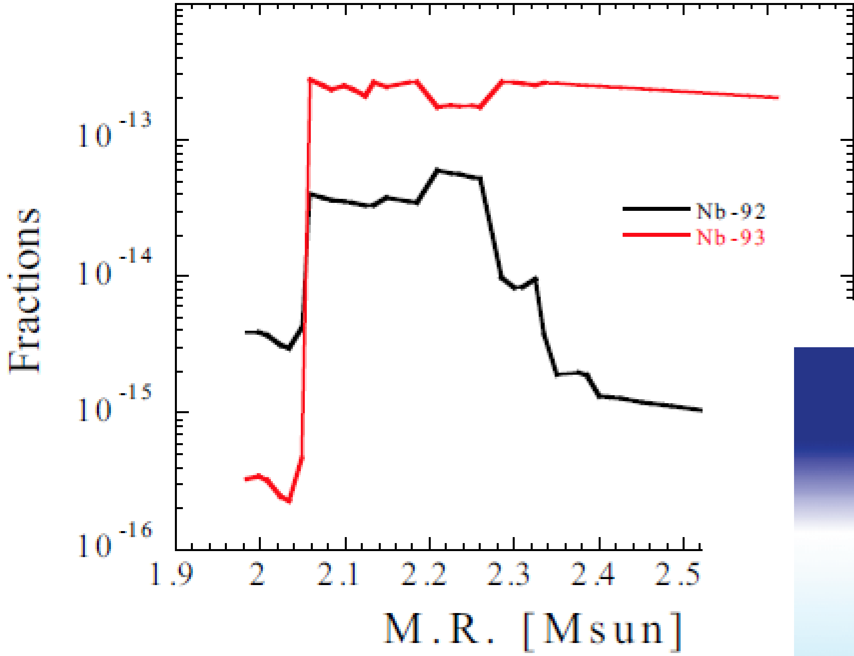


Figure 3: Calculated result of supernova neutrin

Too large ratio !

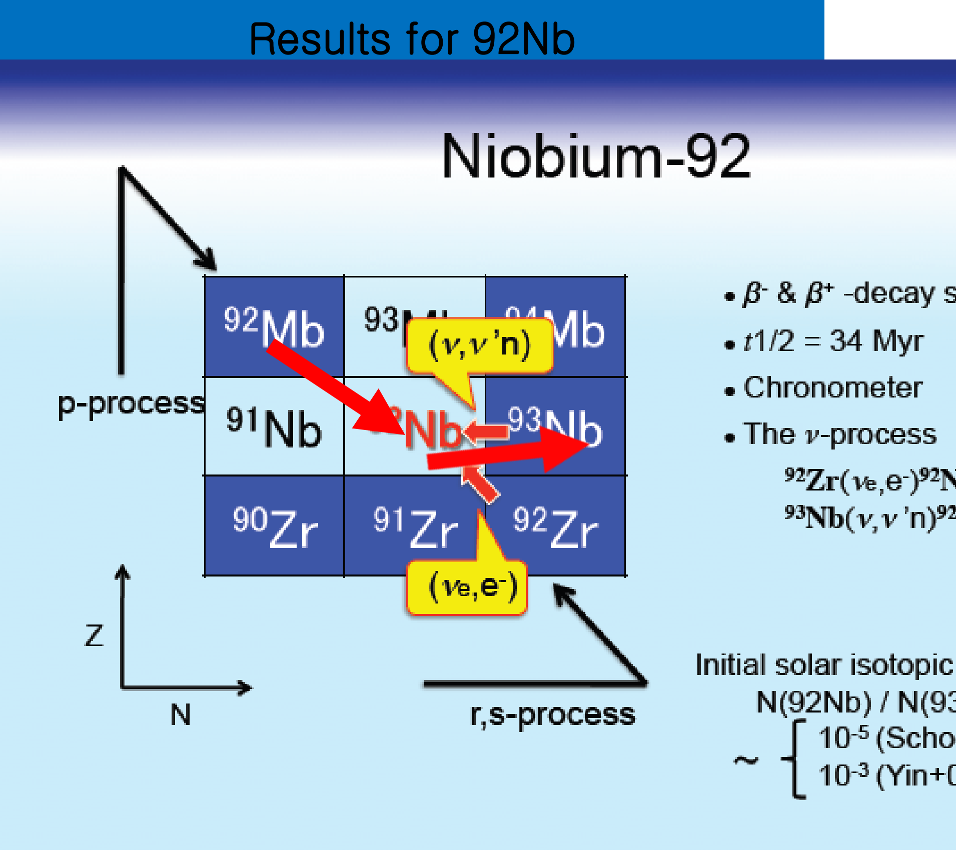
Final mass, ratios, and observations

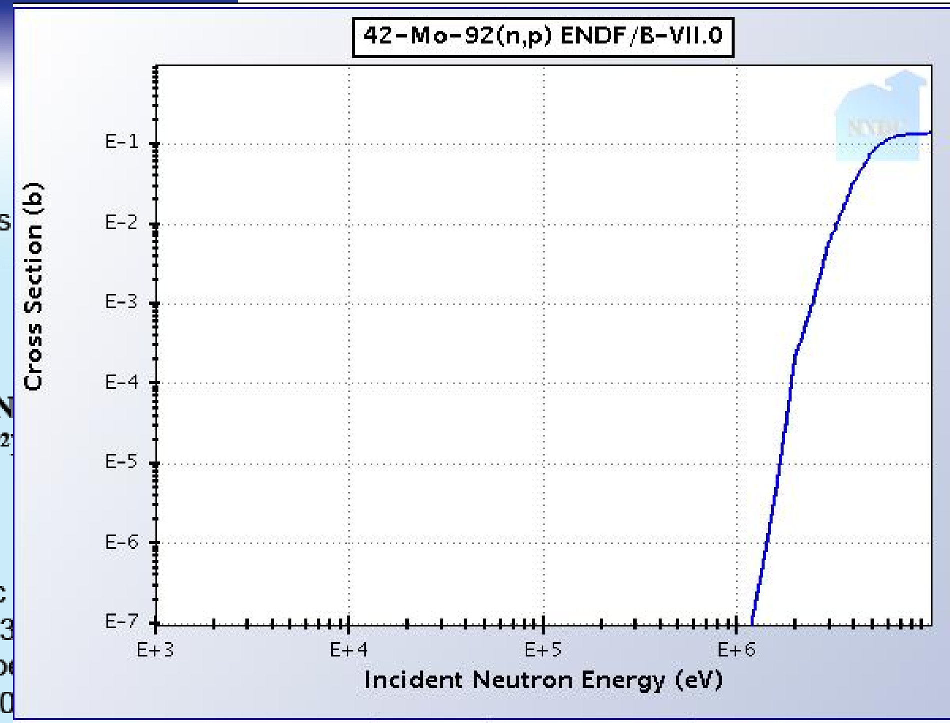
- Total mass [Msun] in ONeMg region:
  - $^{92}Nb = 5.4e-12$
  - $^{93}Nb = 2.6e-11$
  - $^{138}La = 8.8e-12$
  - $^{139}La = 1.4e-09$
  - $^{180}Ta = 9.1e-14$
  - $^{181}Ta = 1.2e-11$

Isotopic ratios:		Solar:
$^{92}Nb/^{93}Nb = 0.21$	>>	10^{-3} - 10^{-5}
$^{138}La/^{139}La = 0.0062$	>	0.001
$^{180}Ta/^{181}Ta = 0.0073$	>	0.0001

- Overproduction of ^{138}La & ^{180}Ta
  They should be averaged over the whole.
  ^{180}Ta is still too much, but a factor of 0.39 helps us.

- Overproduction of ^{92}Nb
  It is reasonable, because ^{92}Nb is radioactive.
  The discrepancy in solar values might be caused by local formation of grains.





Once ^{92}Nb is produced by the (n,p) reaction from ^{92}Mo, it is exposed simultaneously to an intense flux of neutrons and destroyed by the radiative neutron capture reaction ^{92}Nb(n,γ)^{93}Nb. Although the (n,γ) cross section was not measured for the radioactive nucleus ^{92}Nb ($\tau_{1/2} = 3.47 \times 10^7 y$), the ^{92}Nb(n,$\gamma$)^{93}Nb cross section is expected to be as large as those measured for stable Nb isotopes, $< \sigma v > / v_T = 261.3$, 317.2, and 402.6 mb for ^{93,94,95}Nb(n,γ)^{94,95,96}Nb reactions, respectively, at the neutron energy 30 keV [20]. These (n,γ) cross sections are eighteen orders of magnitude larger than the ^{92}Mo(n,p)^{92}Nb cross section at this energy. Therefore, the ^{92}Mo(n,p)^{92}Nb reaction should not contribute much

Summary

- Quasi particle RPA with np pairing was successfully applied to the beta and double beta decays.
- The ambiguities from the nuclear structure should be pinned down for more accurate information in the astronomical data.
- Results for neutrino nucleus interactions (12C, 56Fe, 40Ar, 138La,180Ta), **obtained by QRPA showed quite consistent results with available data. But, overproduction of 92Nb is still open problem. 93Nb should be understood more clearly !!!.**
- We are applying our method to the ν processes as well as other reactions in another nuclei.
- In specific, for the unstable nuclei necessary in NS, more refined theory including the deformation, Deformed Quasi-particle RPA (DQRPA), is under progress.

Thanks for your attention and
Truly thanks
for the INT !!

Neutral and Charged Cuuren Reaction

Cheoun et. al, JPG (2010)

neutrino reactions. For NC reaction,

$$
\begin{aligned}
& < QRPA || \hat{O}_\lambda || \; \omega; JM > \qquad (15) \\
= & \sum_{a\alpha' b\beta'} [\mathcal{N}_{a\alpha' b\beta'} < a\alpha' || \hat{O}_\lambda || b\beta' > \; [u_{pa\alpha'} v_{pb\beta'} X_{a\alpha' b\beta'} + v_{pa\alpha'} u_{pb\beta'} Y_{a\alpha' b\beta'}] \\
& -(-)^{j_a + j_b + J} \mathcal{N}_{b\beta' a\alpha'} < b\beta' || \hat{O}_\lambda || a\alpha' > \; [u_{pb\beta'} v_{pa\alpha'} X_{a\alpha' b\beta'} + v_{pb\beta'} u_{pa\alpha'} Y_{a\alpha' b\beta'}]] + (p \rightarrow n) \; ,
\end{aligned}
$$

where the nomalization factor is given as $\mathcal{N}_{a\alpha' b\beta'}(J) = \sqrt{1 - \delta_{ab}\delta_{\alpha'\beta'}(-1)^{J+T}}/(1 + \delta_{ab}\delta_{\alpha'\beta'})$. Without the np pairing correlation, this expression can be reduced to the following simple form

$$
\begin{aligned}
& < QRPA || \hat{O}_\lambda || \; \omega; JM > \qquad (16) \\
= & \sum_{ab} [\mathcal{N}_{apbp} < ap || \hat{O}_\lambda || bp > \; [u_{pa} v_{pb} X_{apbp} + v_{pa} u_{pb} Y_{apbp}] \\
& -(-)^{j_a + j_b + J} \mathcal{N}_{bpap} < bp || \hat{O}_\lambda || ap > \; [u_{pb} v_{pa} X_{apbp} + v_{pb} u_{pa} Y_{apbp}]] + (p \rightarrow n) \; ,
\end{aligned}
$$

$$
\begin{aligned}
& < QRPA || \hat{O}_\lambda || \; \omega; JM > \qquad (17) \\
= & \sum_{a\alpha' b\beta'} [\mathcal{N}_{a\alpha' b\beta'} < a\alpha' || \hat{O}_\lambda || b\beta' > \; [u_{pa\alpha'} v_{nb\beta'} X_{a\alpha' b\beta'} + v_{pa\alpha'} u_{nb\beta'} Y_{a\alpha' b\beta'}] \; .
\end{aligned}
$$

This form is also easily reduced to the results by pnQRPA without pn pairing

$$
< QRPA || \hat{O}_\lambda || \; \omega; JM > = \sum [\mathcal{N}_{apbn} < ap || \hat{O}_\lambda || bn > \; [u_{pa} v_{nb} X_{apbn} + v_{pa} u_{nb} Y_{apbn}] \; . \qquad (18)
$$

NC reactions cannot be described by the pn QRPA, which should be performed by pp+nn+pn QRPA by following the method for EM transition !!

Core-Collapse, ν-Heating, Nucleosynthesis

Energy Hierarchy due to neutron-rich matter !

$$E_{\nu e} \leq E_{\bar{\nu} e} \leq E_{\nu\mu\tau,\nu\mu\tau}$$

$$\nu_e + n \longrightarrow e^- + p$$
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$
$$\nu_i + A \longrightarrow e^- + A'$$
$$\bar{\nu}_i + A \longrightarrow e^+ + A'$$
$$\nu_i + A \longrightarrow \nu_i' + A'$$

Surface of Iron Core

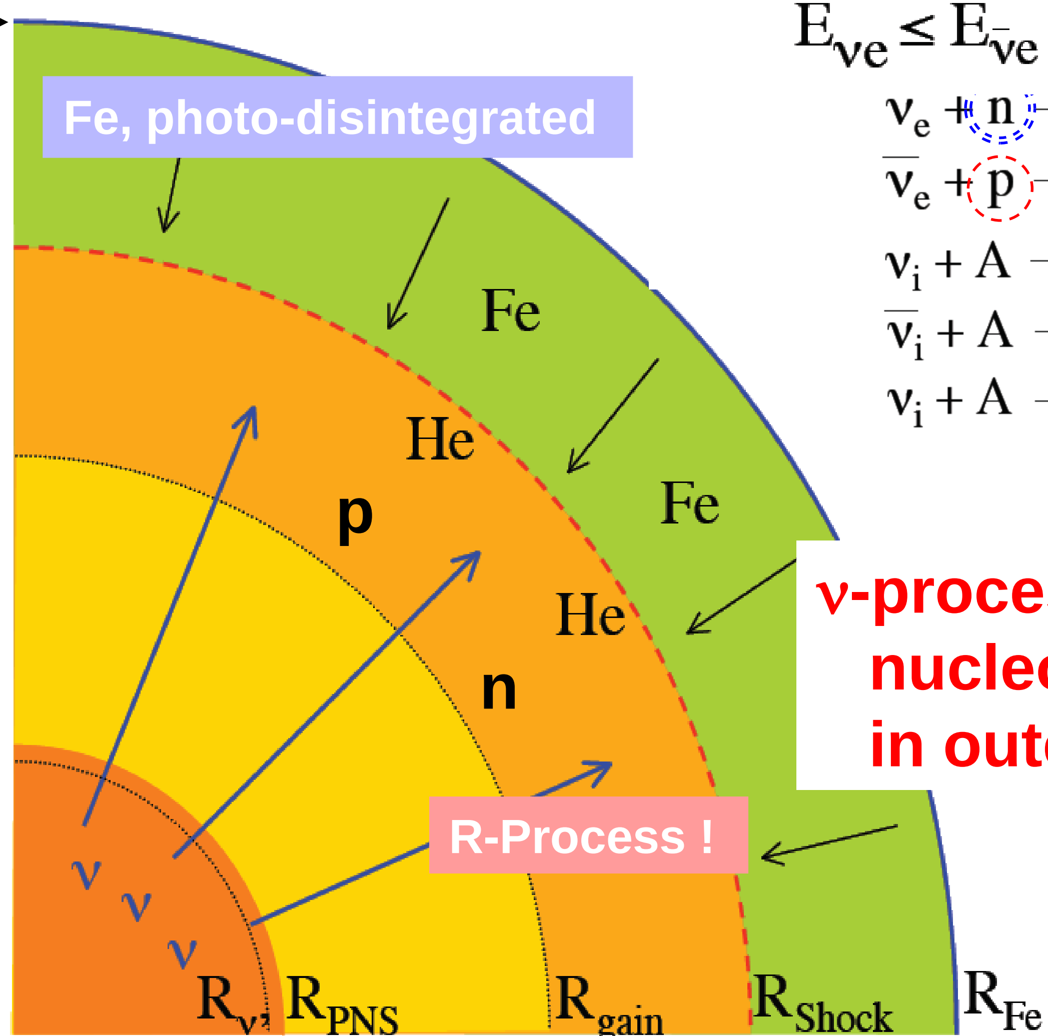
Stalled Shock

Heating Region → Hot Bubble

Gain Radius

Cooling Region

Proto-NEUTRON STAR



ν-process nucleosynthesis in outer layers !

ν–A int. help explosion ?
ν–ν int. & oscillation ?

~ 10km **~20—100km** **~1000km**