2015, Finland, NDM15

Neutrino-process in supernovae

Japan Atomic Energy Agency
T.Hayakawa

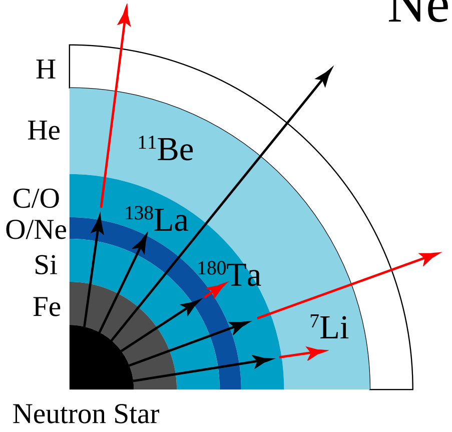
Collaborators
T. Kajino, G. Mathews, K.Nakaramu, M. Cheoun,
S.Chiba

Topics

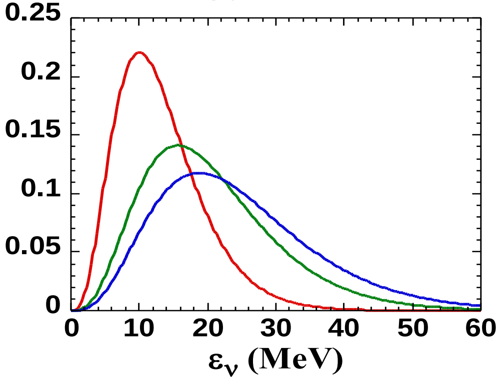
1. Supernova neutrino process
2. The solar abundance of ^{180}Ta
3. Origin of ^{92}Nb observed in primitive meteorites

Physics around Neutrino Process

Stellar model

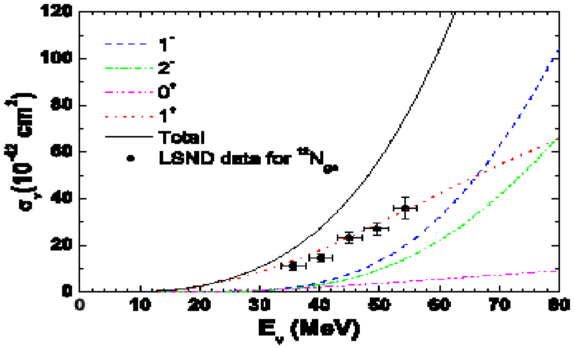


Neutrino Energy Spectra



Unknown

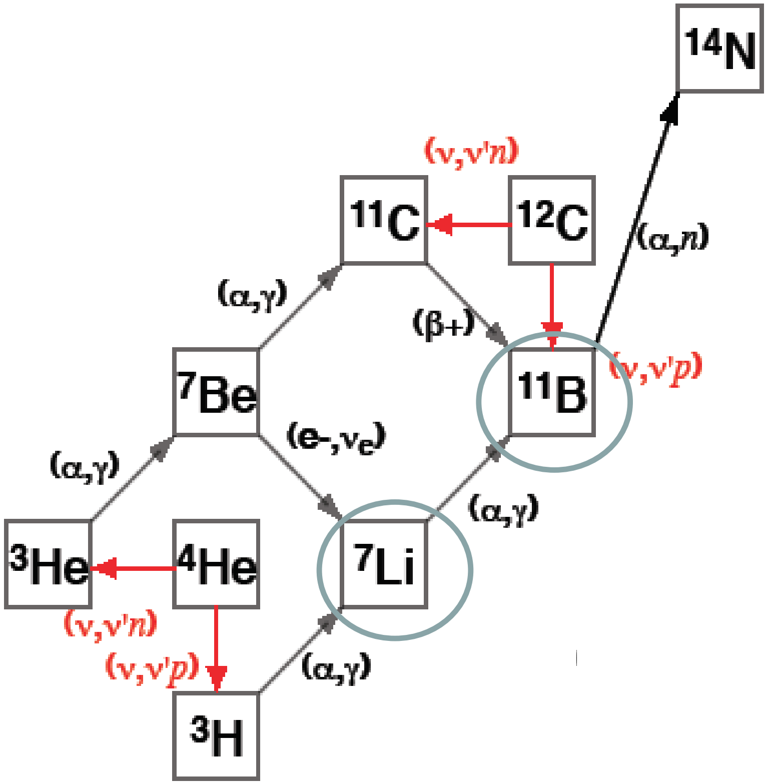
Neutrino Reaction Rate

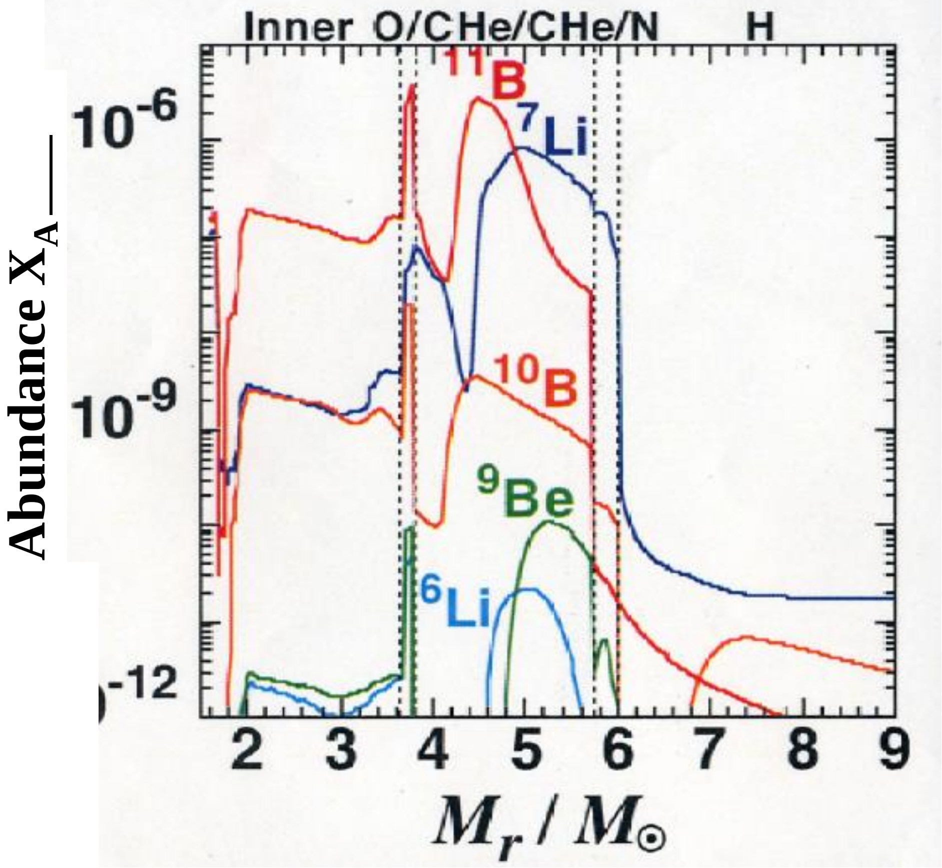


Calculation

Abundances in the solar system or primitive meteorite
Observation

Neutrino process for light elements





SN II: Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.
SNIc + II: Nakamura, ZYoshida, Shigeyama, Kajino, ApJL 718 (2010), L137.

Neutrino-induced reactions

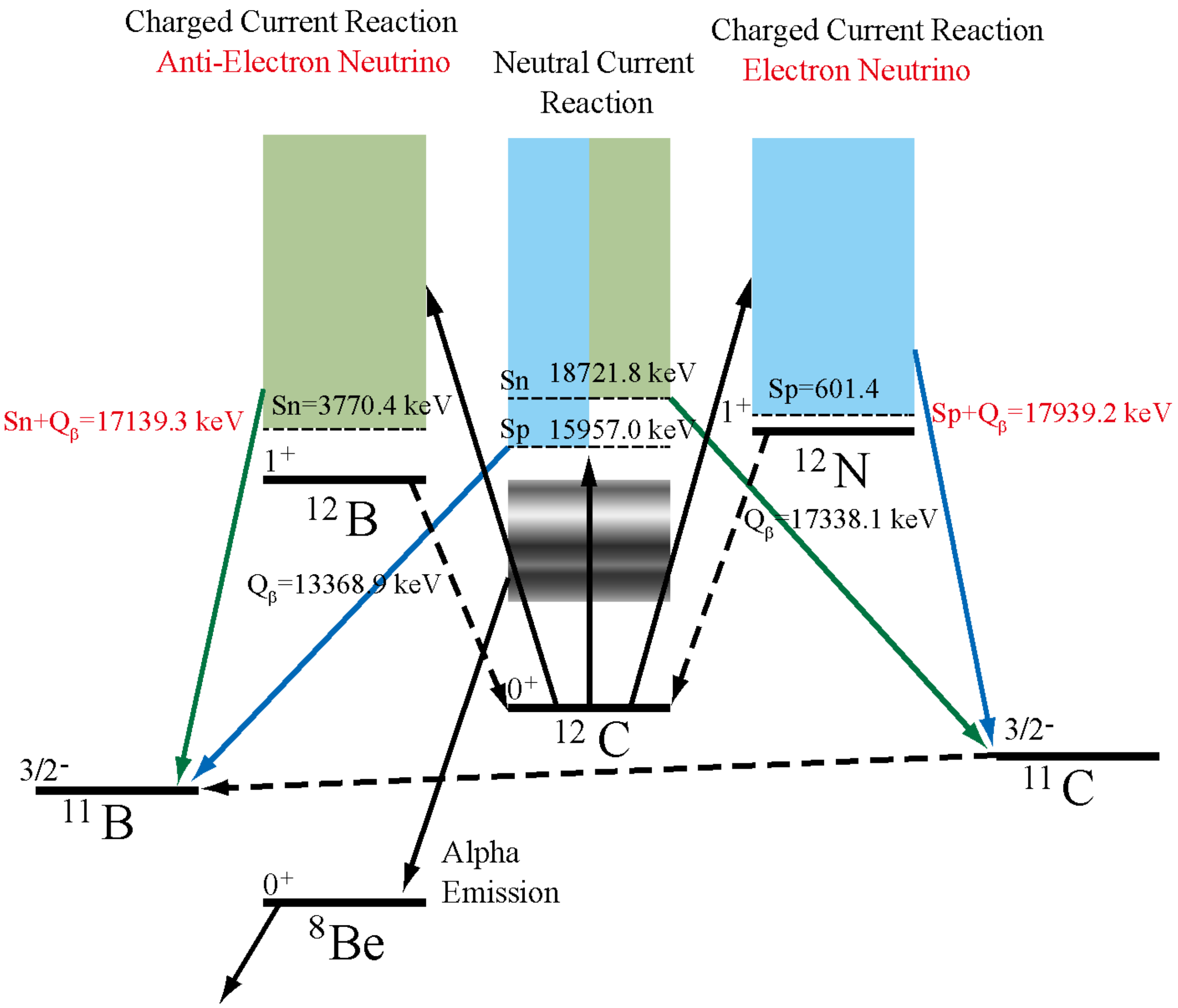
Neutrino-induced reactions can be categorized to the following three groups:

1. Neutral current reactions with all neutrinos.

2. Charged current reaction with electron neutrino.

3. Charged current reactions with anti-electron neutrino.

Neutrino reactions on ^{12}C



Charged Current Reaction
Anti-Electron Neutrino

Neutral Current Reaction

Charged Current Reaction
Electron Neutrino

$S_n + Q_\beta = 17139.3$ keV

$S_n = 3770.4$ keV

1^+

^{12}B

$Q_\beta = 13368.9$ keV

Sn 18721.8 keV

Sp 15957.0 keV

0^+

^{12}C

1^+

Sp=601.4

^{12}N

$Q_\beta = 17338.1$ keV

$S_p + Q_\beta = 17939.2$ keV

3/2-

^{11}B

3/2-

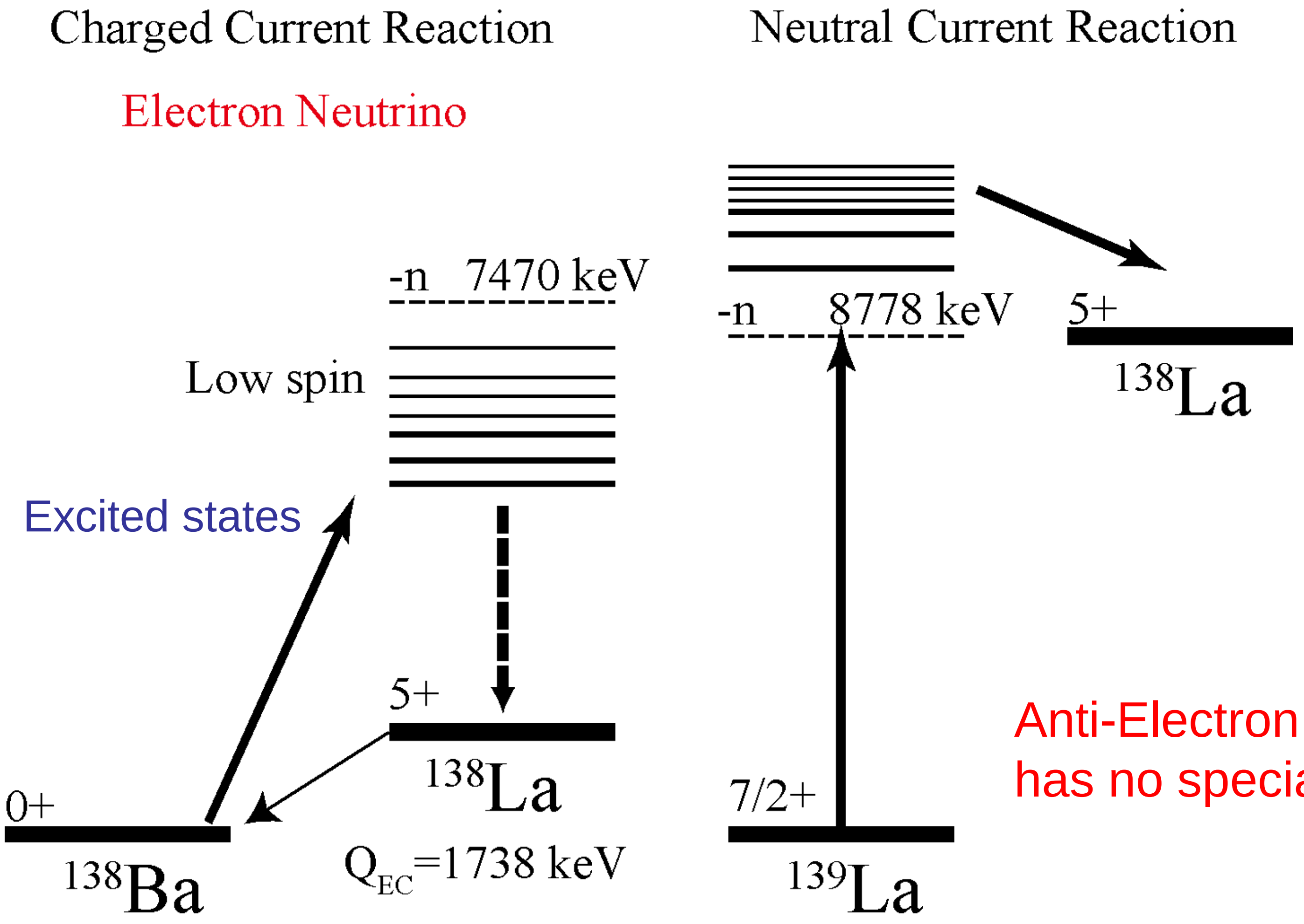
^{11}C

0^+

^{8}Be

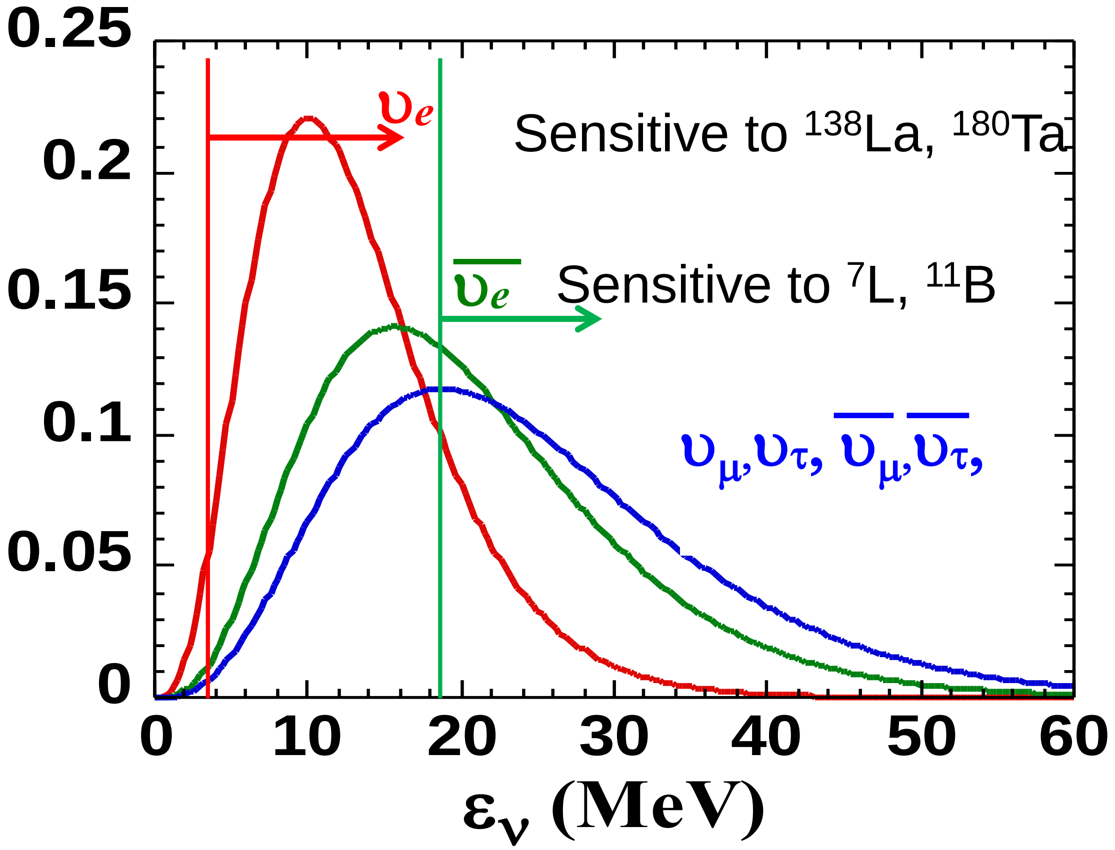
Alpha
Emission

Neutrino reactions on heavy nuclides for ^{138}La and ^{180}Ta



Anti-Electron neutrino has no special role.

Neutrino Spectra and sensitivity for nucleosyntheses



$T(\nu_e) < T(\bar{\nu}_e) < T(\nu_x)$

$x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

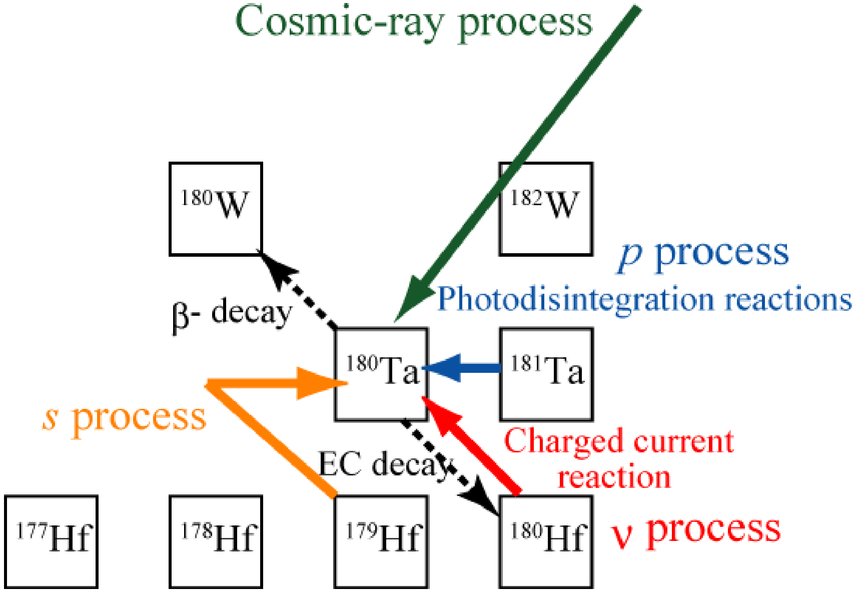
$T(\nu_e) = 3.2$ MeV

$T(\bar{\nu}_e) = 4.0$ MeV

$T(\nu_{\mu,\tau}) = T(\bar{\nu}_{\mu,\tau}) = 6.0$ MeV

Origin of ^{180}Ta

The origin of a p-nucleus ^{180}Ta has been one of the most mysterious.



J. Audouze, A&A (1970)

Cosmic-ray production

M. Arounld, (1976): S.E.Woosley, (1978).

Gamma-process origin

R.A. Ward, Nature 291,308,(1981)

K.Yokoi, Nature (1983)

Proposal of s-process origin

D.Belick, Phys. Rev. Lett. (1999)

Measurement of transition probability between the isomer and the ground state

Goko, Phys. Rev. Lett. (2007)

Measurement of (gamma,n) reactions

S.E.Woosley, Astrophys. J. (1990).

Proposal of neutrino-process origin

A.Heger, Phys. Lett. B (2005)

Model Calculation.

Byelikov , Phys. Rev. Lett. (2007)

(3He,t) experiments for Neutrino-process

Origin of ^{138}La

The origin of ^{138}La has been an open question.

J. Audouze, A&A (1970)

Cosmic-ray nucleosynthesis

M. Arounld, (1976): S.E.Woosley, (1978).

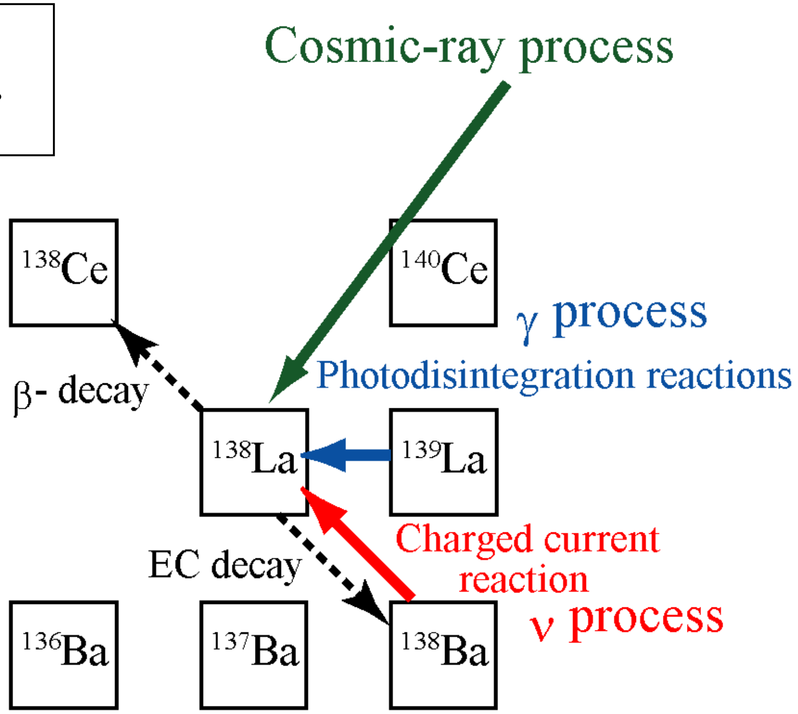
Photodisintegration reactions in supernovae

S.E.Woosley, Astrophys. J. (1990).

Neutrino process in SNe

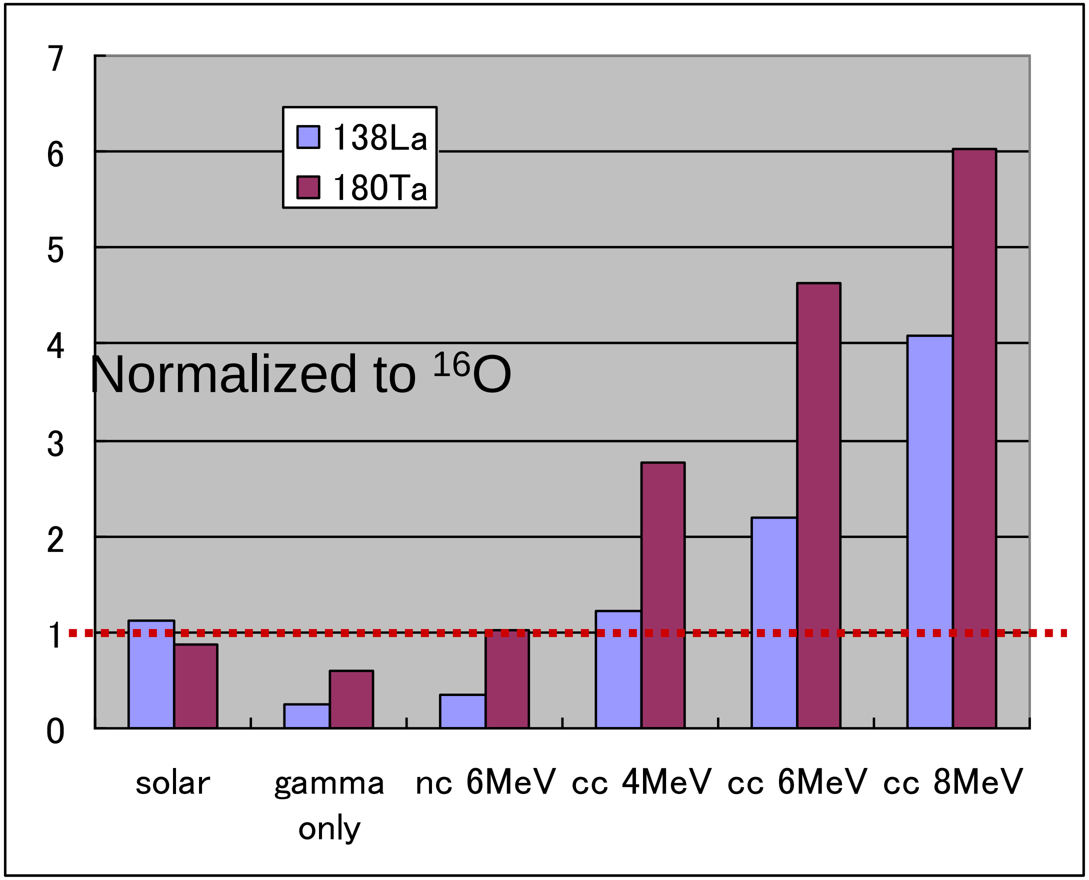
A.Heger, Phys. Lett. B (2005)

About 90% of the solar abundance can be explained by the neutrino process



^{138}La decays to ^{138}Ce with a half-life of 1.05×10^{11} y.

Abundances of ^{138}La and ^{180}Ta



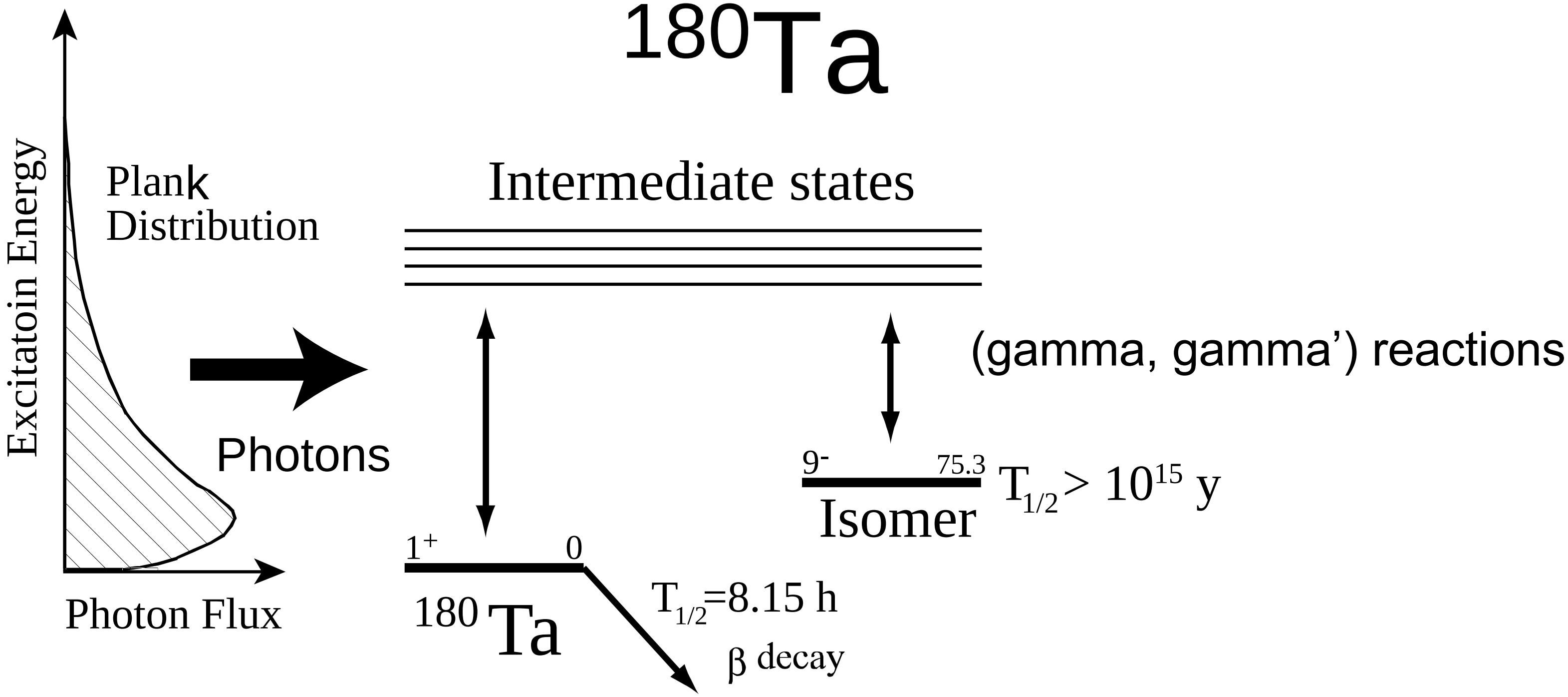
From Heger, PLB, 2005

The solar abundances of ^{138}La and ^{180}Ta was calculated by Heger, 2005.

However, the relative abundance of ^{180}Ta is about 2 times larger than that of ^{138}La in any cases.

There is no solution !

Problem of Isomer Ratio of ^{180}Ta



Excitatoin Energy

Plank
Distribution

Photon Flux

Photons

Intermediate states

(gamma, gamma') reactions

9^- 75.3

Isomer

$T_{1/2} > 10^{15}$ y

1^+ 0

^{180}Ta

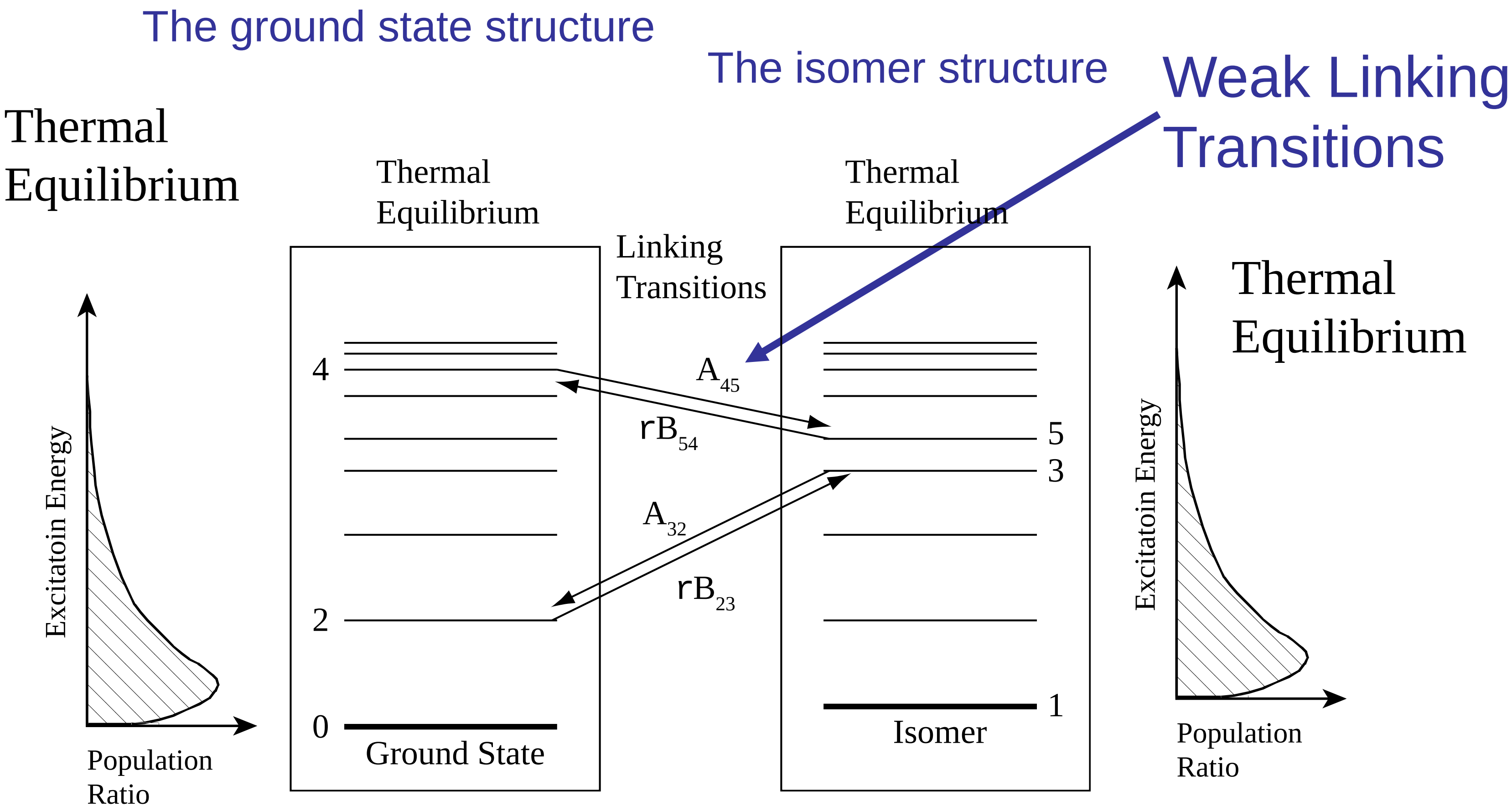
$T_{1/2}$=8.15 h

β decay

- The two states are linked by (gamma,gamma') reactions.
- Transition rate is determined by the temperature.
- The isomer residual ratio depends on the change of the temperature.

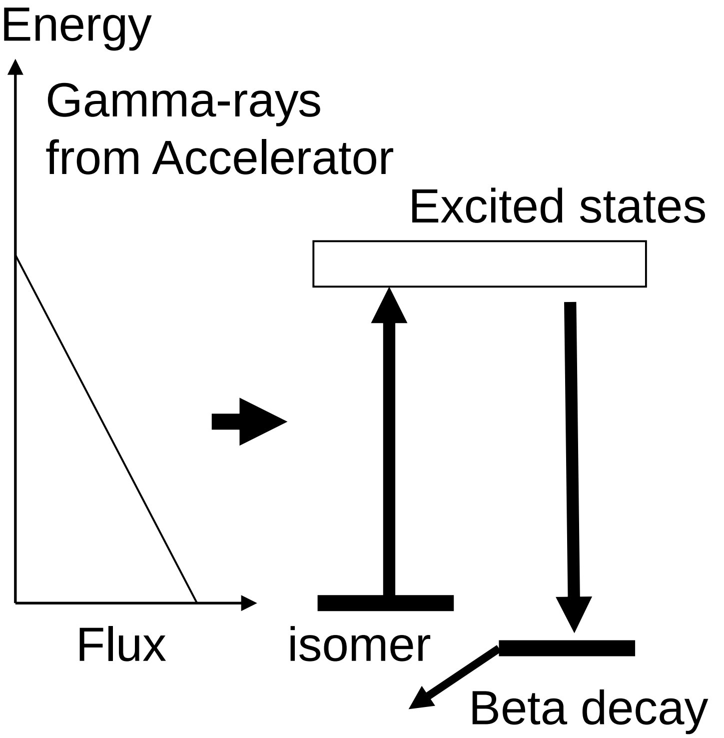
Previous two studies (Heger, 2005, Byelikov, 2007)
pointed out that they can not calculate ^{180}Ta abundance until the isomer residual ratio is determined.

Two structure model

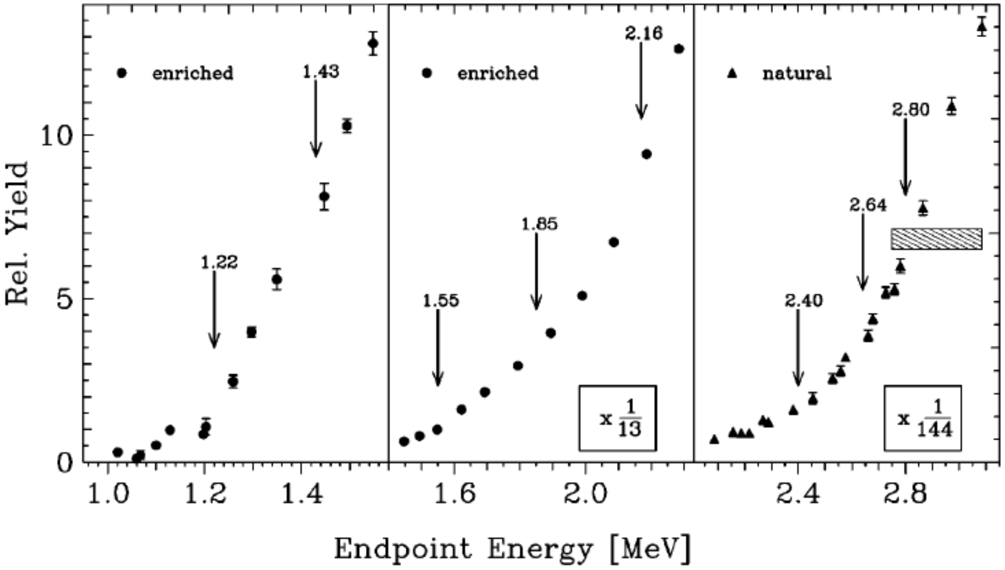


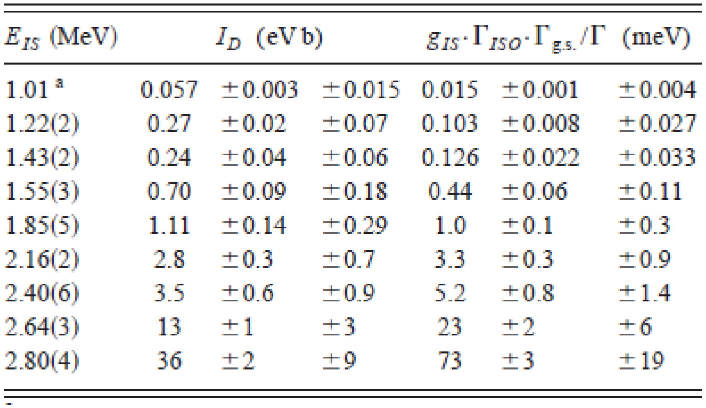
- Ground state structure and isomer structure can be treated as dependent nuclei which are linked weakly.

Measured transition probability



Belic, PRL, 1999   Belic, PRC, 2002



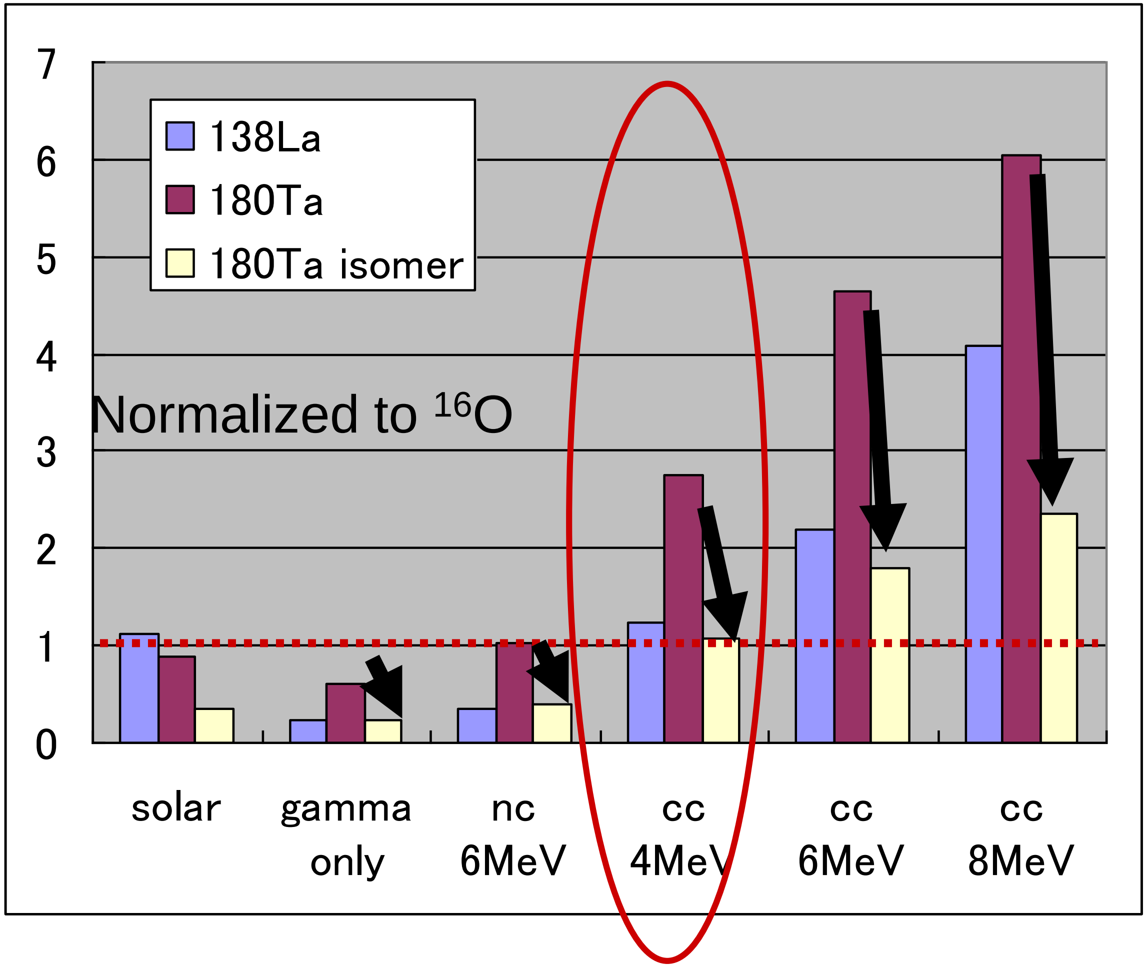


E_{IS} (MeV)	I_D (eV b)			$g_{IS}\cdot\Gamma_{ISO}\cdot\Gamma_{g.s.}/\Gamma$ (meV)		
1.01 [a]	0.057	±0.003	±0.015	0.015	±0.001	±0.004
1.22(2)	0.27	±0.02	±0.07	0.103	±0.008	±0.027
1.43(2)	0.24	±0.04	±0.06	0.126	±0.022	±0.033
1.55(3)	0.70	±0.09	±0.18	0.44	±0.06	±0.11
1.85(5)	1.11	±0.14	±0.29	1.0	±0.1	±0.3
2.16(2)	2.8	±0.3	±0.7	3.3	±0.3	±0.9
2.40(6)	3.5	±0.6	±0.9	5.2	±0.8	±1.4
2.64(3)	13	±1	±3	23	±2	±6
2.80(4)	36	±2	±9	73	±3	±19

The transition probability was measured Using activation method after the gamma-ray irradiation.

9 Linking Transitions were determined.

New Abundances



We multiply the calculated abundance by the factor of Pi = 0.39

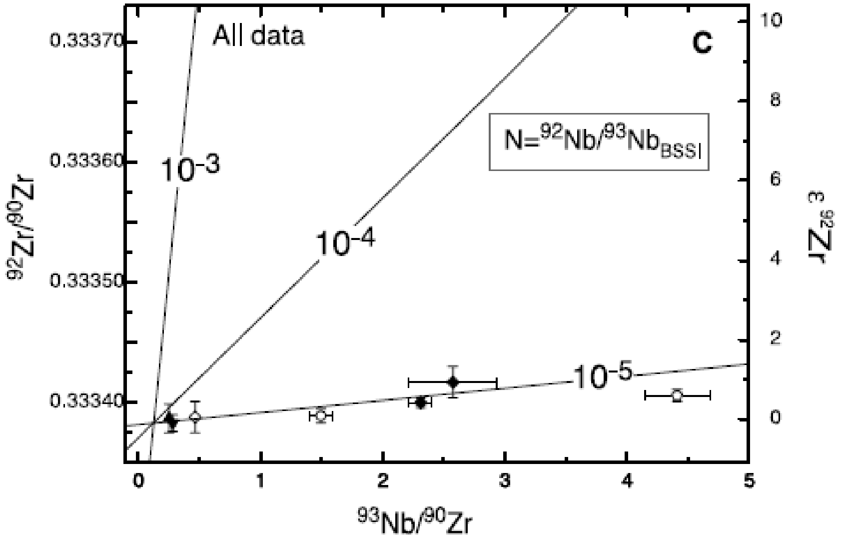
Both the nuclei can be reproduced consistently by +Charged Current Reactions at 4MeV.

T. Hayakawa, Phys. Rev. C 81, 052801(R) (2010);

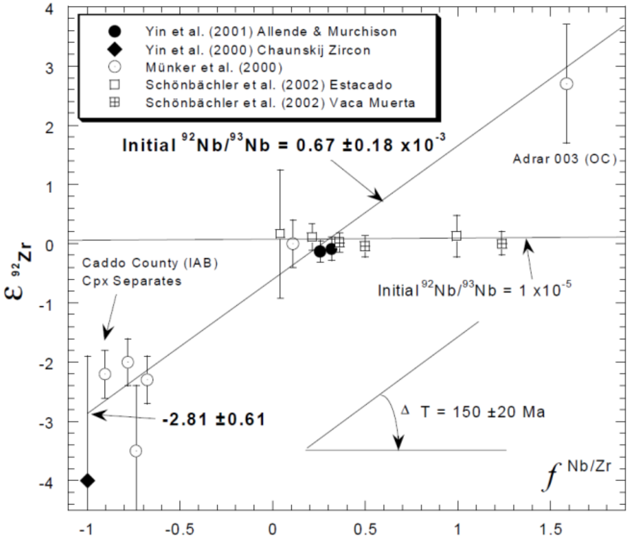
Nb-92 problem

^{92}Nb at the solar system formation

92Nb is a beta-unstable isotope with a half-live of 34.7 Myr.



Schonbanchler, Science, 2002

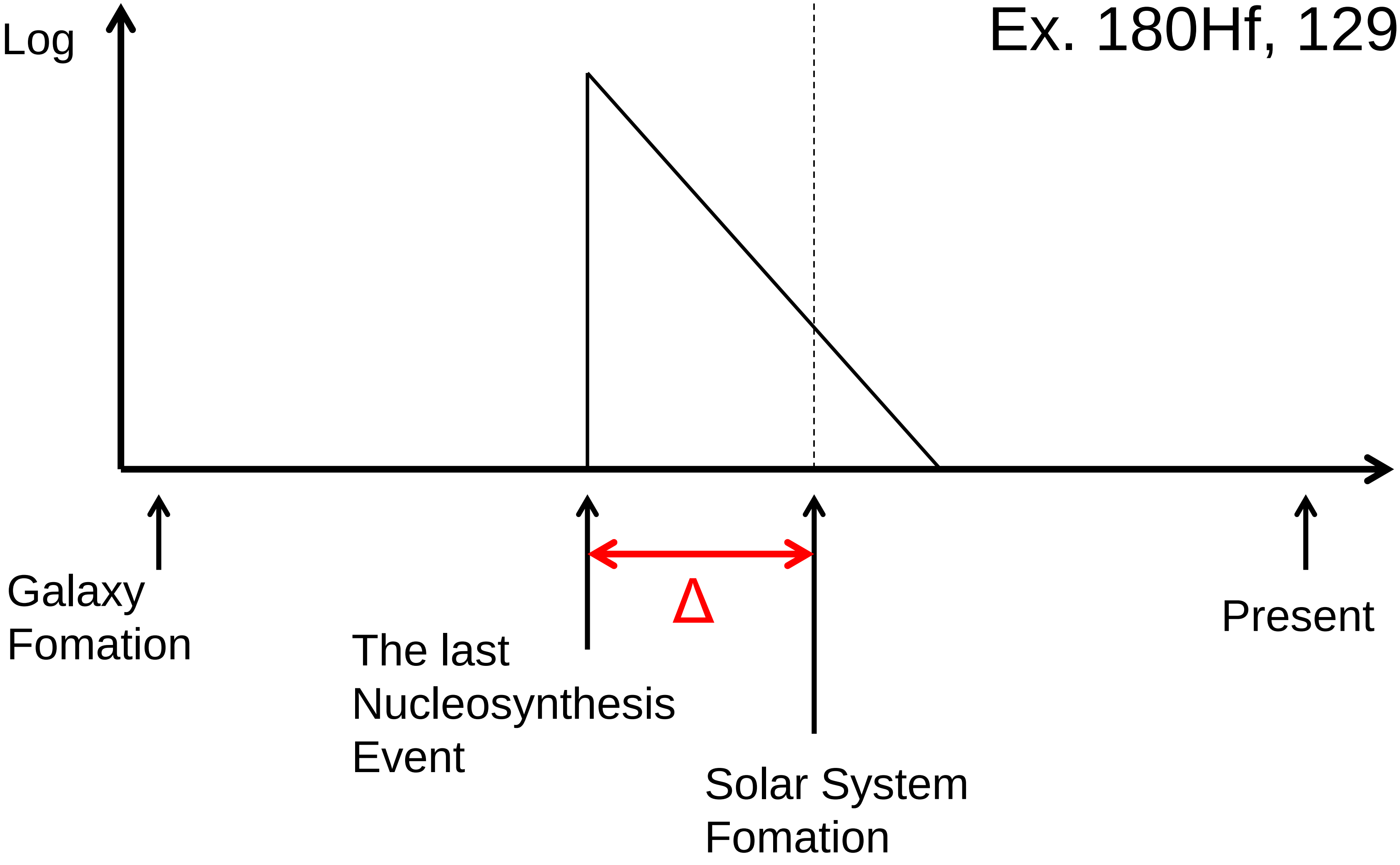


Yin, ApJ, 2001

Two values of 92/93 = 10^{-3} and 10^{-5} have been reported.
The discrepancy has been an open problem.
Origin of 92Nb is unknown.

Short-Lived Clock

Ex. 180Hf, 129I



Log

Galaxy
Fomation

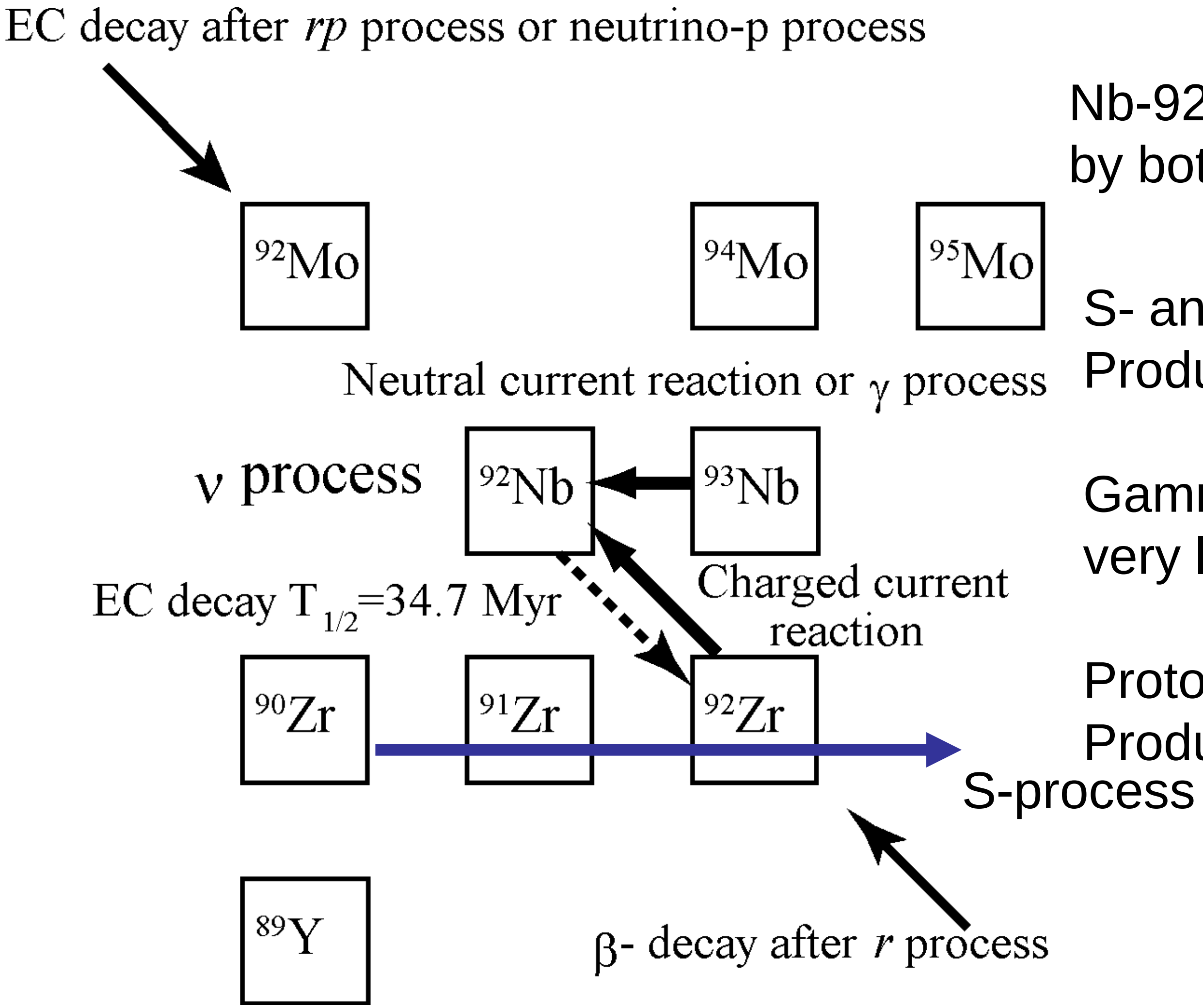
The last
Nucleosynthesis
Event

Δ

Solar System
Fomation

Present

Nucleosynthesis of ^{92}Nb



Nb-92 cannot be synthesized by both the beta decays

S- and r-processes cannot Produce it.

Gamma-process only produce very low abundance.

Proton capture also cannot Produce it.

We here propose neutrino-process origin.

M1 strengths

An example calculated by a QRPA model

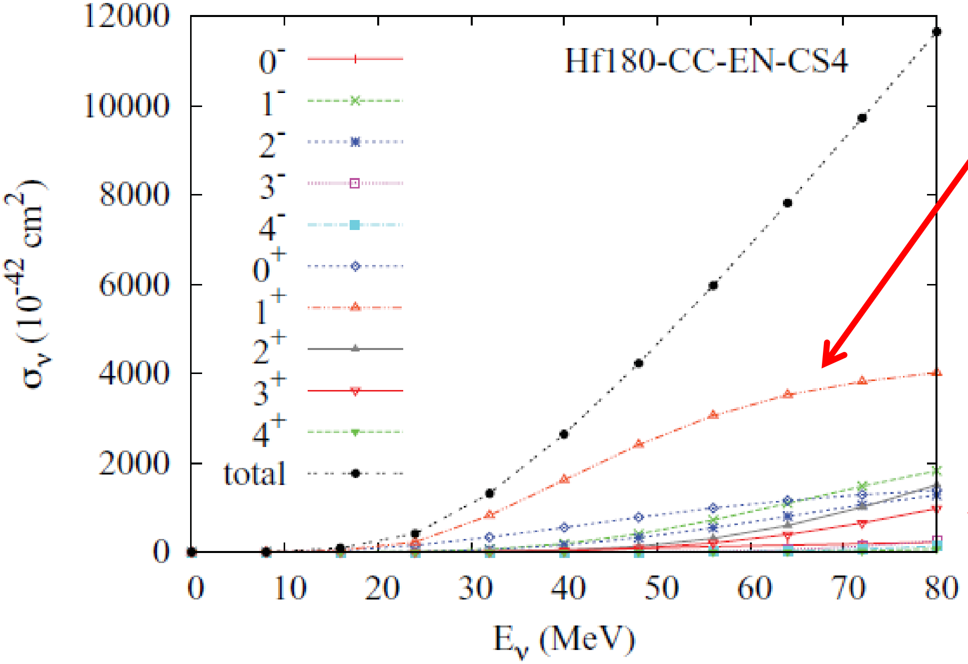


FIG. 2. (Color online) Cross sections by charged current reactions ^{138}Ba(ν_e,e^-)^{138}La* and ^{180}Hf(ν_e,e^-)^{180}Ta* for $J_\pi = 0^\pm \sim 4^\pm$ states. Transition matrix elements are calculated by the QRPA, Eq. (4).

M. Cheoun, et al., Phys. Rev. C82, 035504 (2010)

1+ states（M1）are most important.

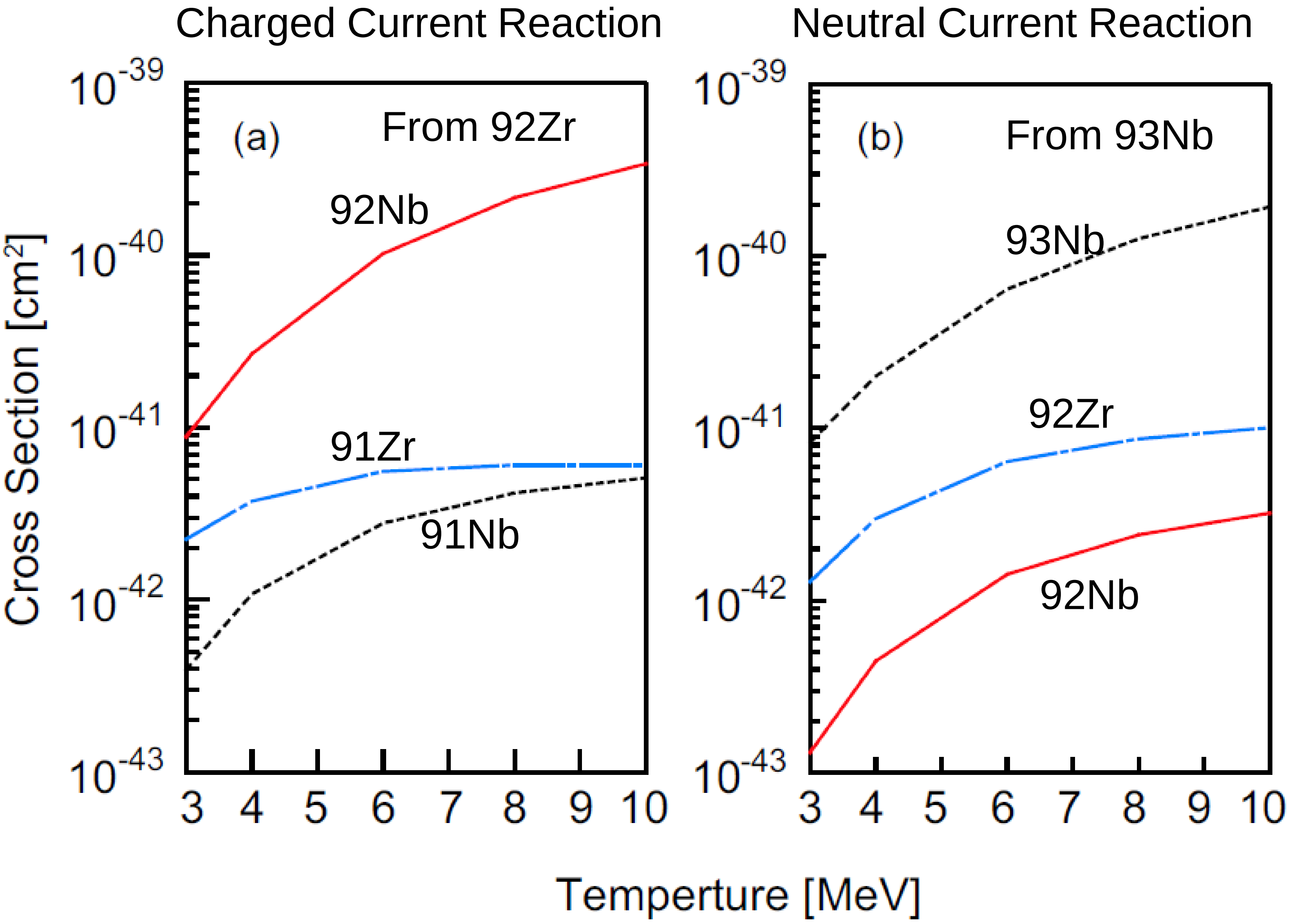
Experimental level density
of 1+ states (M1 strength)
help theatrical calculations !

Other states are also populated via neutrino-induced reactions

Model calculations for nuclear structures are required
even if many types of strengths are measured.

Calculated by M.K. Cheoun et al.

Nb-92


Charged Current Reaction

Neutral Current Reaction

SN model calcualtion

By Ko Nakamura

Core-collapse SN model : Rauscher 2002

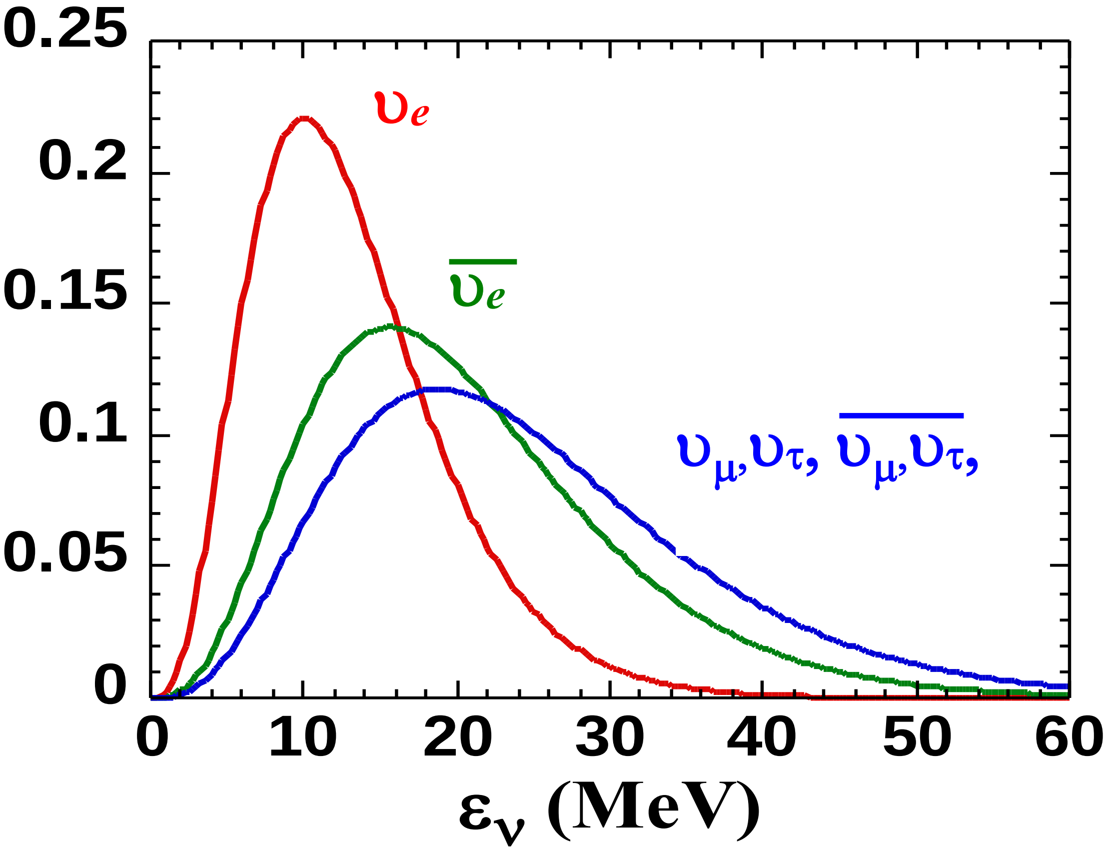
Explosion energy : 10^{51} erg

Seed : C-burning s-processed solar abundance

Neutrino energies: see next pape

Neutrino-nucleus interactions:
QRPA calculation by M.K. Cheoun

Evaluated Neutrino Spectra from light element neutrino process



$T(\nu_e) < T(\overline{\nu_e}) < T(\nu_x)$

$x = \nu_{\mu,}, \overline{\nu_\mu}, \nu_\tau, \overline{\nu_\tau}$

$T(\nu_e) = 3.2$ MeV

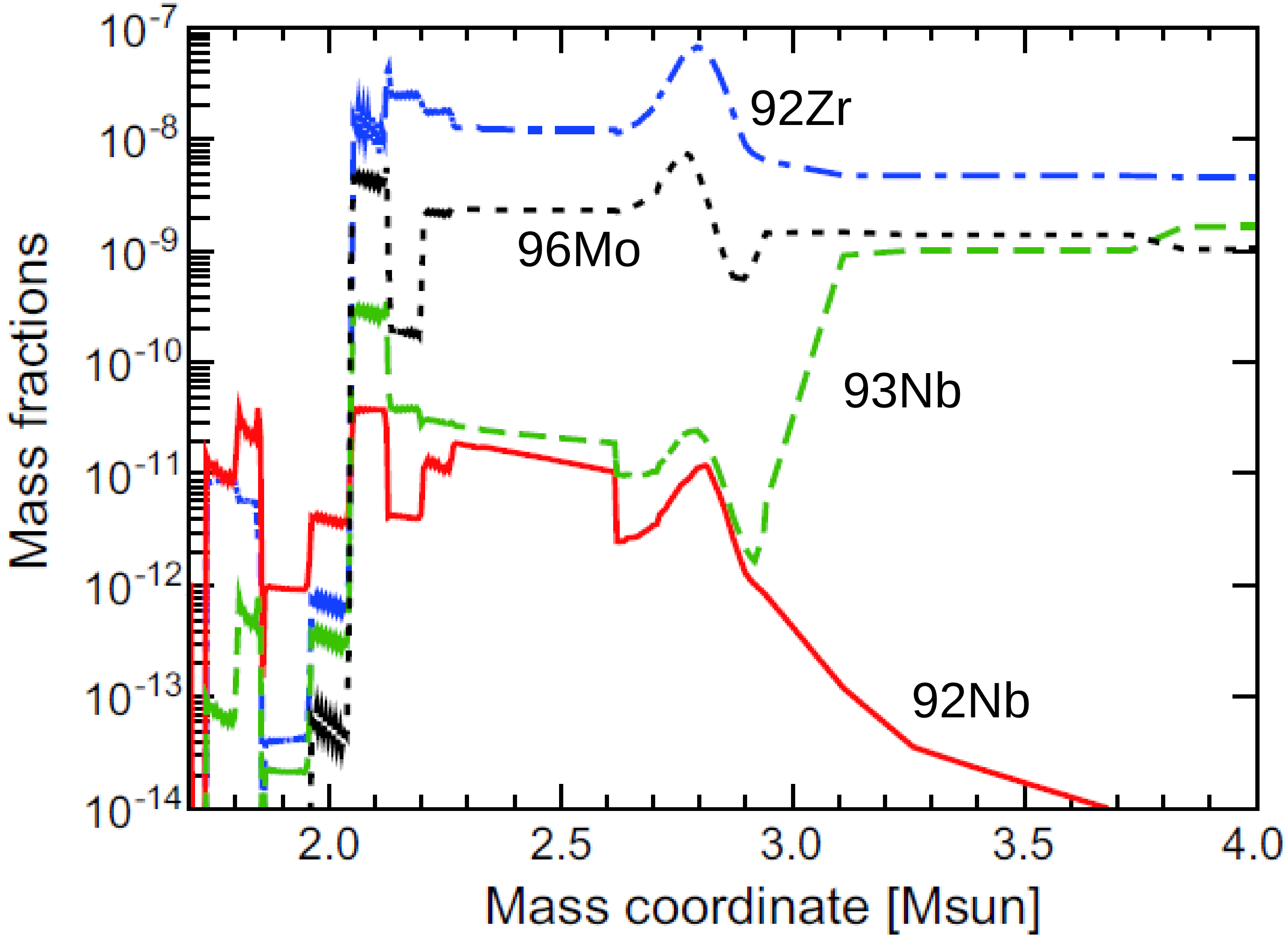
$T(\overline{\nu_e}) = 4.0$ MeV

$T(\nu_{\mu,\tau}) = T(\overline{\nu_{\mu,\tau}}) = 6.0$ MeV

From Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.

Calculated by Ko Nakamura

Final Result



92Nb: 1.1x10-11 Msun

93Nb: 3.7x10-11 Msun 92Nb/93Nb = 0.3 1.9 < M < 2.9

Simple GCE model

Continues production by SN and beta-decay from the formation of the Galaxy.

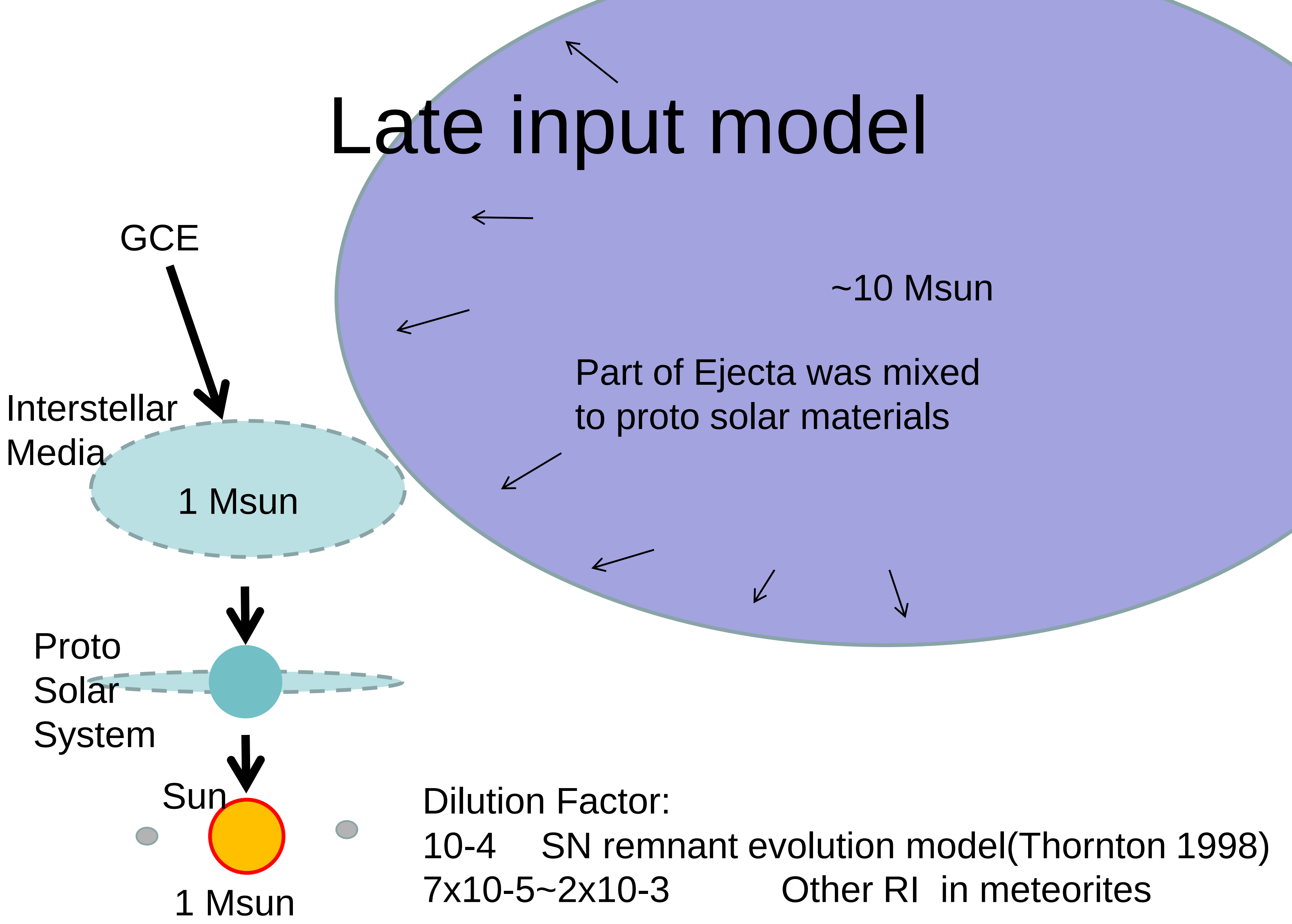
$$\frac{Z_{92\mathrm{Nb}}}{Z_{93Nb}} = \frac{2P_{92}}{P_{93}}\frac{\tau_{92}}{T}$$

= ~ 4 x 10-7

This is negligibly small compared with observed values of 10^{-3} -10^{-5}

The observed value requires another model.

Late input model



GCE

~10 Msun

Part of Ejecta was mixed
to proto solar materials

Interstellar
Media

1 Msun

Proto
Solar
System

Sun

1 Msun

Dilution Factor:
10-4 SN remnant evolution model(Thornton 1998)
7x10-5~2x10-3 Other RI in meteorites

Calculation and Result

$$\left[\frac{92Nb}{93Nb}\right]_{solar} = \frac{fN(92Nb)_{SN}\, e^{-\Delta/\tau 92}}{N(93Nb)_{solar}+fN(93Nb)_{SN}}$$

92Nb Fraction	f	Δ	$\left[\frac{92Nb}{93Nb}\right]_{solar}$
1.1x10-11	10-4	3x107	2.8x10-7
1.1x10-11	10-4	106	4.9x10-7
1.1x10-11	3x10-3	3x107	8.2x10-6
1.1x10-11	3x10-3	106	1.5x10-5

Initial abundance of 92Nb at the solar system formation can be explained by supernova neutrino process.

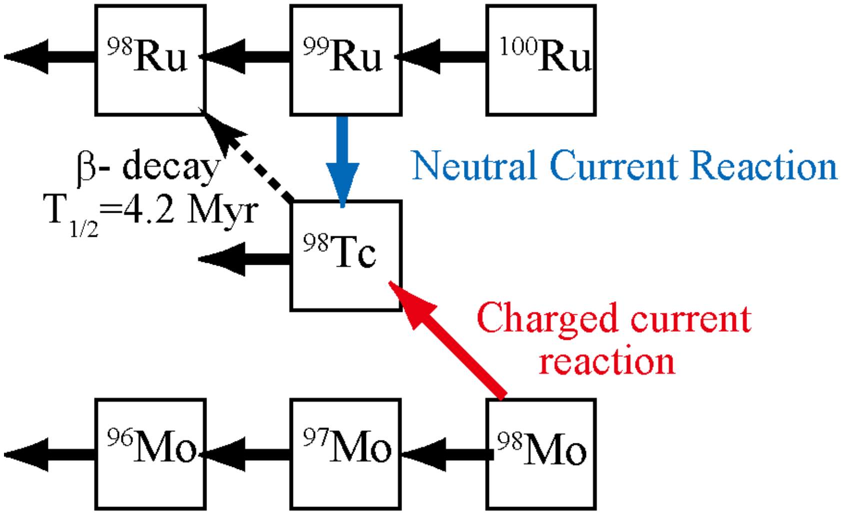
T.Hayakawa, et al, Astrophys. J. Lett. 779, L9 (2013)

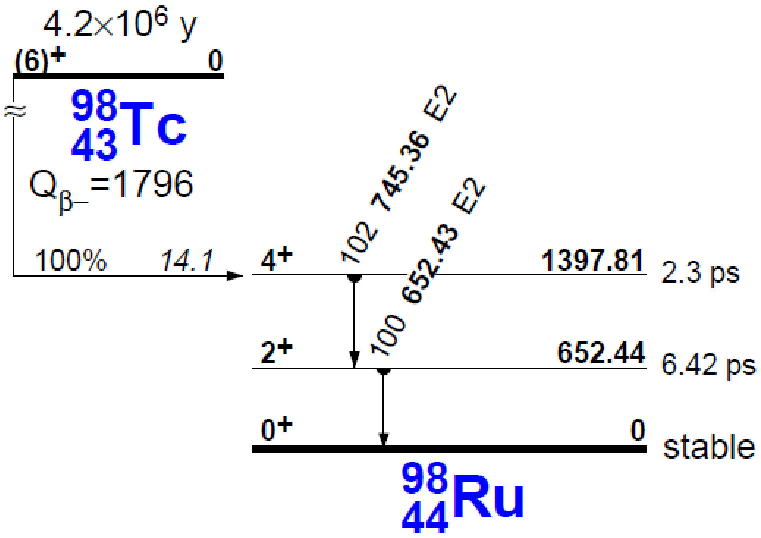
Advantage of Neutrino-process chronometer

1. Its astrophysical origin is clear:
   Neutrino window driven supernova

2. Key reactions are simple:
   Charged current reaction is dominant !
   Uncertainty is small.

Candidate of 4th heavy neutrino-isotope





There is a possibility to measure gamma-rays from cosmic Tc-98 in future.

Summary

Neutrino process is a key for understanding neutrino energy spectra in SNe and neutrino oscillation.

Before 2010, about 5 neutrino isotopes are known. However, the solar abundances of only two heavy neutrino-isotopes, ^{138}La and ^{180}Ta, cannot be reproduced consistently.

With a new model for ^{180}Ta isomer ratio, we reproduced consistently the abundances of ^{138}La and ^{180}Ta.

We have proposed the third heavy neutrino isotope, ^{92}Nb, observed meteorites. We reproduced the initial abundance of 92Nb and estimate the time from SN to the solar system formation.

We have proposed a candidate for the fourth heavy neutrino isotope.