NDM12、Nara、2012

Synthesis of heavy isotopes by neutrino-induced reaction in supernovae explosion

Japan Atomic Energy Agency
National Astronomival Observaotory in Japan
T.Hayakawa

Collaborators

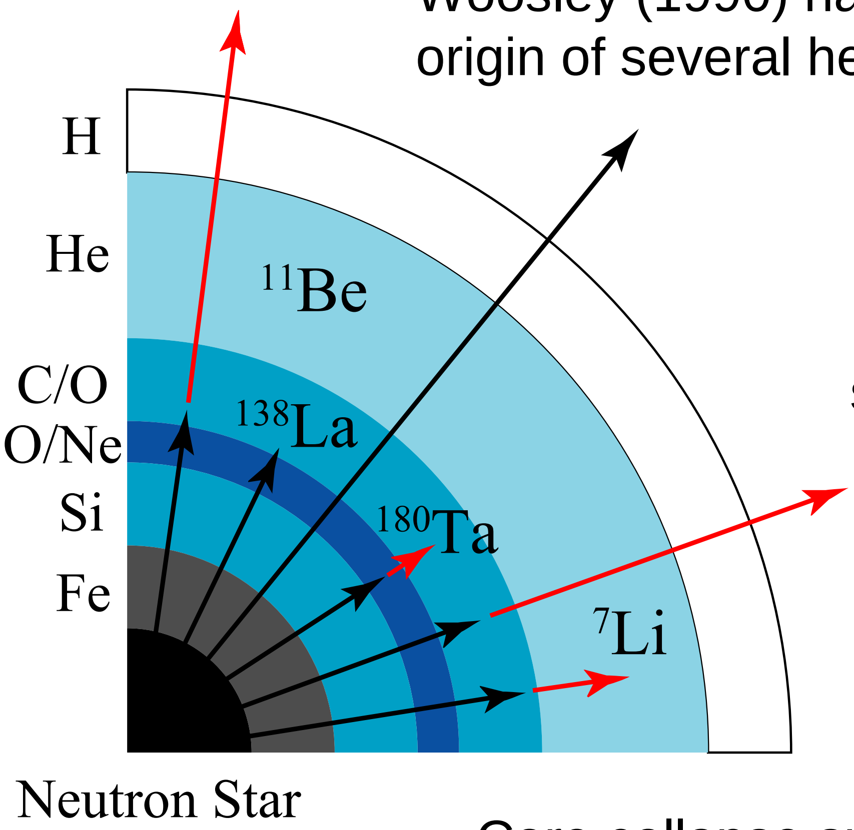
T.Hayakawa, T. Kajino, G. Mathews, K.Nakaramu,
N.Iwamoto, M. Cheoun, S.Chiba

Introduction

- Neutrino process
- ^{180}Ta and ^{138}La
- ^{92}Nb and ^{98}Tc

Supernova Neutrino process

Woosley (1990) has proposed neutrino-process as the origin of several heavy isotopes.

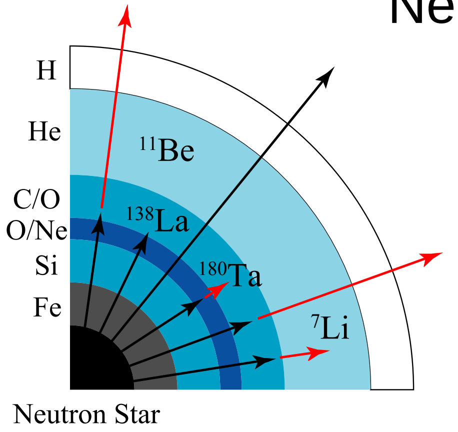


Rare isotopes are produced from Interaction between neutrinos and seed nulci.

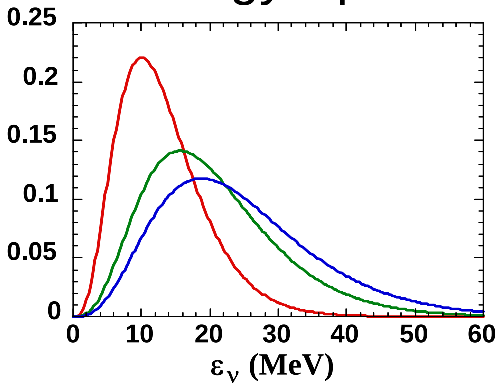
Core collapse supernova explosions
Neutrino wind originates from Neutron star

Physics around Neutrino Process

Stellar model

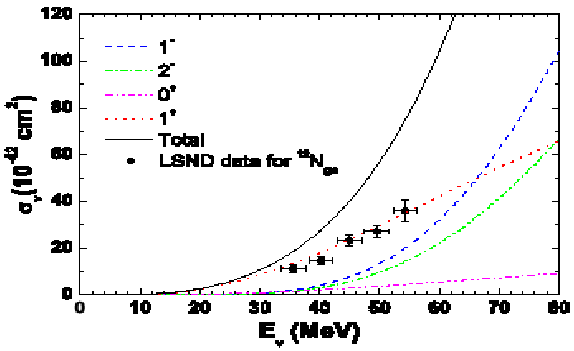


Neutrino Energy Spectra

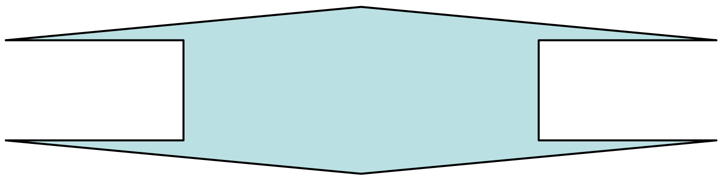


Unknown

Neutrino Reaction Rate



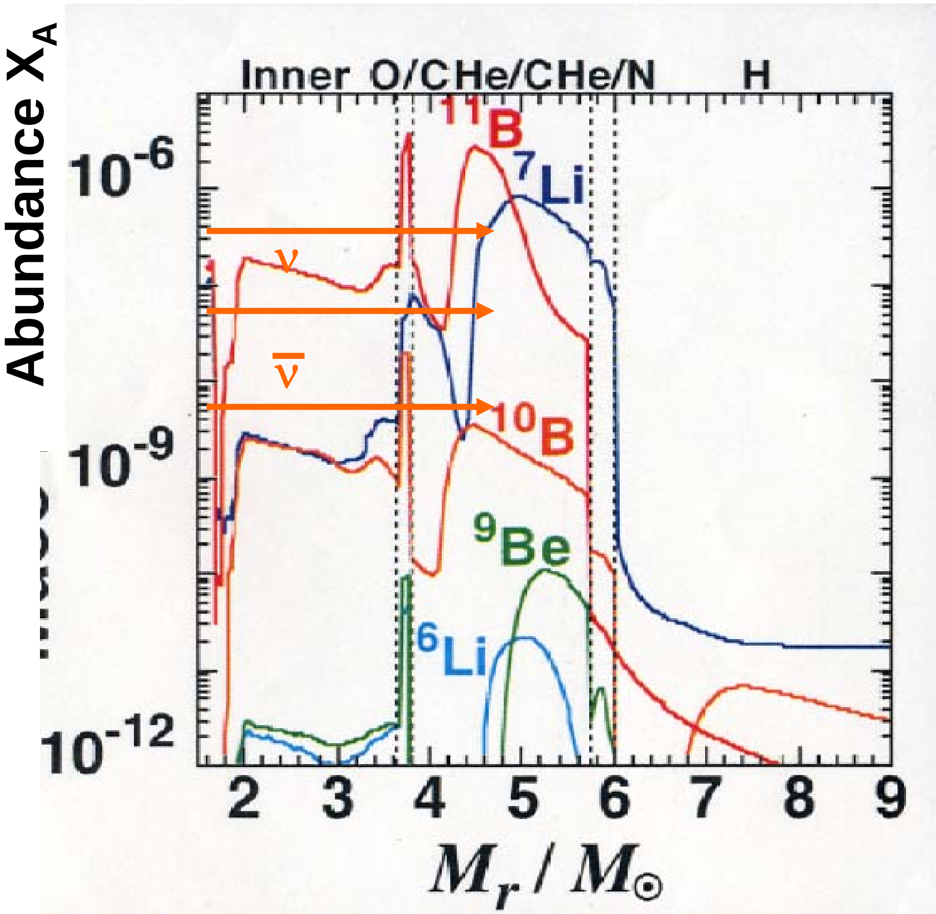
Calculation

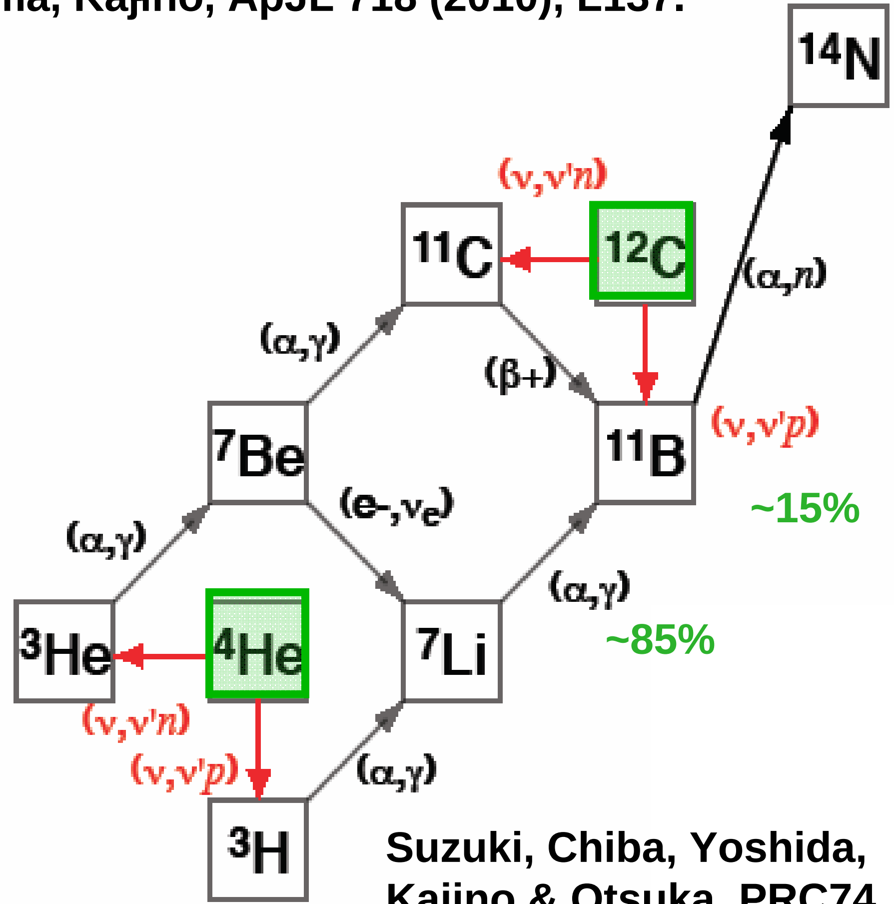


Abundances in the solar system or primitive meteorite
Observation

Synthesis of light elements by neutrino-process

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

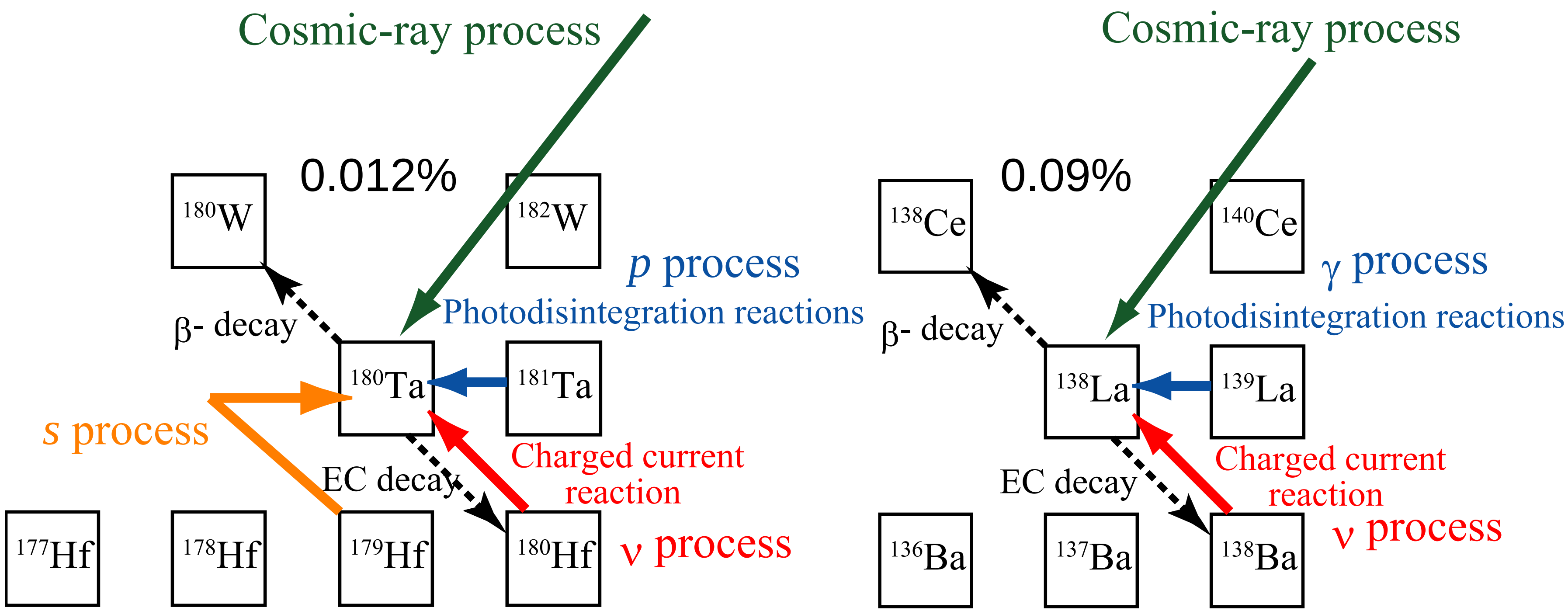




Suzuki, Chiba, Yoshida, Kajino & Otsuka, PRC74 (2006), 034307

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

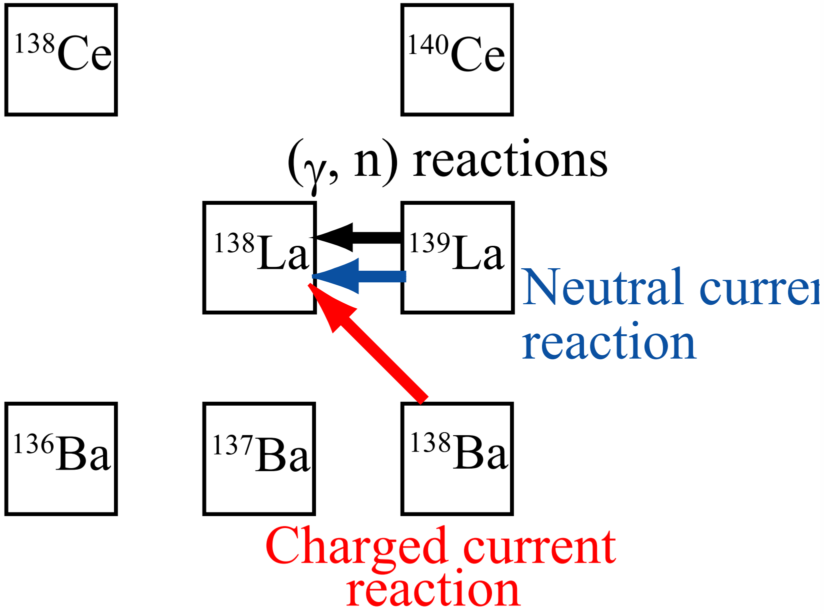
Astrophysical origins of two isotopes are unresolved problems for long time.



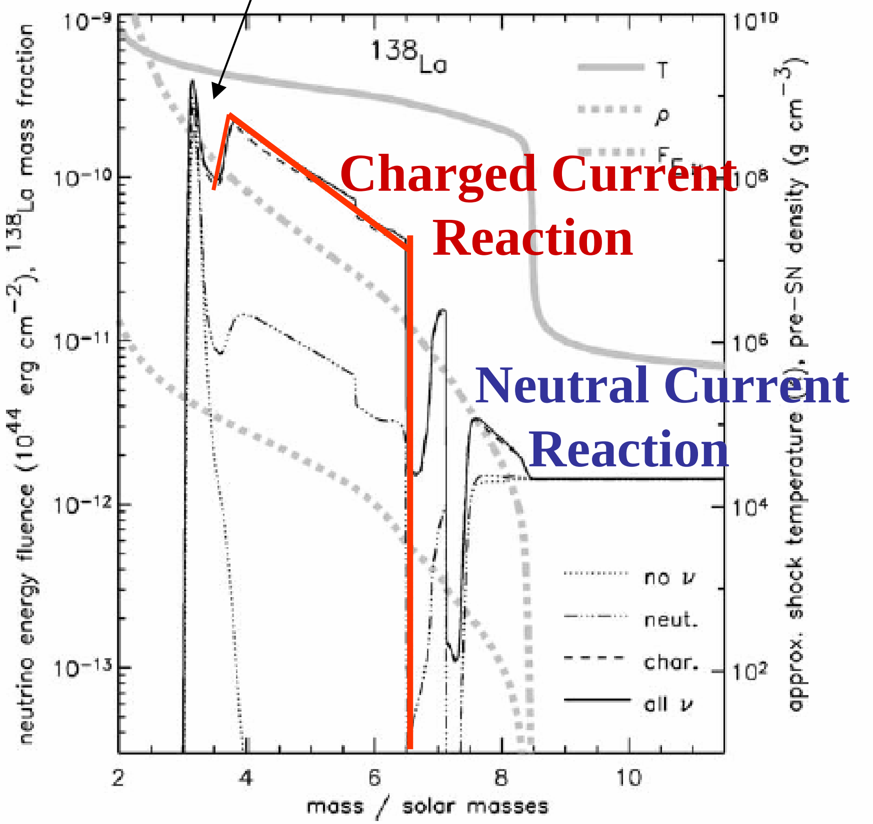
- Odd-odd nuclei
- Both the beta decay are shielded
- s-process and r-process cannot produce them
- Isotopic abundances are rare, 0.012% and 0.09%

Nuclear Reactions in neutrino-process

A. Heger, Phys. Lett. B 606, 258 (2005)



(gamma, n) reactions



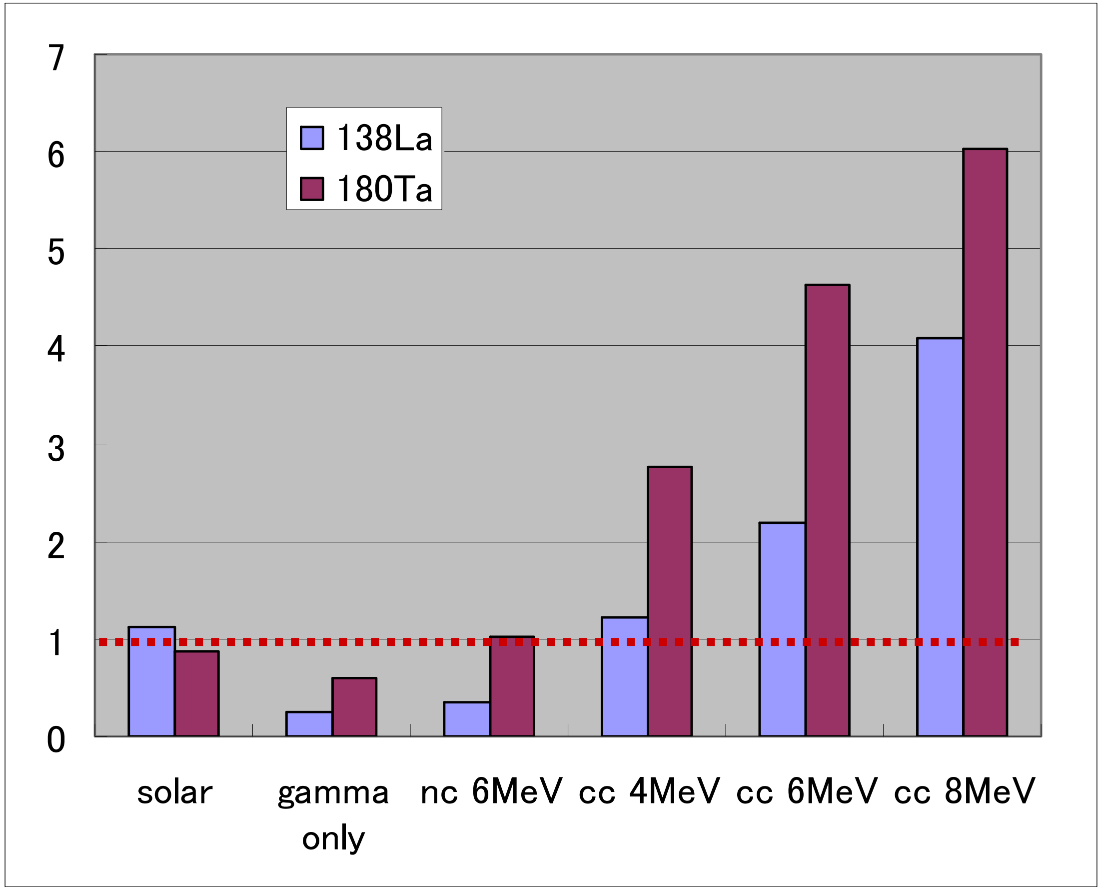
Charged Current Reaction (CC)
Is most important.

Neutrino-process production for ^{11}Be, ^{19}F, ^{138}La, and ^{180}Ta were calculated.
^{138}La is reproduced (to ^{16}O) BUT ^{180}Ta is overproduced by a factor of 2.

Previous study

A. Byelikov, Phys. Rev. Lett. 2007

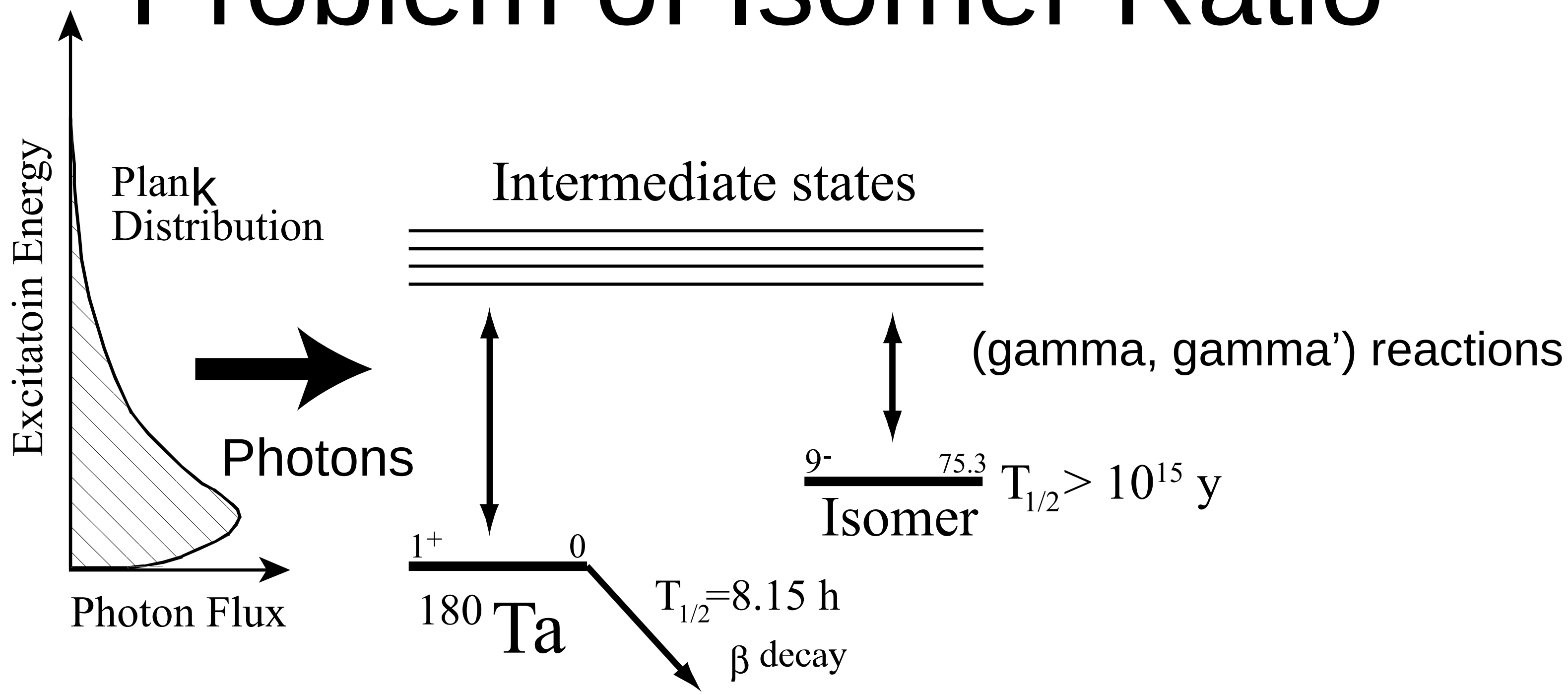
Improved calculation based on Heger 2005.



- The abundance of ^{138}La can be reproduced by + CC at 4MeV but that of ^{180}Ta is overproduced.

- There is no solution !

Problem of Isomer Ratio



- 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.

Time-dependent calculation

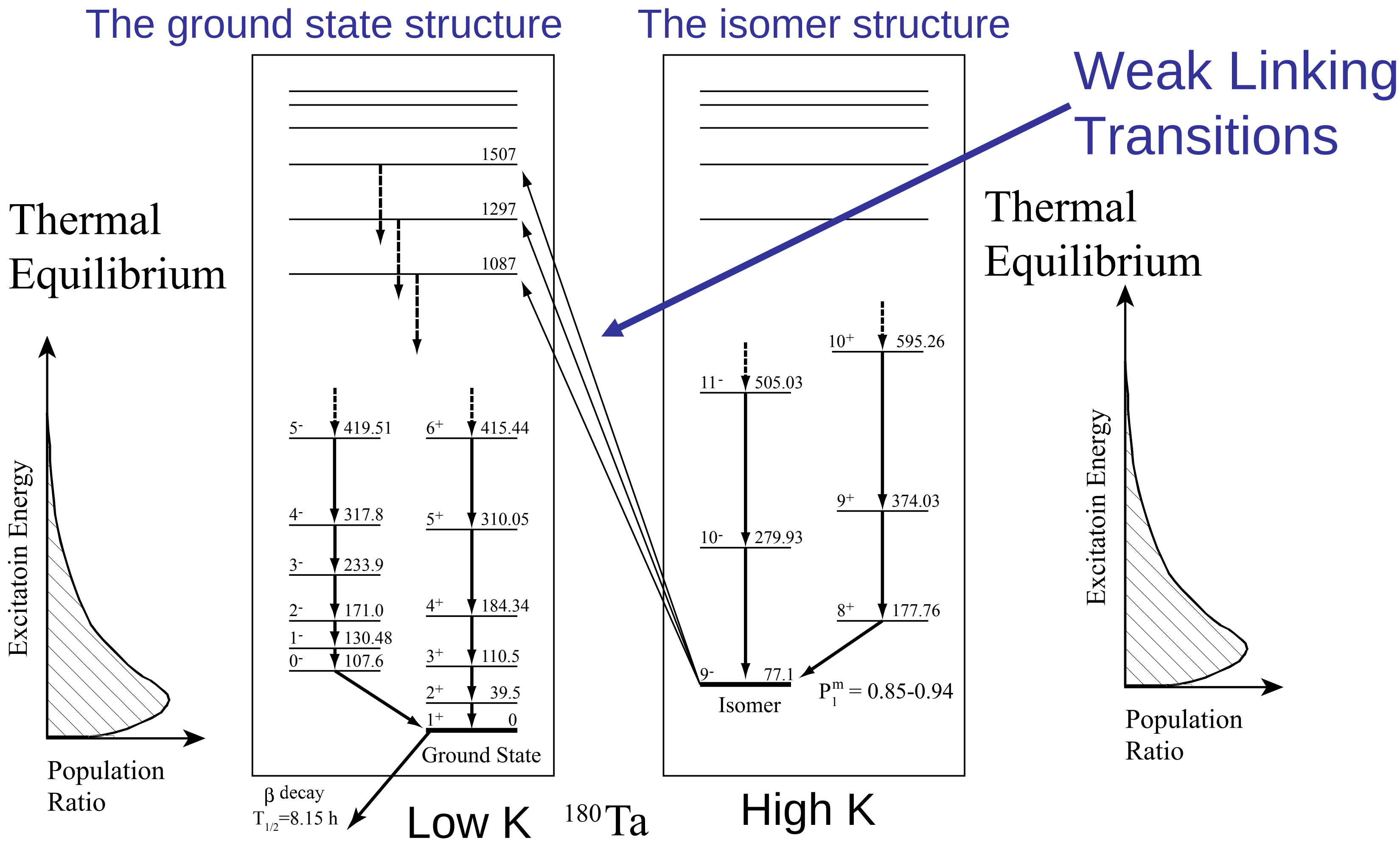
Time scale of nuclear excitations fs

↕ Difference of 10^{15}

Supernova explosions s

Numerical Calculation is almost impossible.

New model: Two structure model



- Each structure is independently in thermal equilibrium
- Two structures are linked by weak interactions.

In general case

$$\frac{dN_0}{dt} = -\sum_{i,p} P_i^g A_{ip} N_0 + \sum_{i,p} P_i^m \rho B_{pi}(1 - N_0)$$

$$- \sum_{j,q} P_j^g \rho B_{qj} N_0 + \sum_{j,q} P_j^m A_{jq}(1 - N_0)$$

$$= -\sum_{i,p} P_0^g \frac{g_i}{g_0} \exp[-(E_i - E_0)/kT] A_{ip} N_0$$

$$+ \sum_{j,q} P_1^m \frac{g_j}{g_1} \exp[-(E_j - E_1)/kT] A_{jq}(1 - N_0)$$

$g_i/g_1 \Gamma_i \Gamma_0/\Gamma \approx g_i/g_1 \Gamma_i$ と　$A = \Gamma/\hbar$ を入れて、

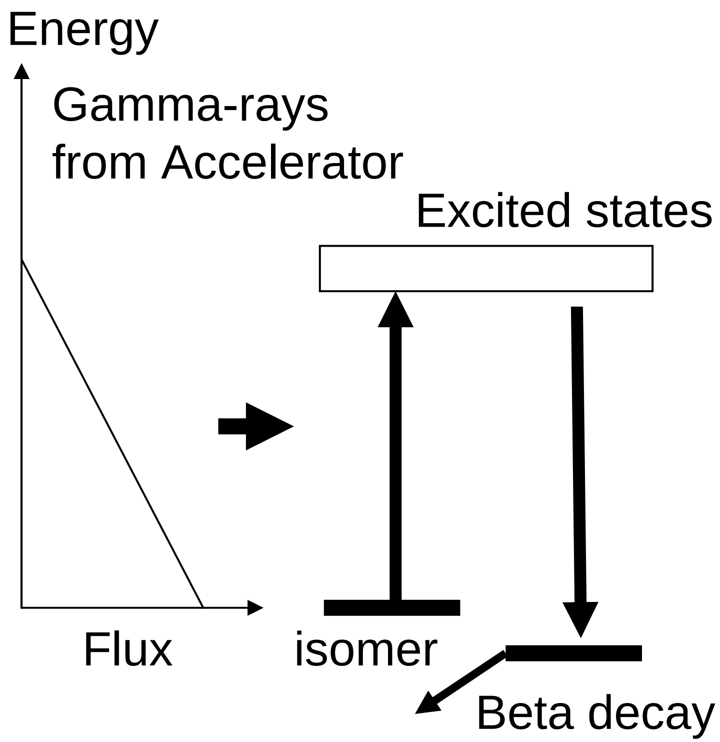
$$\frac{dN_0}{dt} = -\sum_{i} P_0^g \frac{g_1}{g_0} \exp[-(E_i - E_0)/kT] \frac{g_i}{g_1} \frac{\Gamma_i}{\hbar} N_0$$

$$+ \sum_{j} P_1^m \exp[-(E_i - E_1)/kT] \frac{g_j}{g_1} \frac{\Gamma_j}{\hbar} (1 - N_0)$$

Transition Probability

How estimate ?

Observed transition probabilities



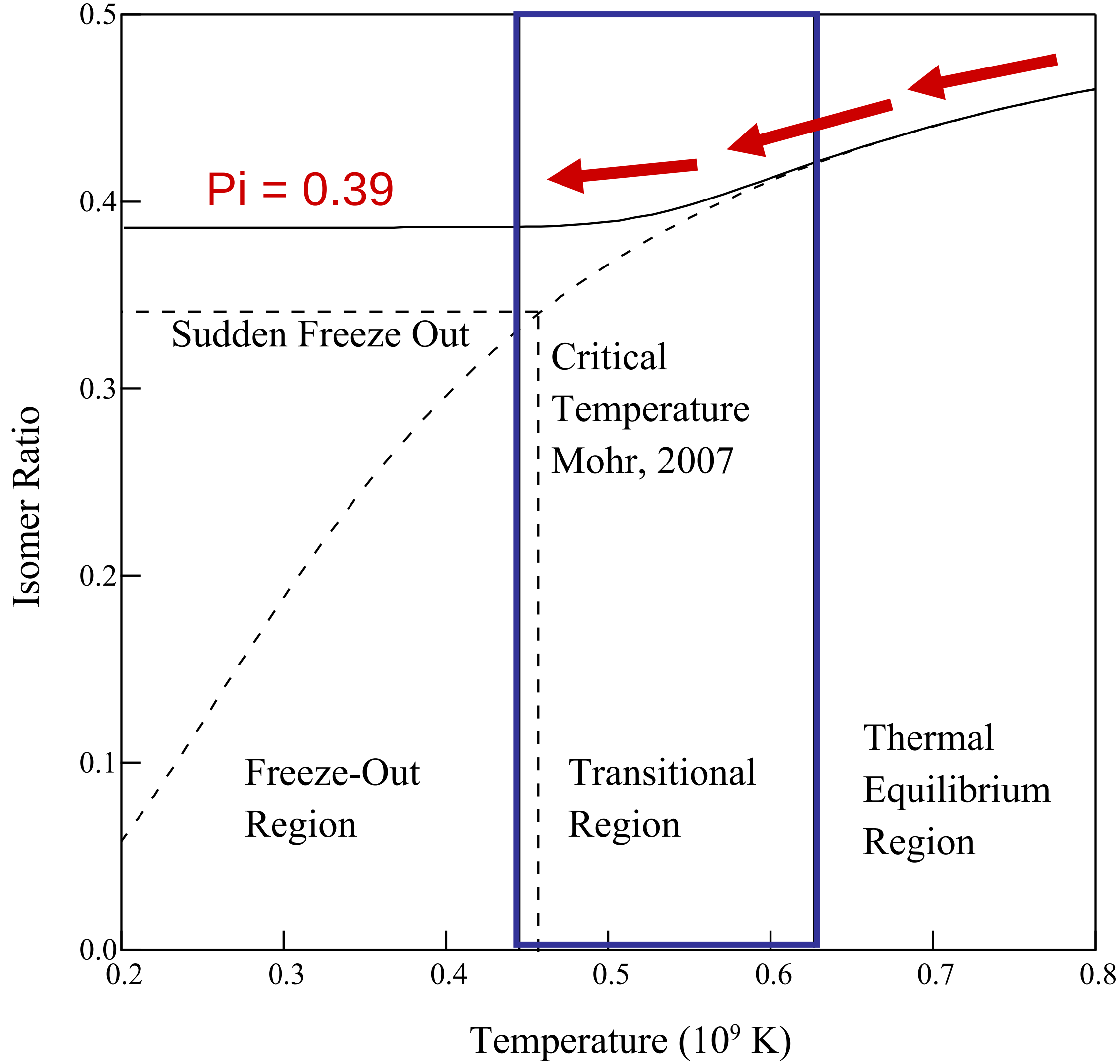
Belic, PRL, 1999   Belic, PRC, 2002

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

They measured transition probability from the meta-stable isomer to the Ground state.

9 linking transitions were found.

Result



$T = \exp(-t/\tau)$

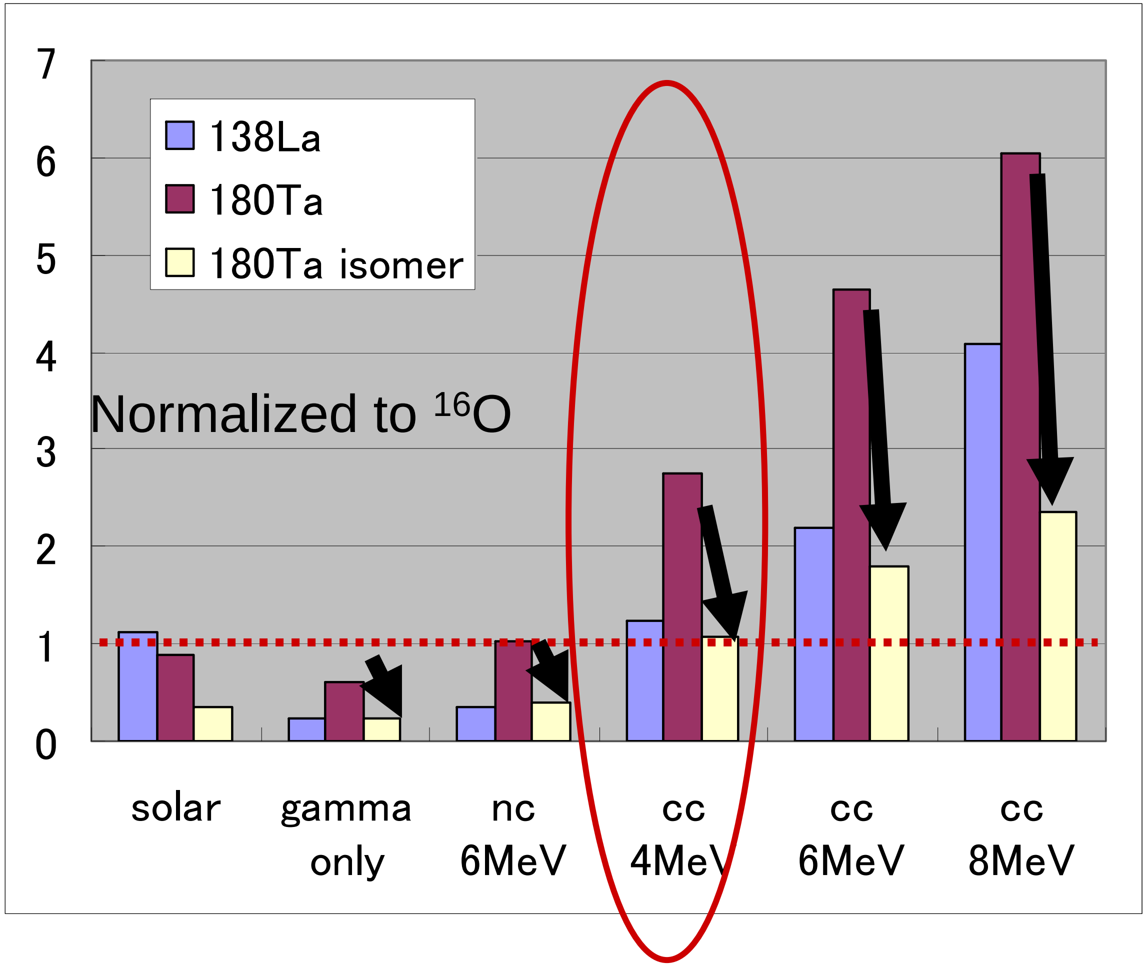
τ =1s

Init : T9 = 1.0

We perform the time-dependent calculations.

In the cases of τ =0.3 or 3 s, results are almost same.

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);
T. Hayakawa, P. Mohr, et al., PRC, 2010

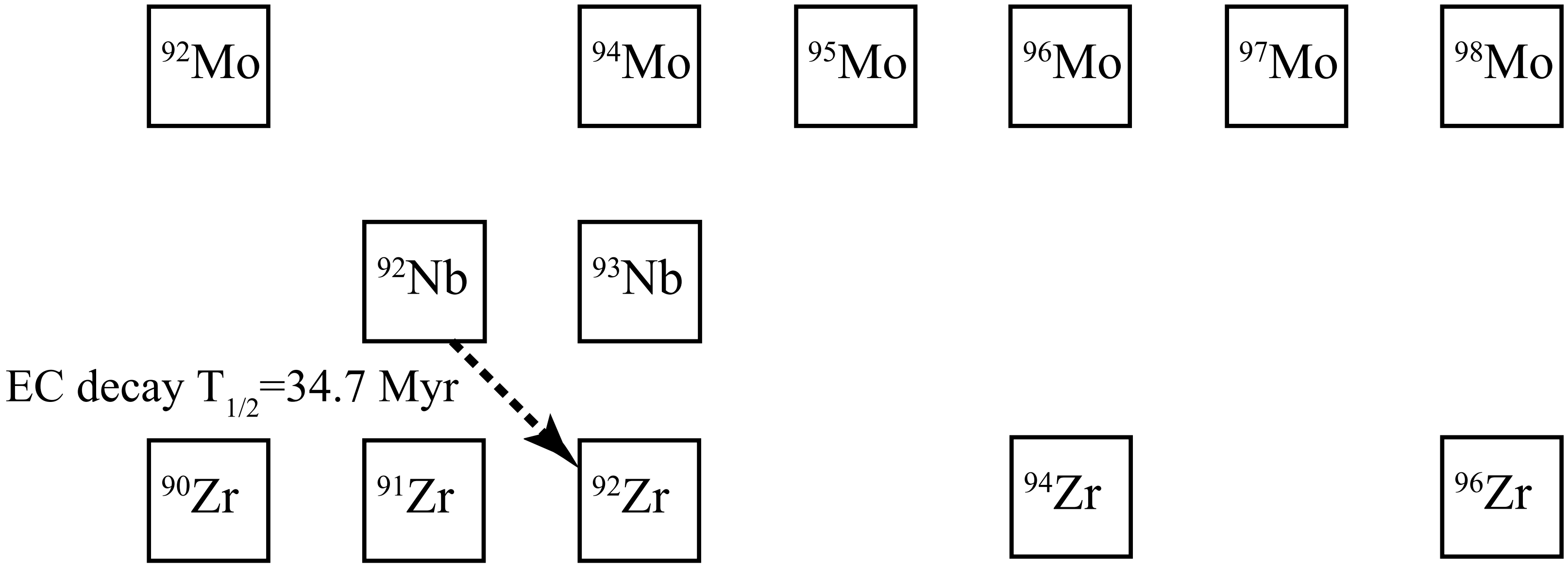
Other neutrino-isotopes

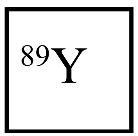
Neutrino process are useful for constrain supernova neutrino spectra.

However, there are two isotopes in the heavy mass region.

Which is a new neutrino isotope ?

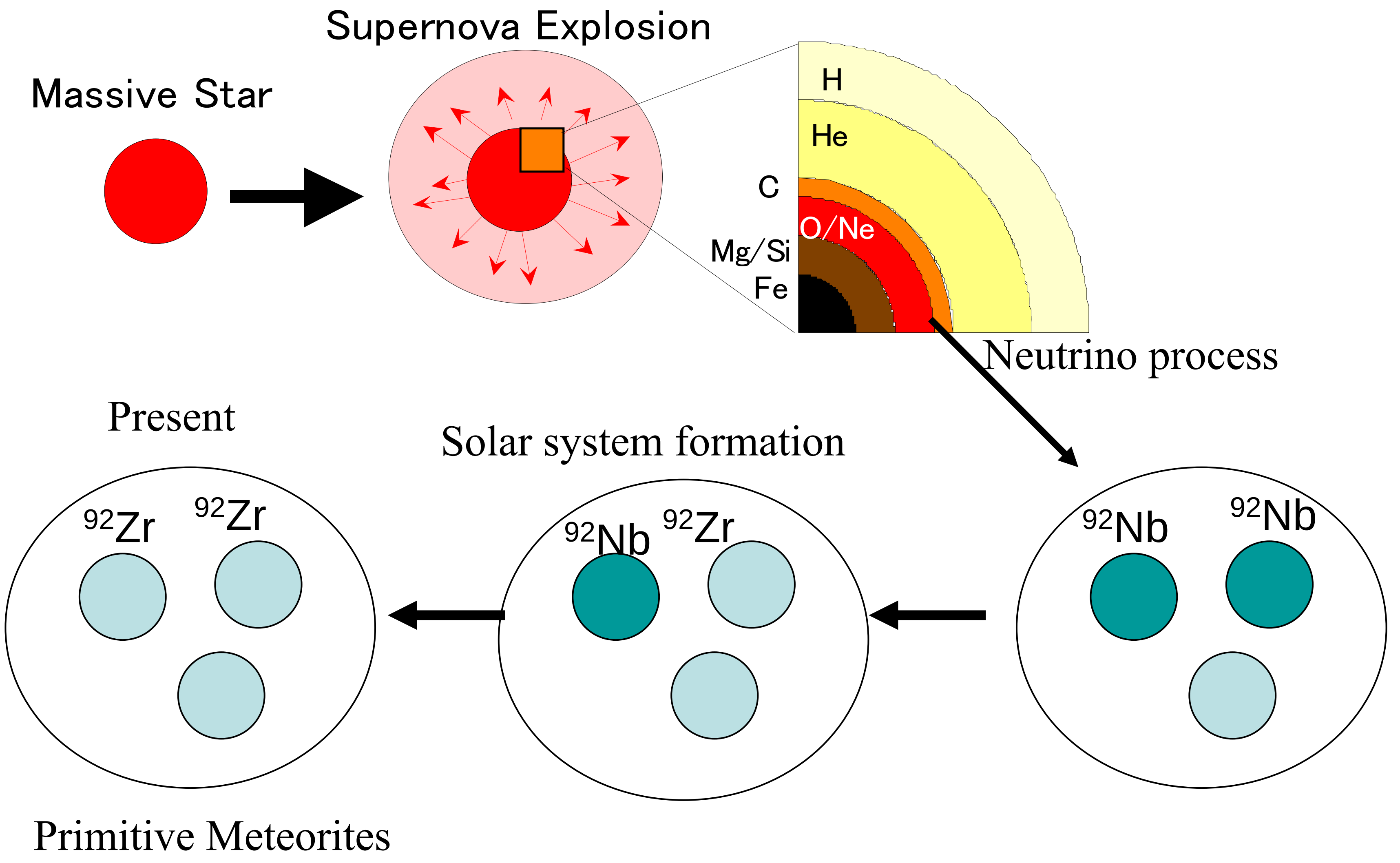
Long-lived radioactivity ^{92}Nb





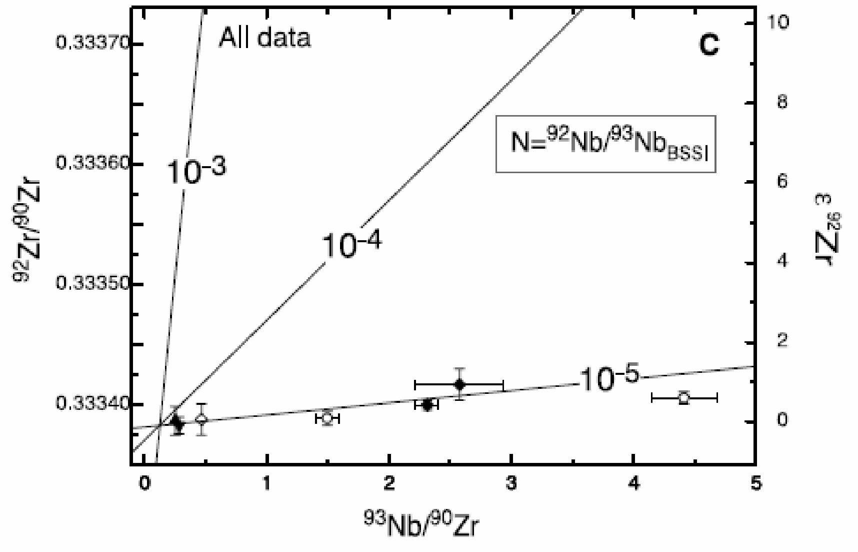
Nb-92 is a unstable isotope.
Nuclear chart around Nb-92 is similar to those of Ta-180 and La-138.

Measurement of Nb-92 in Primitive meteorites

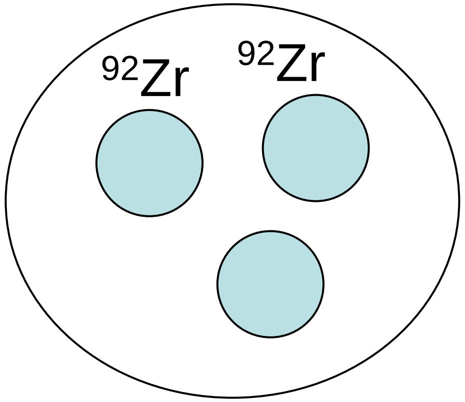


Initial abundance ratio

Schonbanchler, Science, 2002

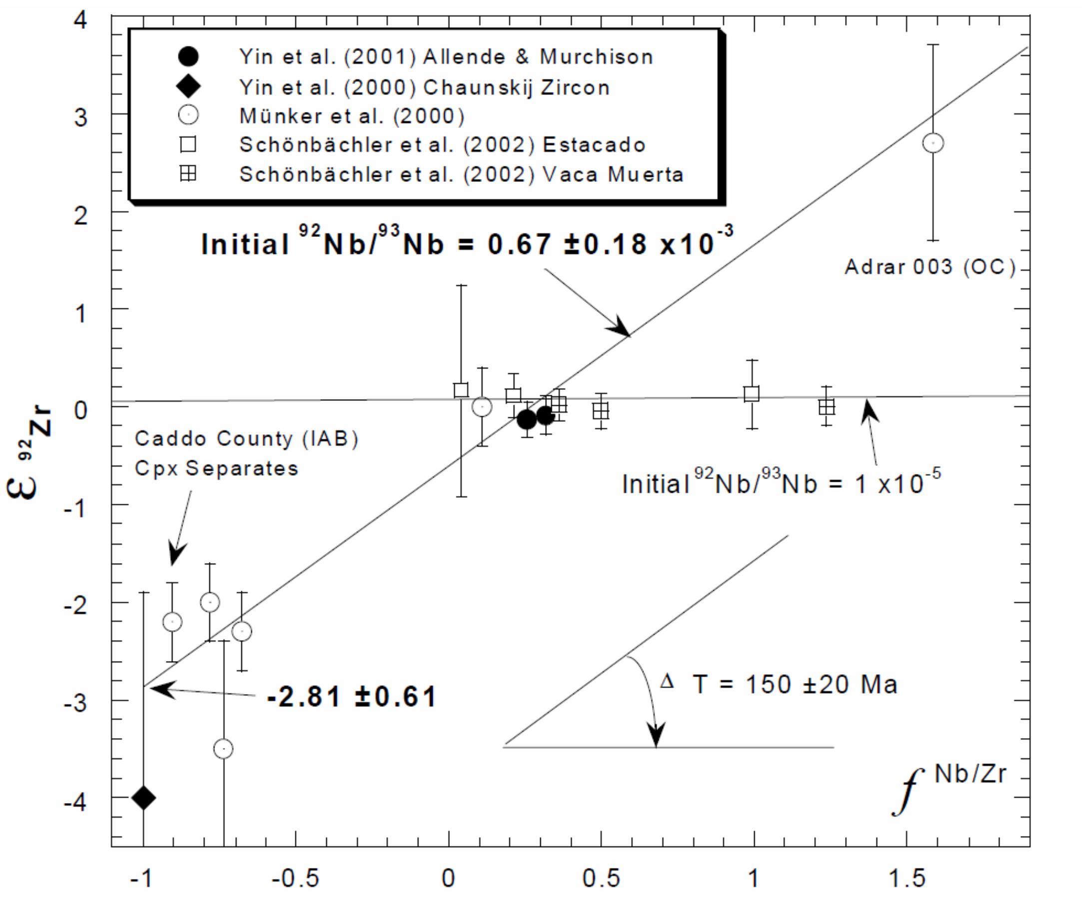


Primitive meteorite is a closed box
Nb-92 decays to Zr-92.



They measured an initial abundance ratio at SSF of 92/93 = 10 $^{-5}$.
They estimate free decay time from the last nucleosynthesis to SSF.

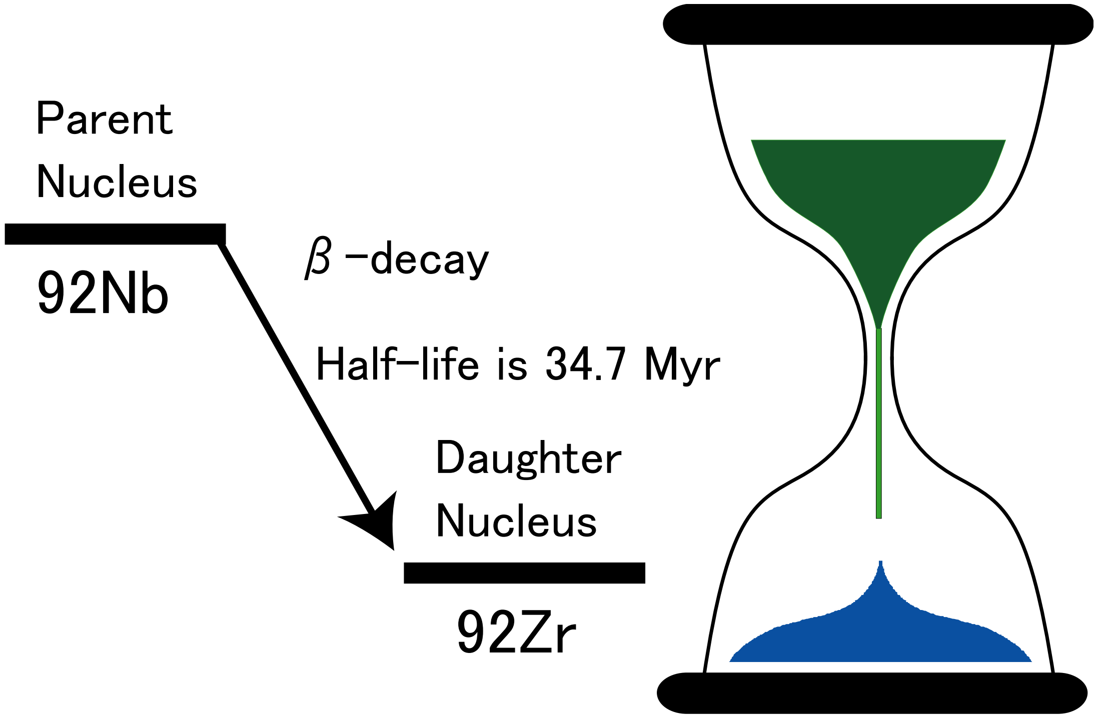
Problem of Meteorite analysis



Yin et al. reported another value of 92/93 = 10^{-3}.

The discrepancy between 10^{-3} and 10^{-5} has been an open problem.

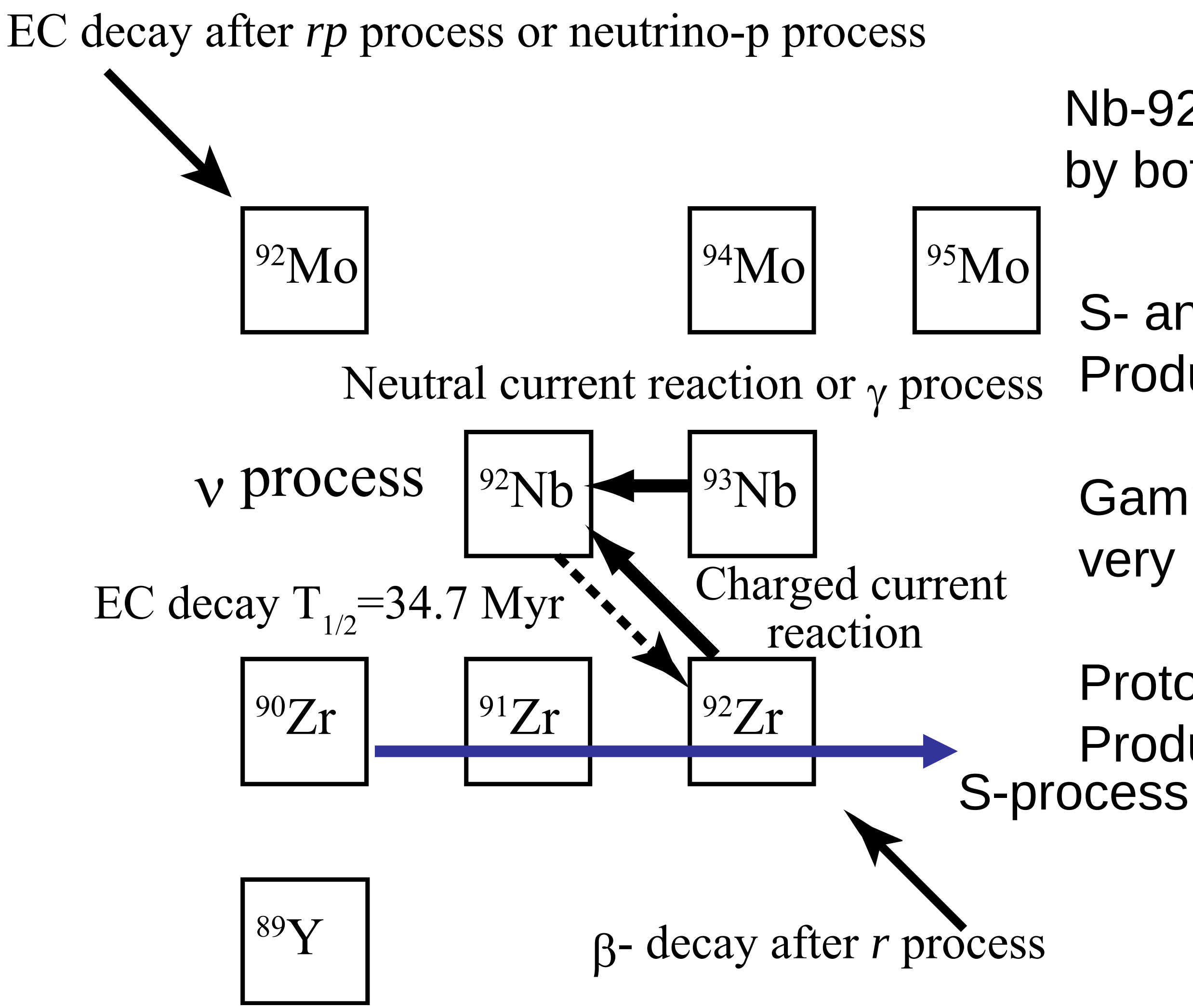
Nuclear Cosmochronometer



If we know the stellar origin of Nb-92, we evaluate the time from the astrophysical event, producing Nb-92, to the solar system formation.

What synthesis Nb-92 ?

Nucleosynthesis of ^{92}Nb



Nb-92 cannot be synthesized by both the beta decays

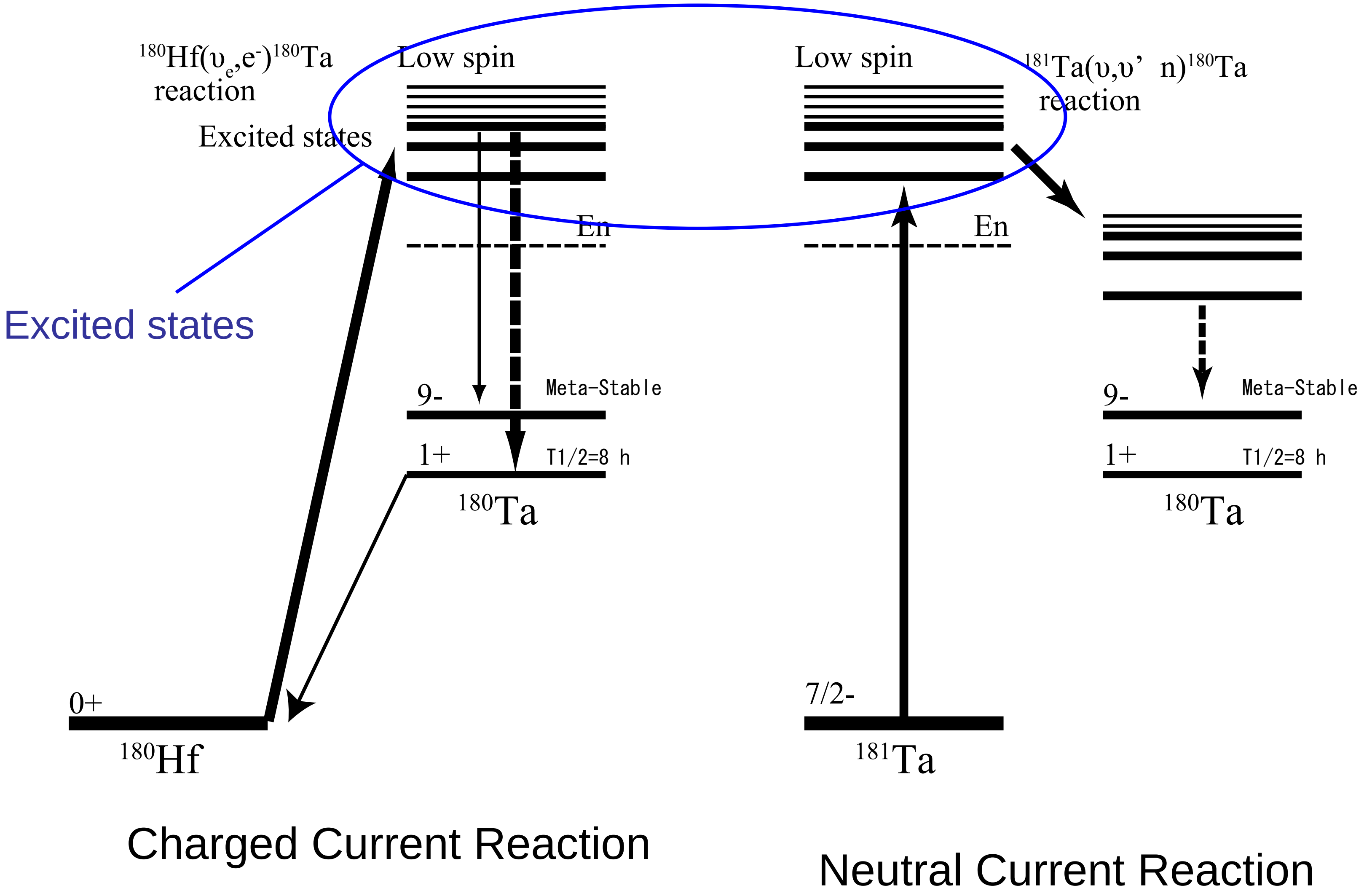
S- and r-processes cannot Produce it.

Gamma-process only produce very low abundance.

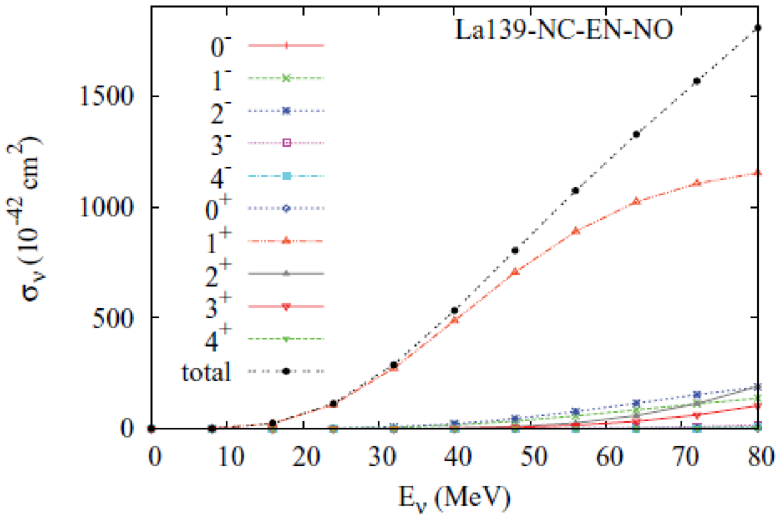
Proton capture also cannot Produce it.

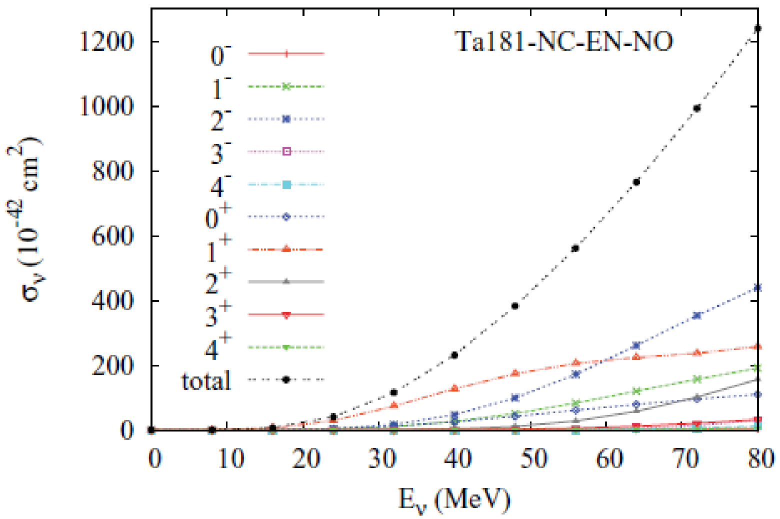
We have proposed the neutrino-process origin.

Neutrino-induced reactions



QRPA calculation





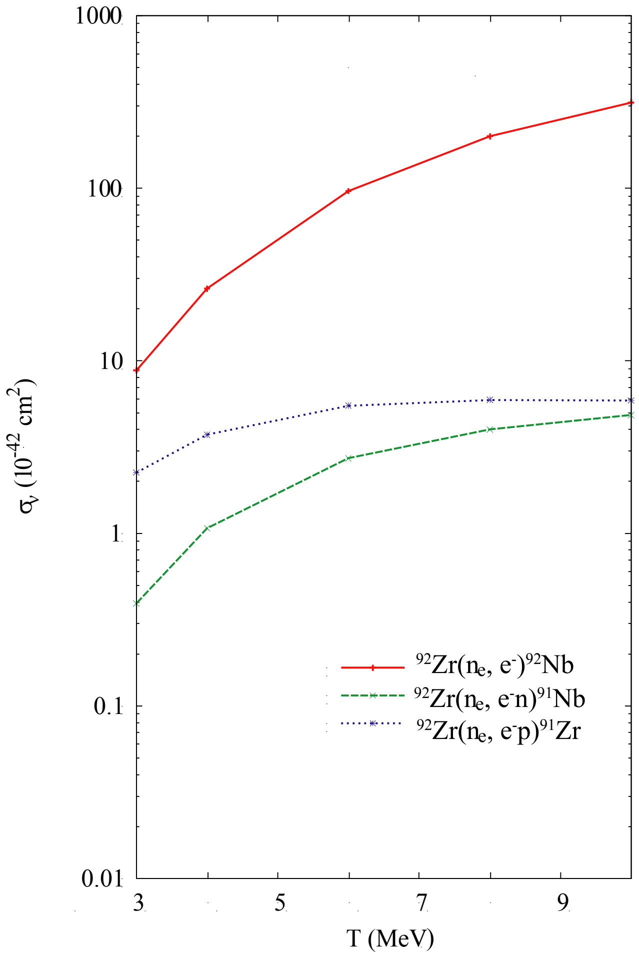
Reaction Rate is critical information for nucleosynthesis calculations.

We calculated the rates using quasi-particle random phase approximation (QRPA) model.

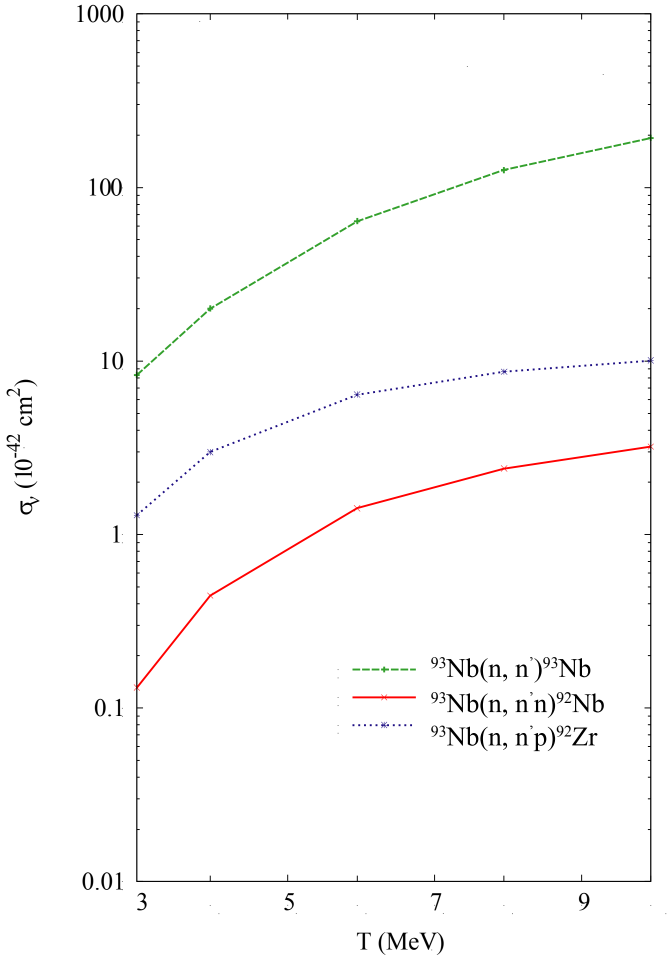
M. Cheoun, et al. Phys. Rev. C 82, 035504(2010).

Nb-92

Charged Current Reaction

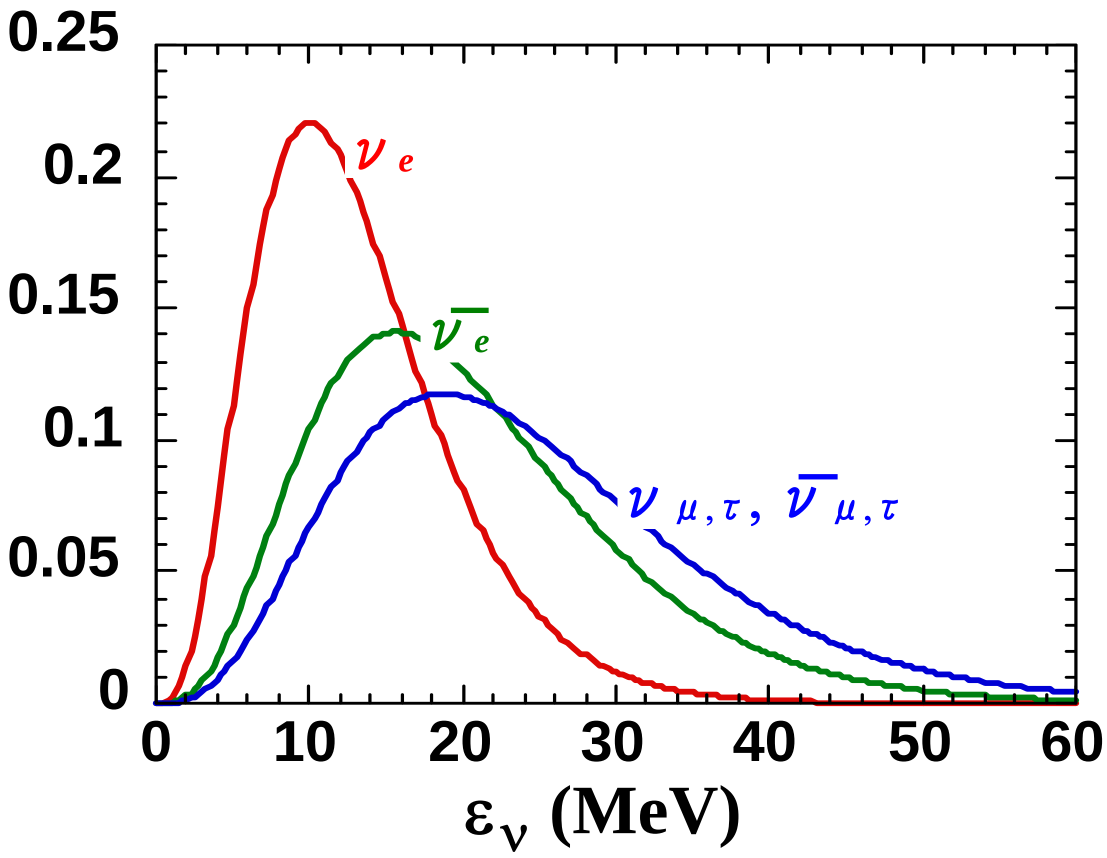


Neutral Current Reaction



Calculated by M.K. Chuen et al.

Evaluated Neutrino Spectra from light element neutrino process



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

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

$T(\nu_e)$ = 3.2 MeV

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

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

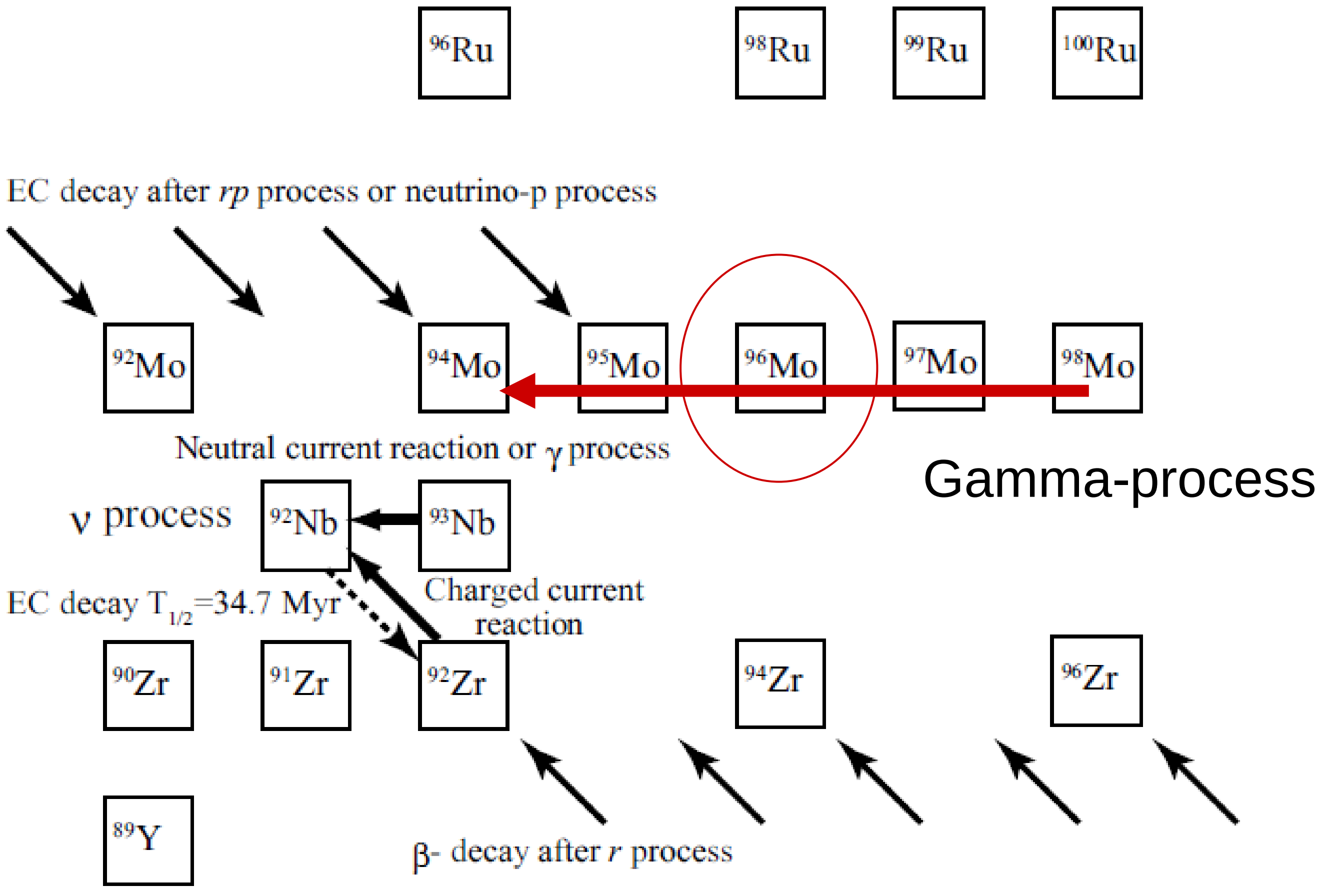
Yoshida, Kajino & Hartman, Phys. Rev. Lett. 94 (2005), 231101.

How compare ?

^{93}Zr is produced in many nucleosynthesis such as s-process and r-process.

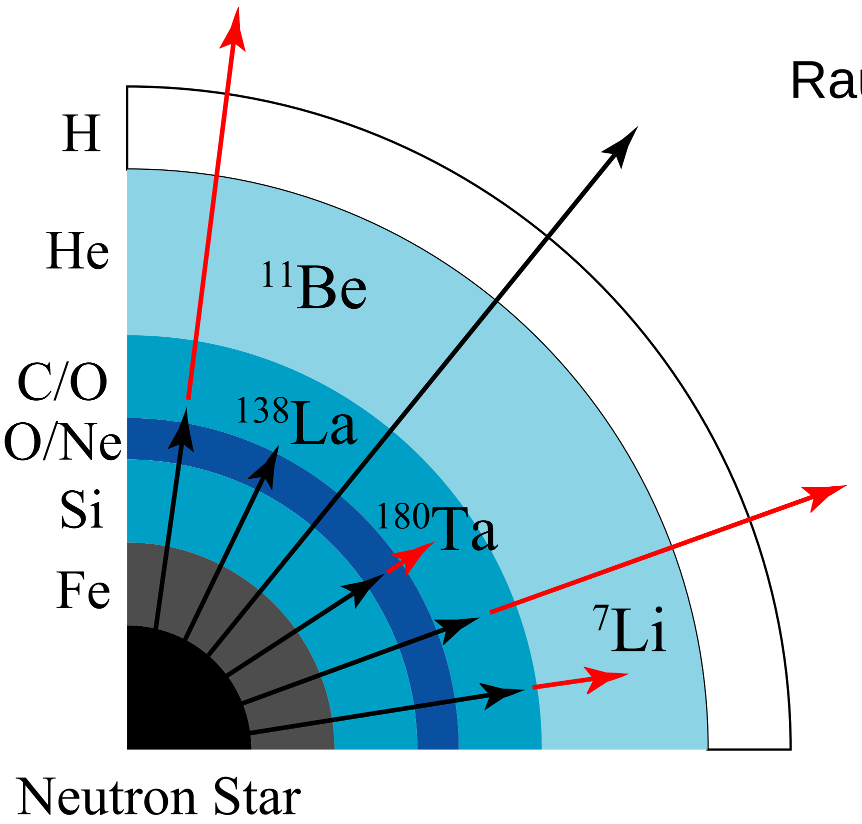
Mo-96

Mo-96 is produced by gamma-process



T. Hayakawa, ApJ. 2008

Supernova calculation



Rauscher, ApJ 2002

Mass: 15 Solar mass
Explosion: 10^{51} erg
Seed: Solar and s-processed

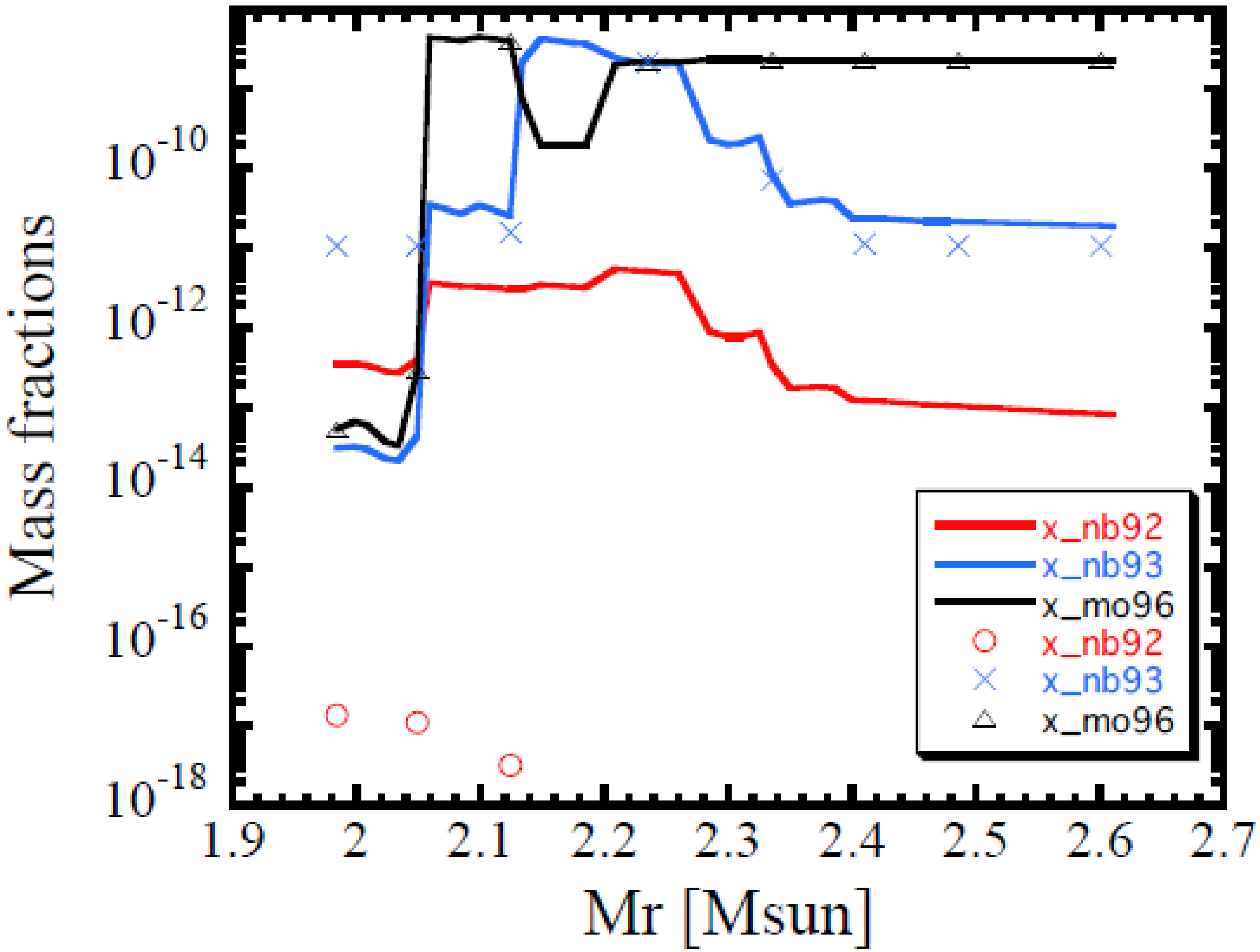
$T(\nu_e) = 3.2$ MeV

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

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

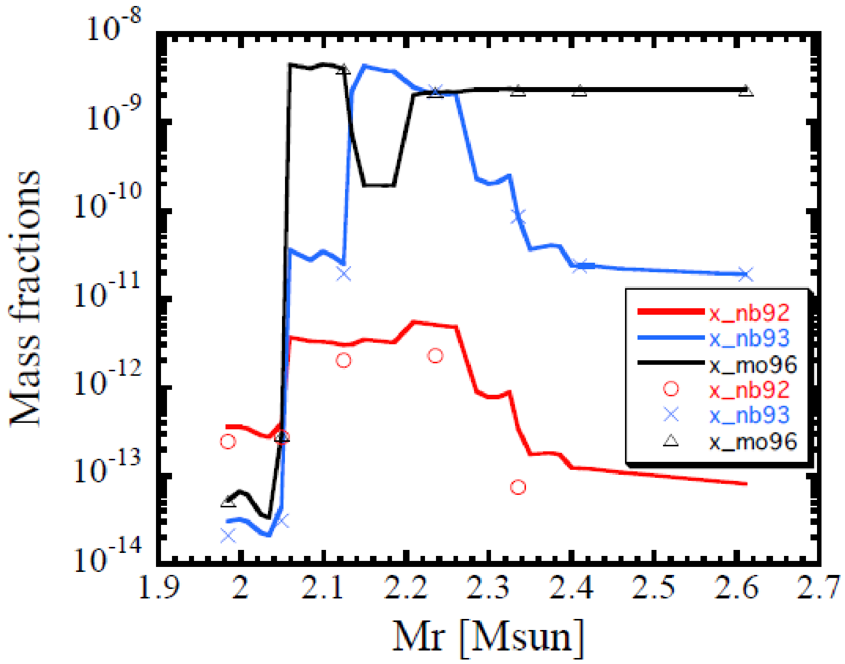
Calculated by K. Nakamura, et al. Next Speaker !

Only gamma-process

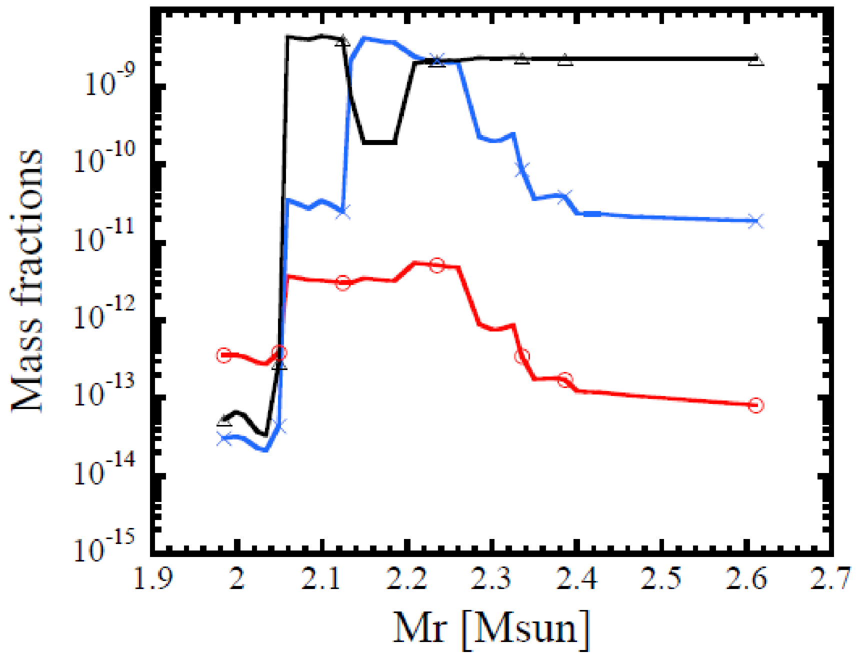


Results

With NCR

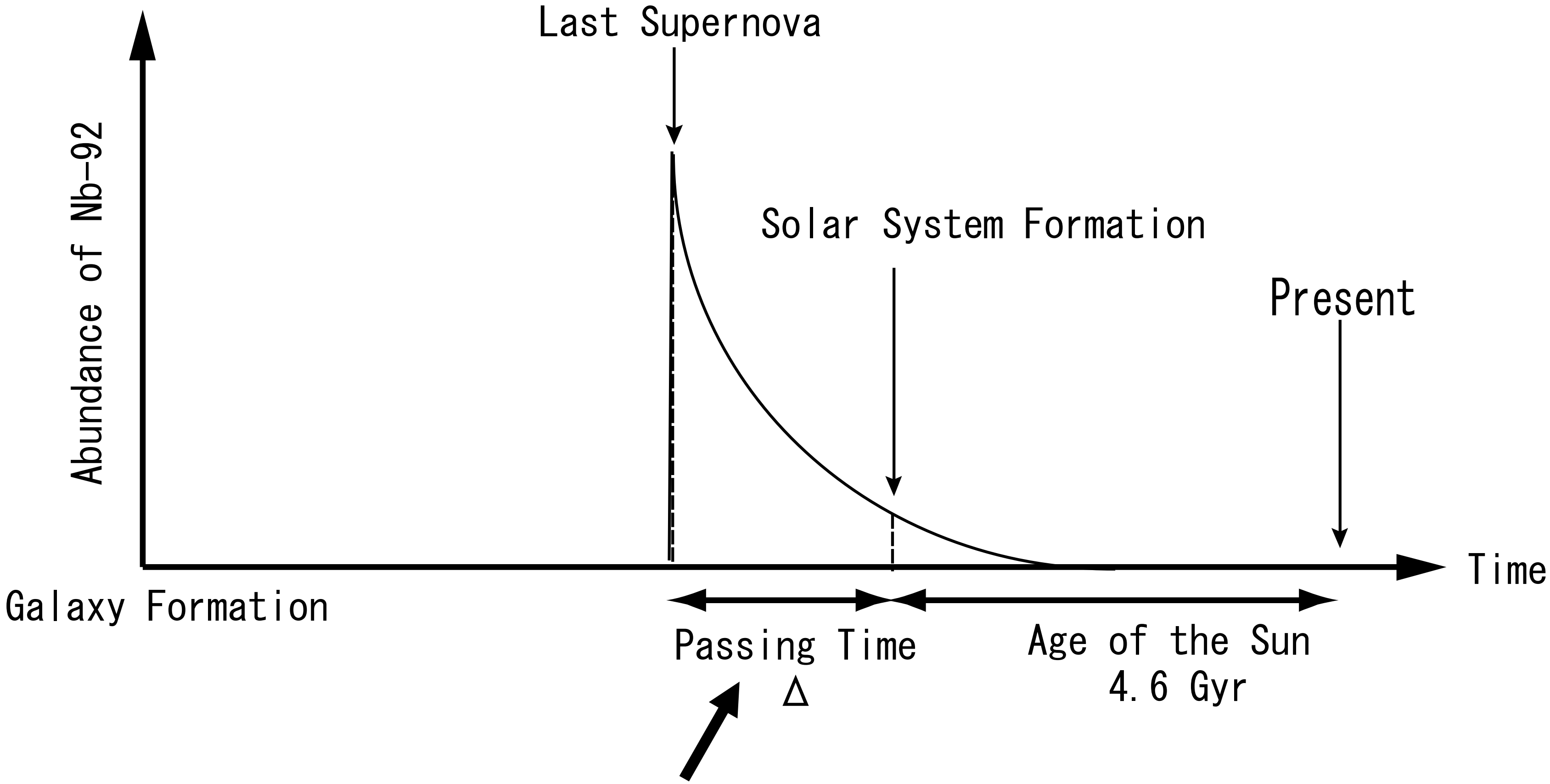


With CCR



The charged current reaction has critical for 92Nb synthesis.

Passing Time



Duration time from the last SN to the solar system formation

Time from SN to SSF

Single event model

$$\left[\frac{^{92}\mathrm{Nb}}{^{96}\mathrm{Mo}}\right]_{SSF} = \left[\frac{p(^{92}\mathrm{Nb})}{p(^{96}\mathrm{Mo})}\right]_{\nu} \cdot f\nu(^{96}\mathrm{Mo}) \cdot \exp\{-\Delta/\tau\}$$

$$\left[\frac{^{92}\mathrm{Nb}}{^{93}\mathrm{Nb}}\right]_{SSF} = \left[\frac{p(^{92}\mathrm{Nb})}{p(^{96}\mathrm{Mo})}\right]_{\nu} \left[\frac{p(^{96}\mathrm{Mo})}{p(^{93}\mathrm{Nb})}\right]_{\odot} \cdot f\nu(^{96}\mathrm{Mo}) \cdot \exp\{-\Delta/\tau\}$$

Mo-96 is shielded against both the beta decays.

Calculated abundance ratio

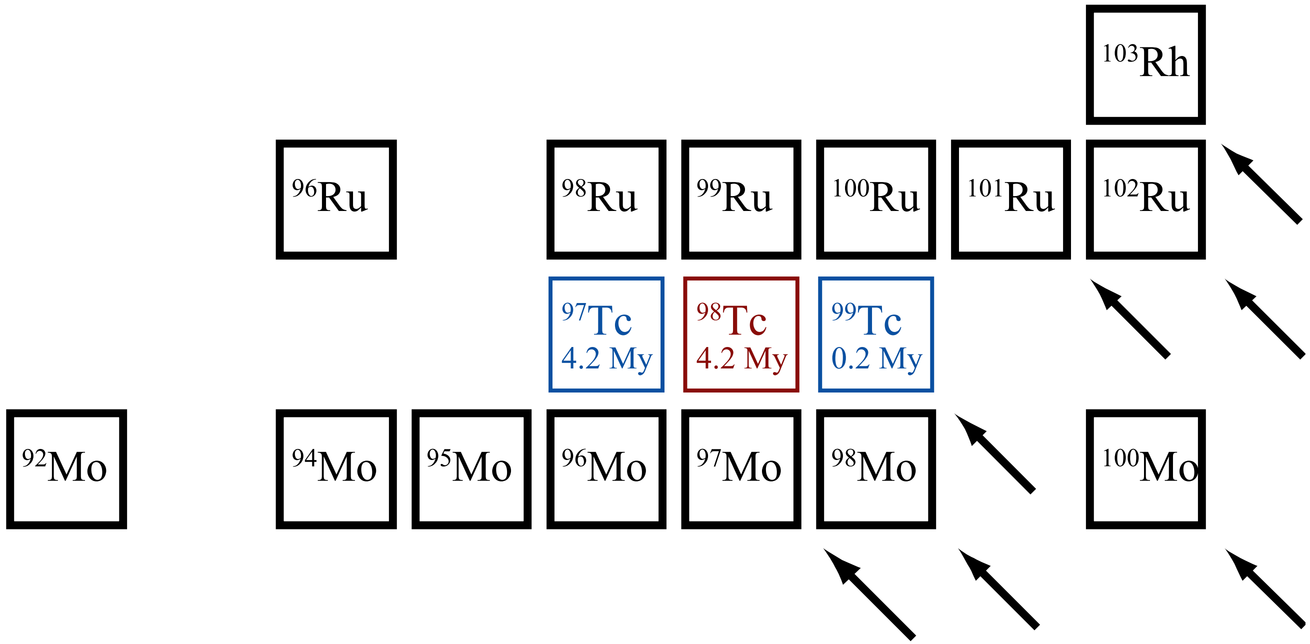
$(\frac{^{92}Nb}{^{96}Mo})\nu$	$f_\nu(^{96}Mo)$	Δ	$(\frac{^{92}Nb}{^{93}Nb})cal$
0.0013	8%	3×10^{7}	3.5×10^{-5}
0.0013	8%	10^{8}	8.6×10^{-6}
0.0013	3%	3×10^{7}	1.3×10^{-5}
0.0013	3%	10^{8}	3.2×10^{-6}

•This result shows that neutrino process can reproduce only Lower value of 10^{-5}.

• We obtain about 30 Myr for the passing time, which is consistent with time measured by other r-process chronometers.

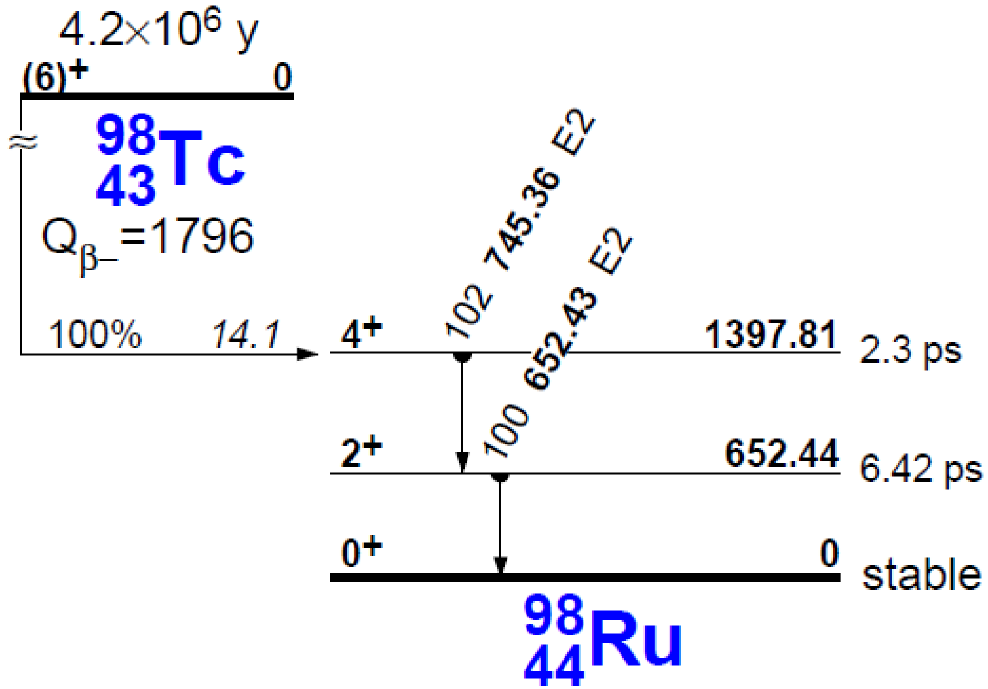
4th neutrino nucleus

We have proposed Tc-98 may be produced by supernova Neutrino process.



1. How observe evidence of synthesis of Tc-98 ?

Gamma-ray line astronomical observation



Decay gamma-rays of some Radioactivities such as 26Al, 60Fe have been observed.

We have proposed two gamma-rays of 745 keV and 652 keV gamma-rays.

Summary

Light isotope, ^{7}Li, ^{11}Be, can be reproduced by the neutrino process.
Heger, PLB, 2005
Yoshida, Kajino, PRL, 2005
However, heavy isotopes, ^{138}La, ^{180}Ta, can not explained.

We have made a new model and reproduce their abundances.
Hayakawa, PRC, 2010; Hayakawa, PRC, 2010

We have proposed neutrino process for ^{92}Nb and reproduced

$$\mathbf{T(\nu_e) = 3.2\ MeV,\ \ T(\overline{\nu_e}) = 4.0\ MeV,\ \ T(\nu_{\mu,\tau}) = 6.0\ MeV}$$

Neutrino process predict neutrino energy spectra.
We have proposed a new cosmochronometer for neutrino process.