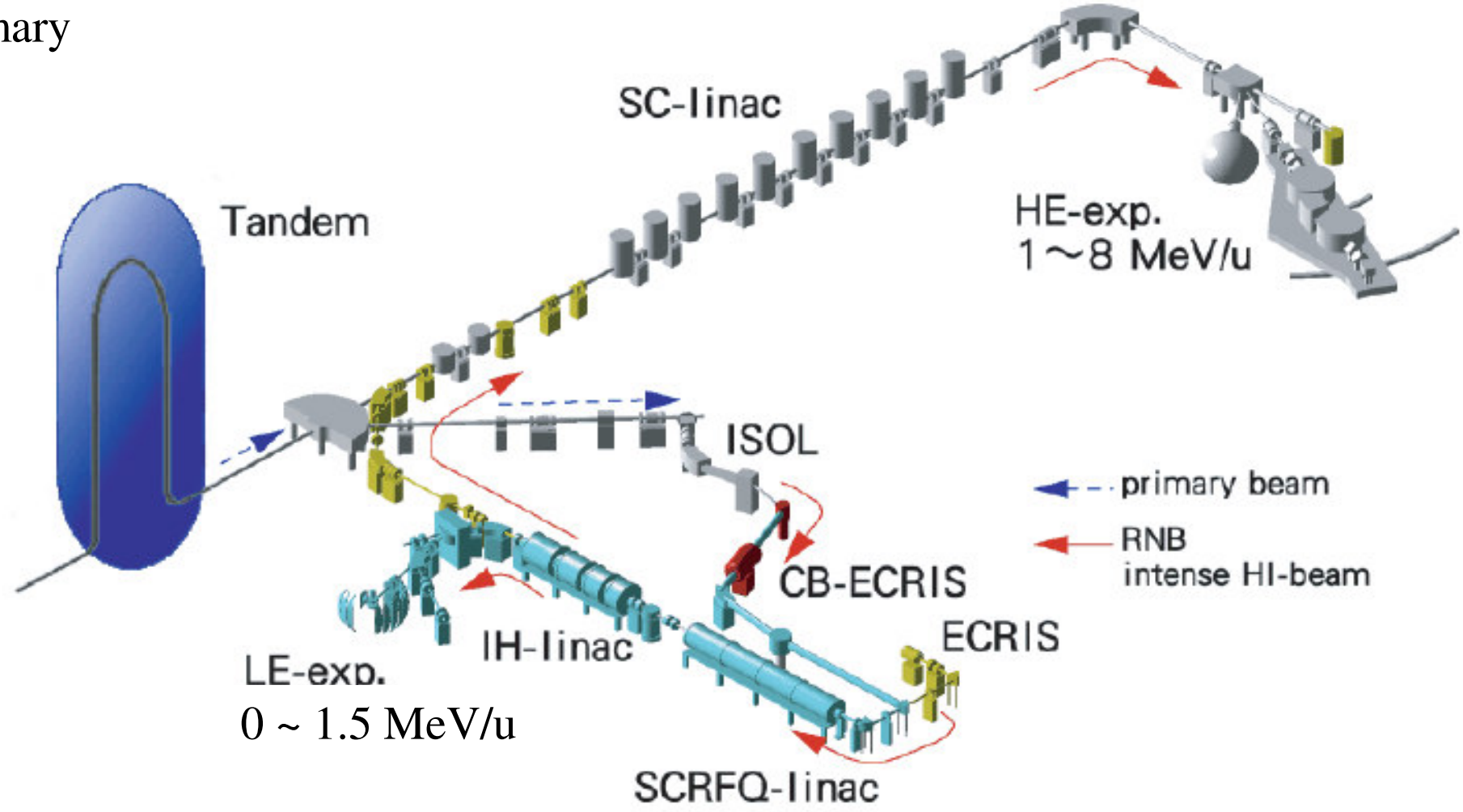
TRIAC
Tokai Radioactive Ion Accelerator Complex

Nuclear astrophysics at TRIAC facility

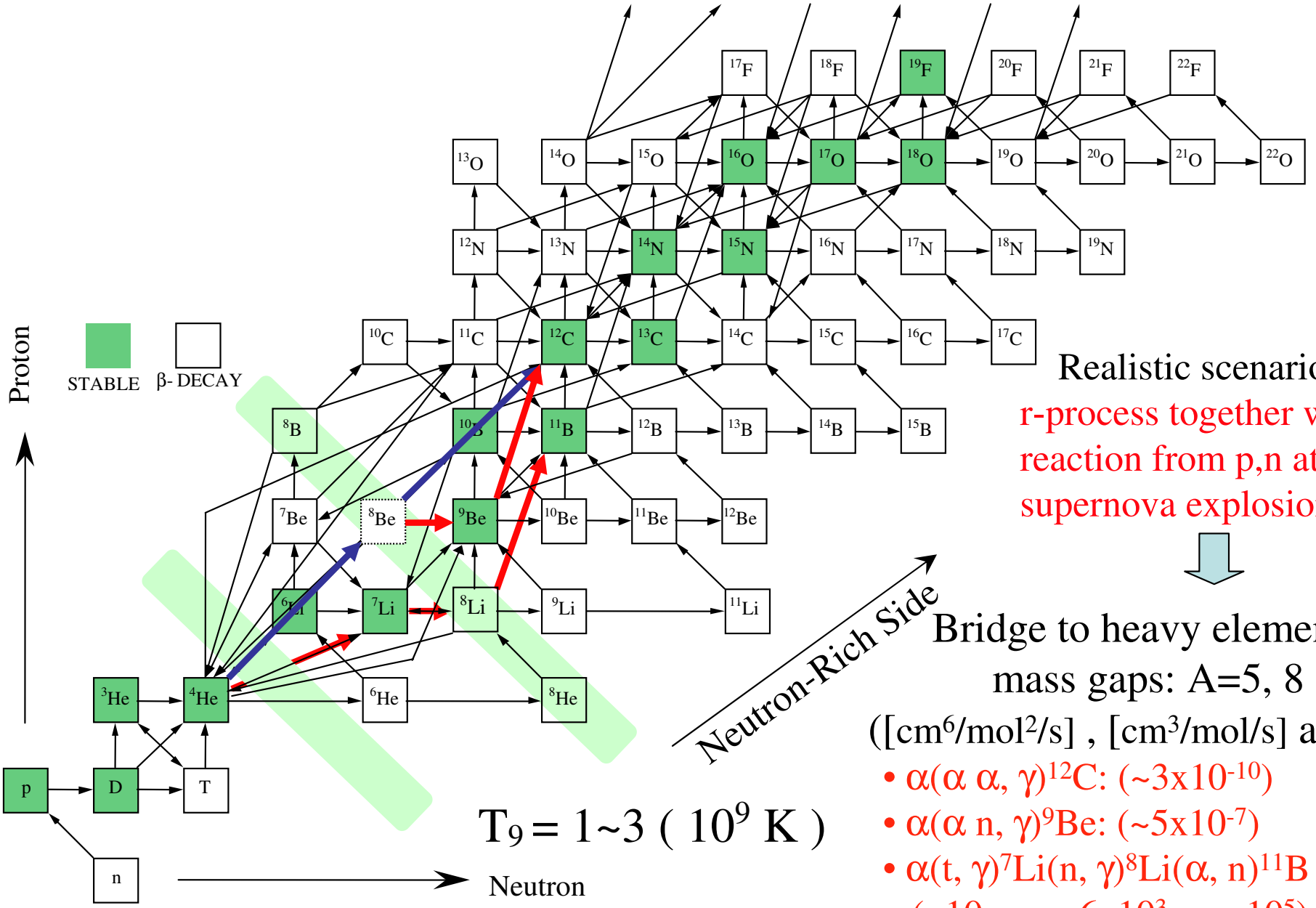
H. Miyatake @ IPNS, KEK
2008.1.22-25 JUSTIPEN@ORNL

- Introduction: KEK Tokai campus
- Heavy element synthesis beyond mass gaps of A=5 and 8
- Summary



TRIAC
Tokai Radioactive Ion Accelerator Complex

r-process associated with supernova explosion



$T_9 = 1\sim3$ (10^9 K)

Realistic scenario:

r-process together with (α,n) reaction from p,n at the supernova explosion

Bridge to heavy elements over mass gaps: A=5, 8

([cm^6/mol^2/s] , [cm^3/mol/s] at T_9=1)

- α(α α, γ)^{12}C: (~3x10^{-10})
- α(α n, γ)^{9}Be: (~5x10^{-7})
- α(t, γ)^{7}Li(n, γ)^{8}Li(α, n)^{11}B (~10, ~6x10^3, ~10^5)

sensitivities for r-process abundance pattern

sensitivity: α_i: $Y_r / Y_r(0) \propto [\sigma_i / \sigma_i(0)]^{\alpha_i}$

	Sensitivity (α_i)				
	A=126 - 134	A=191 - 199			
Reaction	Second Peak	Third Peak	Th	^{235}U	^{238}U
$\alpha(\alpha n, \gamma)^{9}$Be	0.0045	−0.0099	−0.0304	−0.0306	−0.0330
$\alpha(t, \gamma)^{7}$Li	1.5255	−1.9525	−8.4970	−8.6190	−9.1254
^{7}Li$(n, \gamma)^{8}$Li	0.5260	−0.5790	−2.8761	−2.9151	−3.0879
^{8}Li$(\alpha, n)^{11}$B	0.0552	−0.0613	−0.2939	−0.2985	−0.3155
^{9}Be$(n, \gamma)^{10}$Be	0.0005	−0.0012	−0.0029	−0.0028	−0.0031
^{11}B$(n, \gamma)^{12}$B	0.0009	−0.0294	−0.0295	−0.0295	−0.0282
^{17}C$(n, \gamma)^{18}$C	0.0779	−0.1152	−0.4049	−0.4111	−0.4347

Fast steady flow model for the neutrino driven wind: τ_{dyn}=50 ms, s/k=1700, Ye=0.45

(T. Sasaqui, et al., Astrophys. J. 634('05)1173.)

- Reactions around mass gap play important roles in production of the r-process abundance.
- Hauser Feshbach estimation may not be applicable due to the low level density.

Experiments relevant to reactions around mass-gap A=8

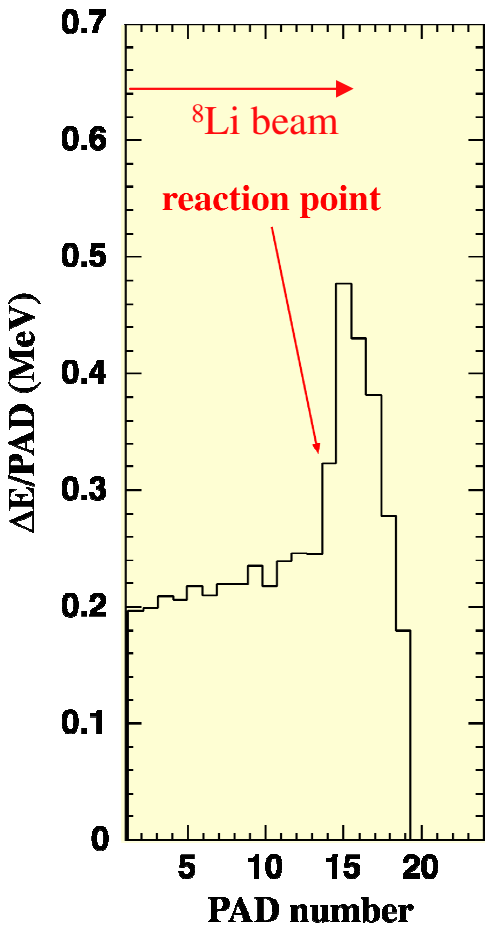
TRIAC
Tokai Radioactive Ion Accelerator Complex

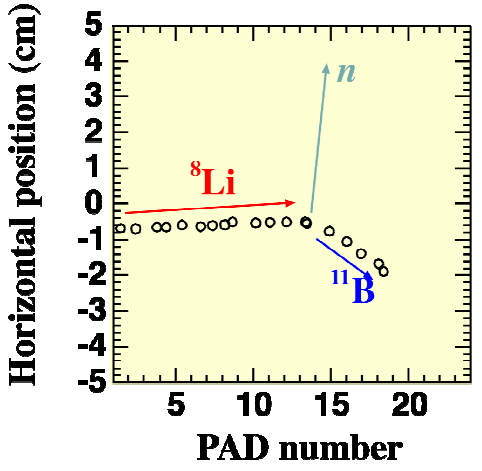
Reaction	beam	detector	status
^{8}Li(α, n)^{11}B	RMS(10^4)	GMSTPC + n	0.4-2.7 MeV
^{8}Li(α, n)^{11}B	TRIAC(10^6)	GEM-MSTPC + n	< 0.5 MeV, 2008
^{8}Li(p, α)	TRIAC(10^6)	SSD	
^{8}Li(d, t)^{7}Li	TRIAC(10^6)	SSD	0.5 – 1.5 MeV
^{8}Li(d, p)^{9}Li	TRIAC(10^6)	SSD	
^{8}Li(d, α)^{6}He	TRIAC(10^6)	SSD	0.5 – 1.5 MeV
^{8}Li(d, n)^{9}Be	TRIAC(10^6)	GEM-MSTPC + n	
^{12}B(α, n)^{15}N	RMS(10^4)	GMSTPC + n	1.1 – 3.7 MeV
^{16}N(α, n)^{19}F	RMS(10^4)	GMSTPC + n	1.3 – 3.6 MeV

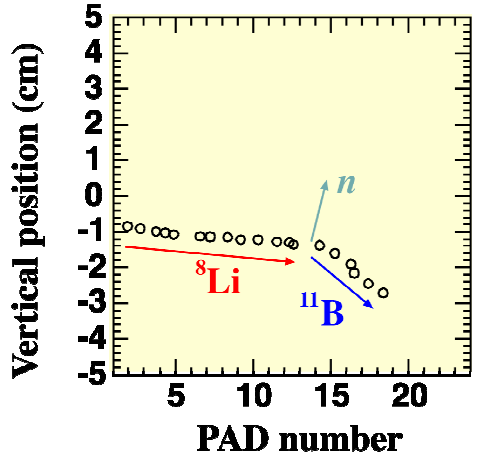
Nuclear Astrophysics Exp.

Neutron

Neutron Counter (back)

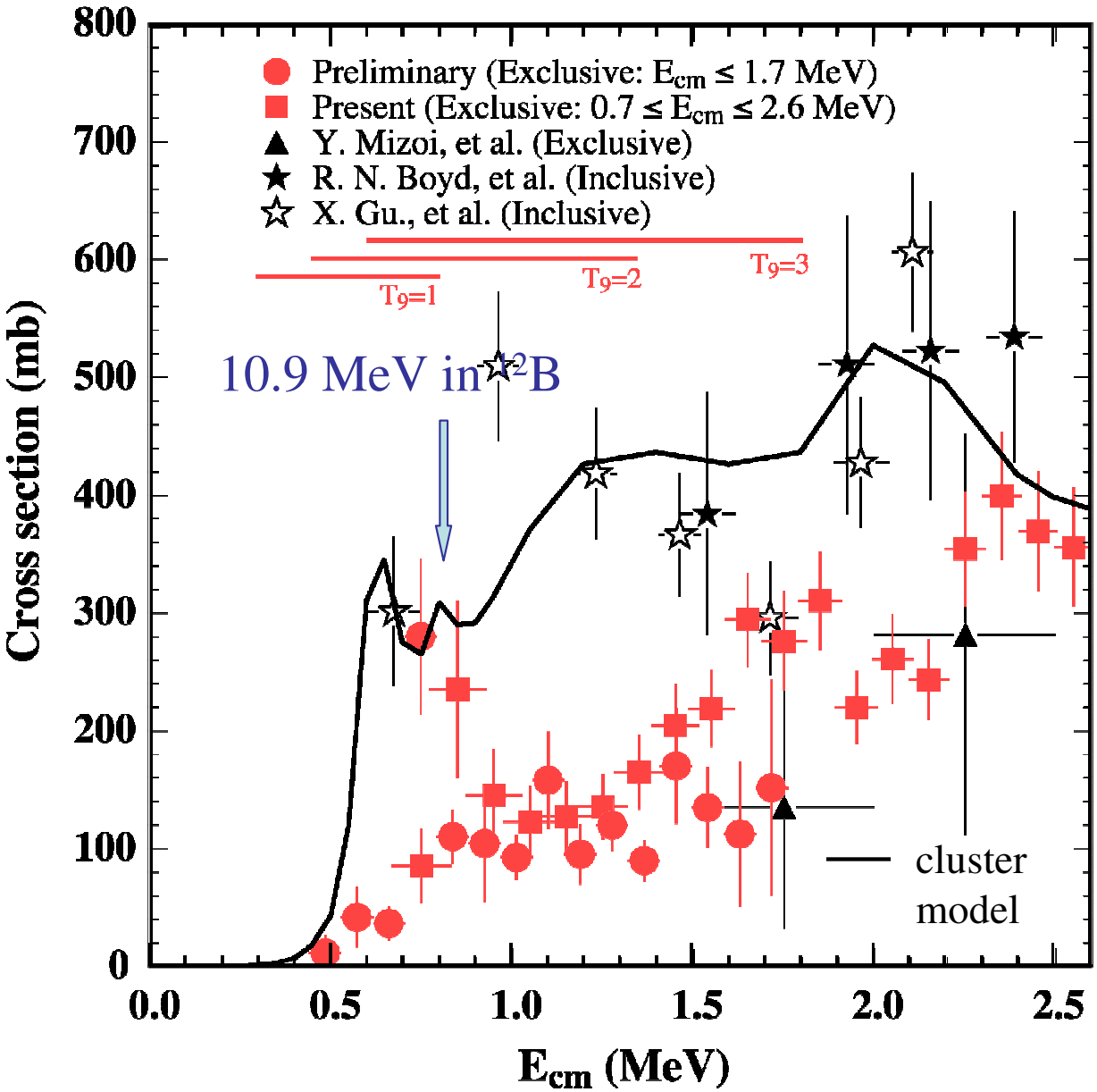






Measured cross section

H. Ishiyama et al., Phys. Lett. B640('06)82.



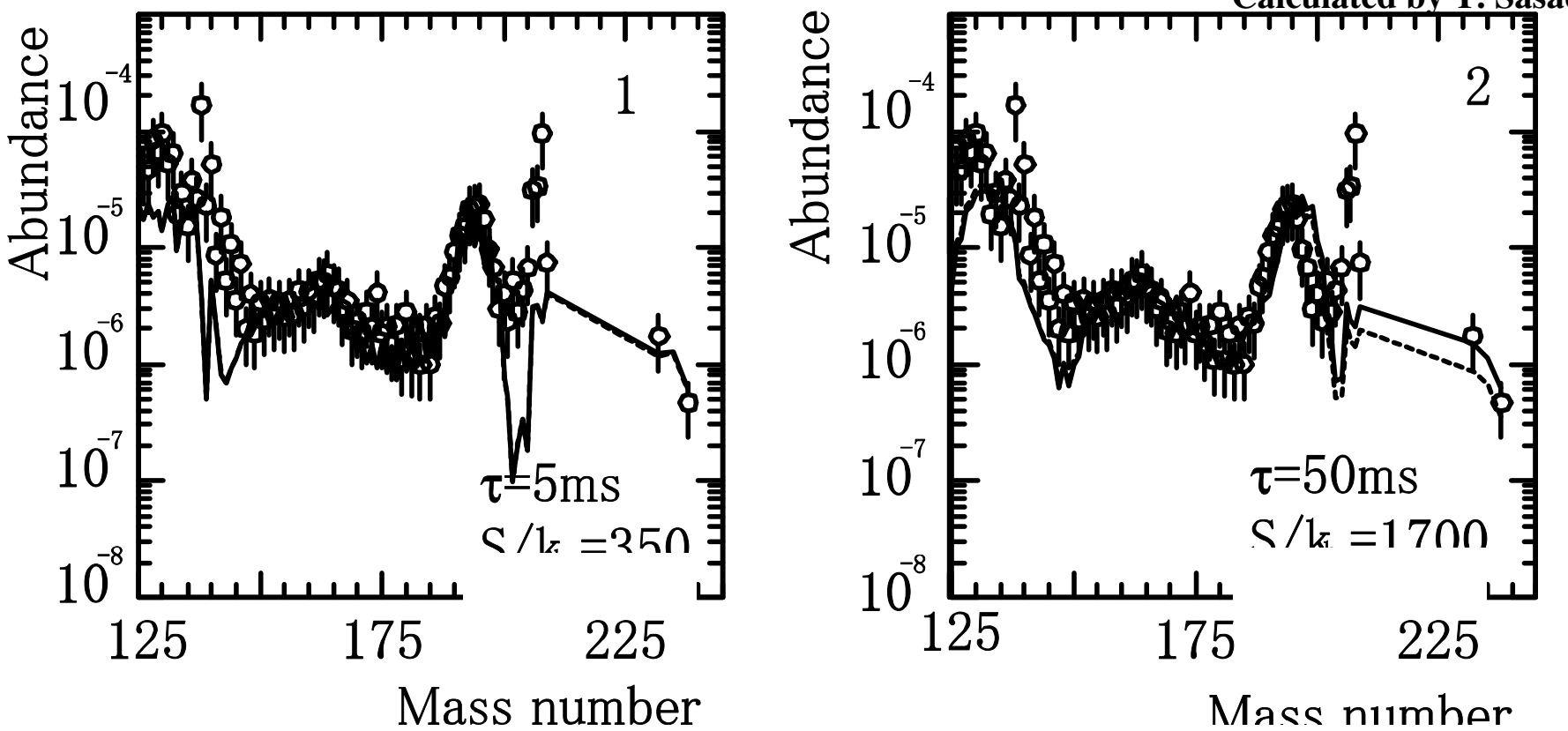
- exclusive meas.:
  $2.6\ \text{MeV} \geq E_{cm} \geq 0.5\ \text{MeV}$
- $T_9 = 2\sim3$
- $\Delta\sigma/\sigma\sim15\%$
- ~ x5 to the inclusive meas.
- $E_x(^{12}B)\sim10.8$ MeV

ref. α-resonance st. at 10.9 MeV by N. Soic et al., Eur. Lett. 63('03)247c

- Extended cluster model did not reproduce. ref.P. Descouvemont, Ncul. Phys. A596('96)285.

Results of network calculations

Calculated by T. Sasaqui



Fast steady flow model for the neutrino driven wind

τ_{dyn}:time from T=5 MeV to 5/e MeV

—— Present

..... Inclusive

τ_{dyn}=0.005sec:

$Y_{present}/Y_{inclusive}$=1.04

τ_{dyn}=0.05sec:

$Y_{present}/Y_{inclusive}$=1.80

- Present reaction rate results 1.8 times large production in the uranium region compared to the inclusive data.

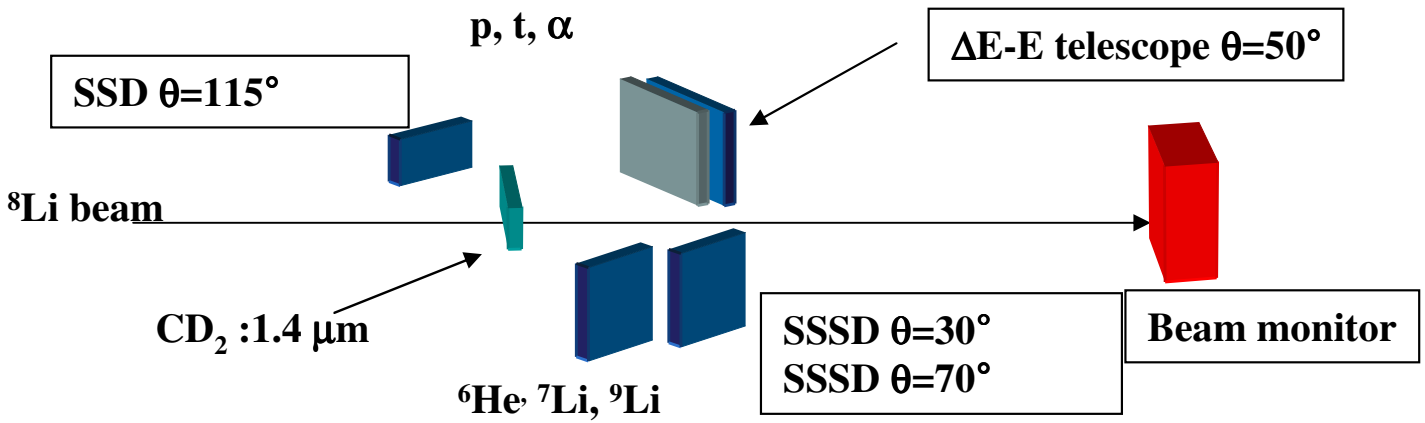
^{8}Li(d, t), (d, p), (d, α) reactions

TRIAC
Tokai Radioactive Ion Accelerator Complex

19.717
^{4}He + 2t

QuickTimeý Ç²
TIFF (LZW) êLíÉvÉçÉOÉâÉÄ
Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾å©ÇÈÇžÇ½Ç…ÇÕïKóvÇ-Ç□ÅB

8.477 ^{8}Be + 2n
6.812
^{9}Be + n

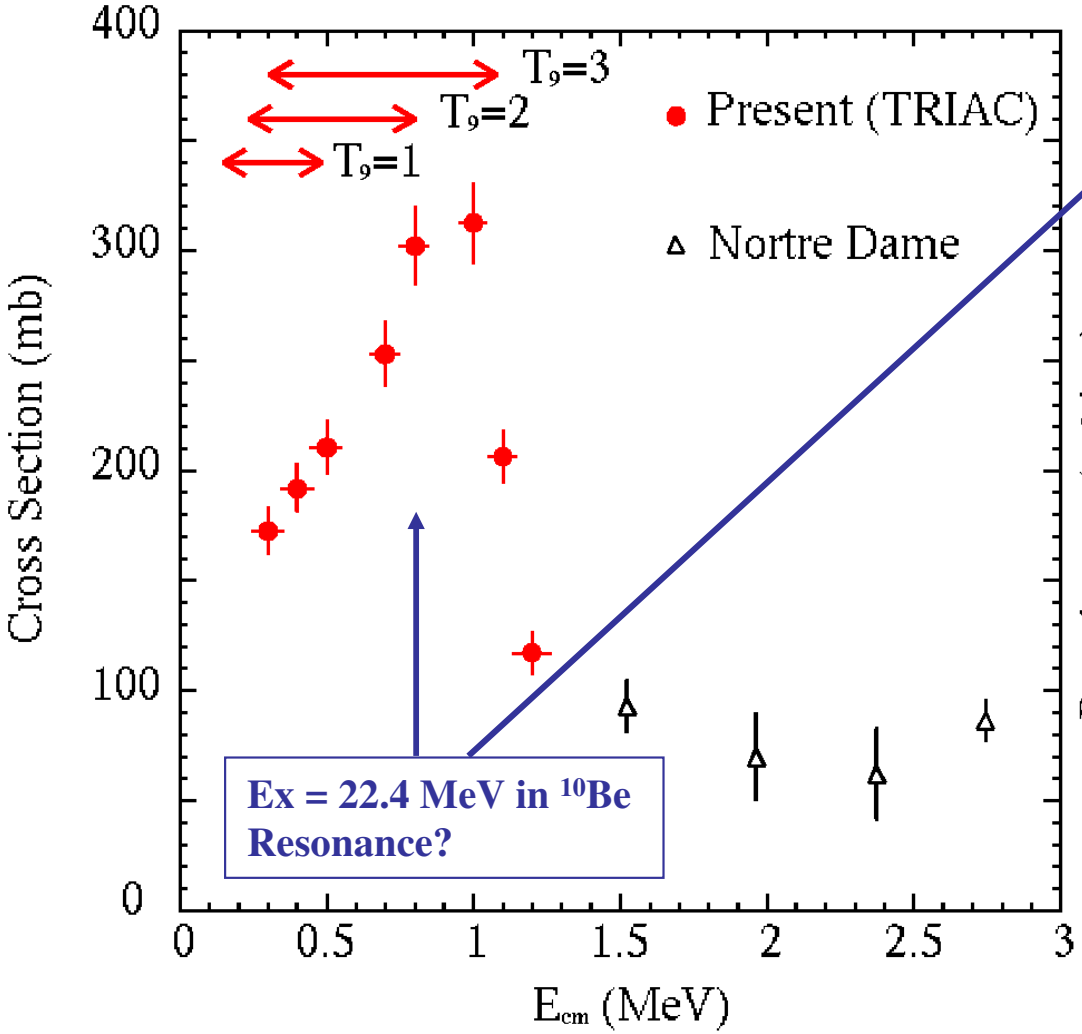


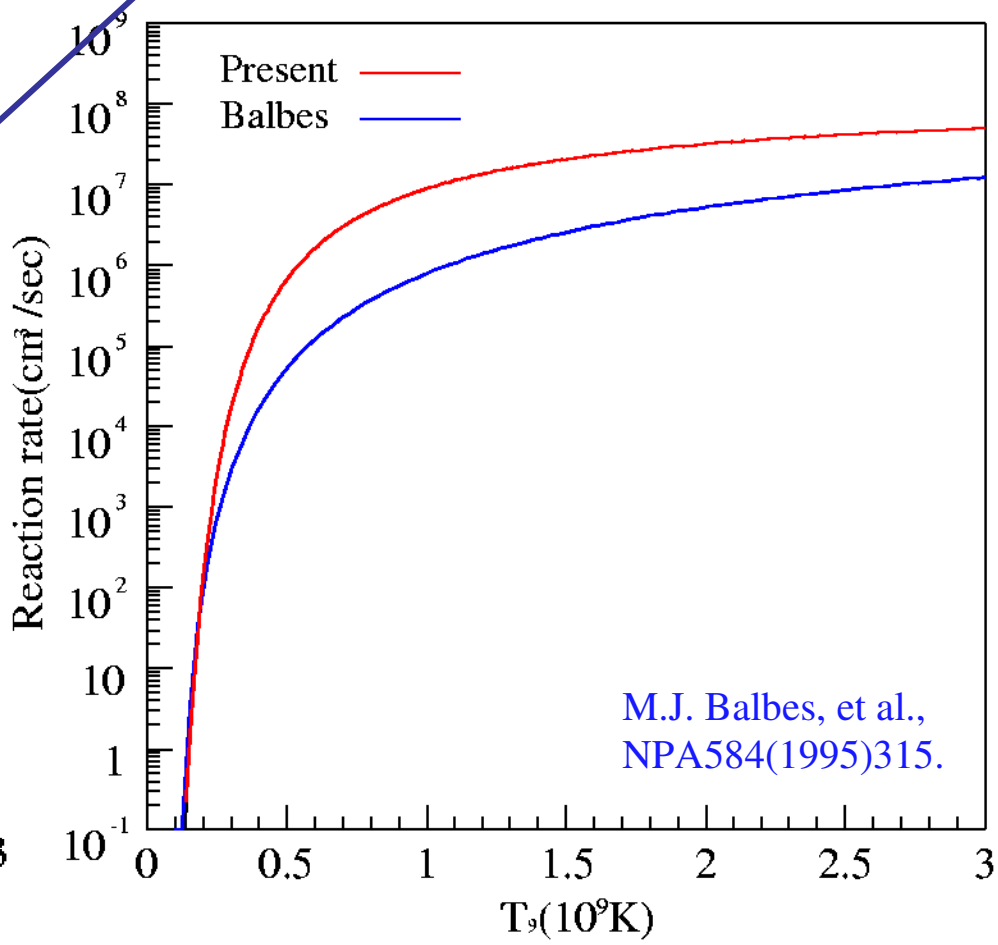
^{8}Li(d, t)^{7}Li reaction

- absolute cross section in the low energy region of astrophysical interest
- Gamow peaks T_9=1 - 3
- large cross section (300 mb) around 0.8 MeV

E_{cm} (MeV)	E_x (MeV)	decays
0.2	21.8	p, (d)
0.8	22.4	p, t
1.4	23.0	p

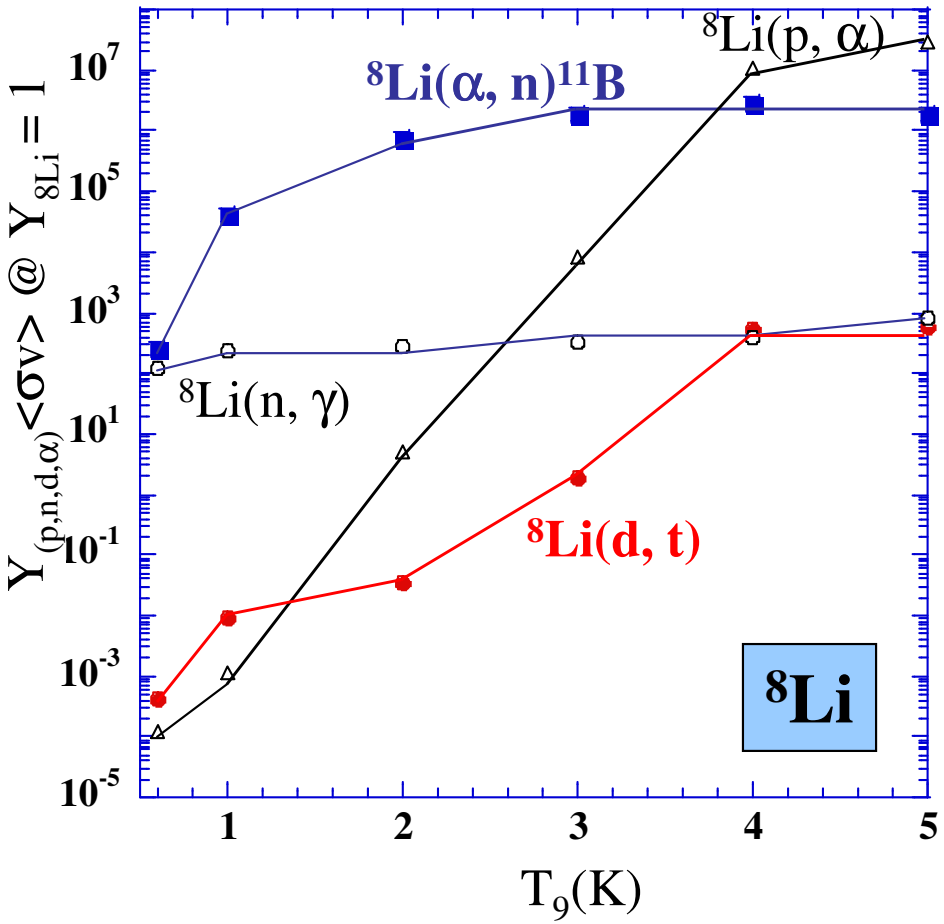
N.R. Fletcher, et al., Phys. Rev. C68(03)024316



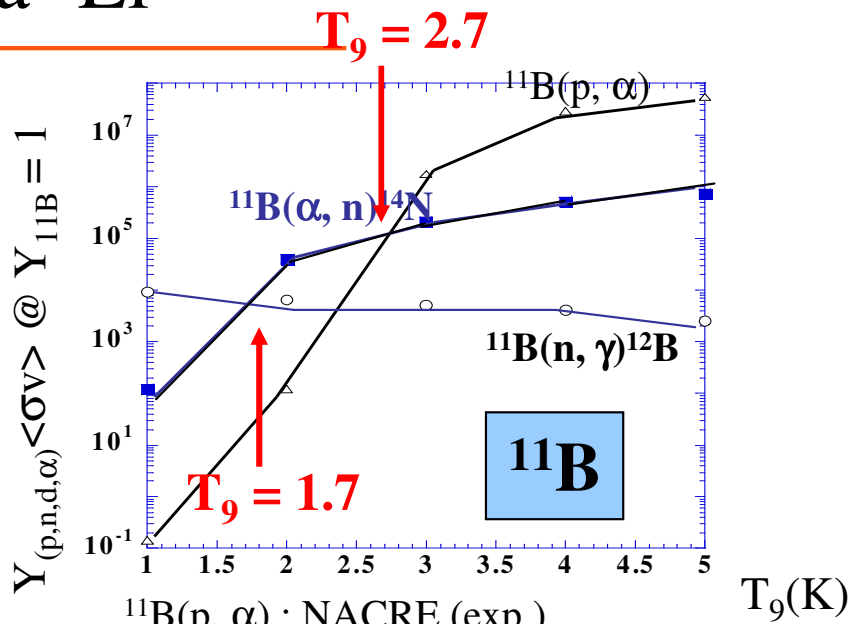


Reaction path via ^{8}Li

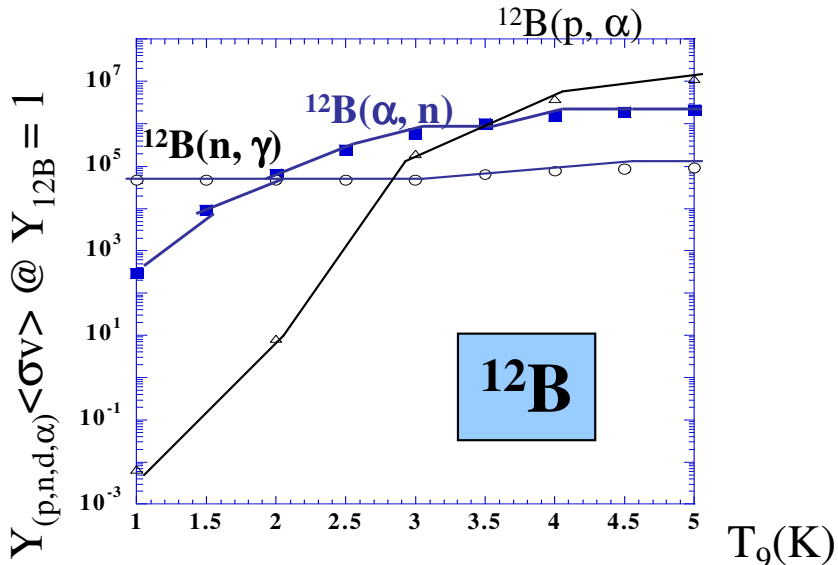
Yp, Yn, Yα, Yd ← fast steady state flow model of the neutrino driven wind (K. Otsuki)
Yx<σv> (x = p, n, α, d)



^{8}Li(p, α) : F.D. Becchetti, et al., NPA550(1992)507. (exp. in part)
^{8}Li(n, γ) : Z.H. Li, et al., PRC71(2005)052801. (exp. indirect)



^{11}B(p, α) : NACRE (exp.)
^{11}B(α, n), (n, γ) : T.R. Wang, et al., PRC43(1991)883. (exp.)



^{12}B(p, α) : Wagoner (theoretical)
^{12}B(n, γ) : F.-K.Thielemann, in pri.com. (theoretical)

Reaction path via ^{8}Li

T_9= 2.7 - 3.6

^{8}Li(α, n)^{11}B(p, α)^{8}Be(2α)

T_9 = 1.7 – 2.7

^{8}Li(α, n)^{11}B(α, n)^{14}N

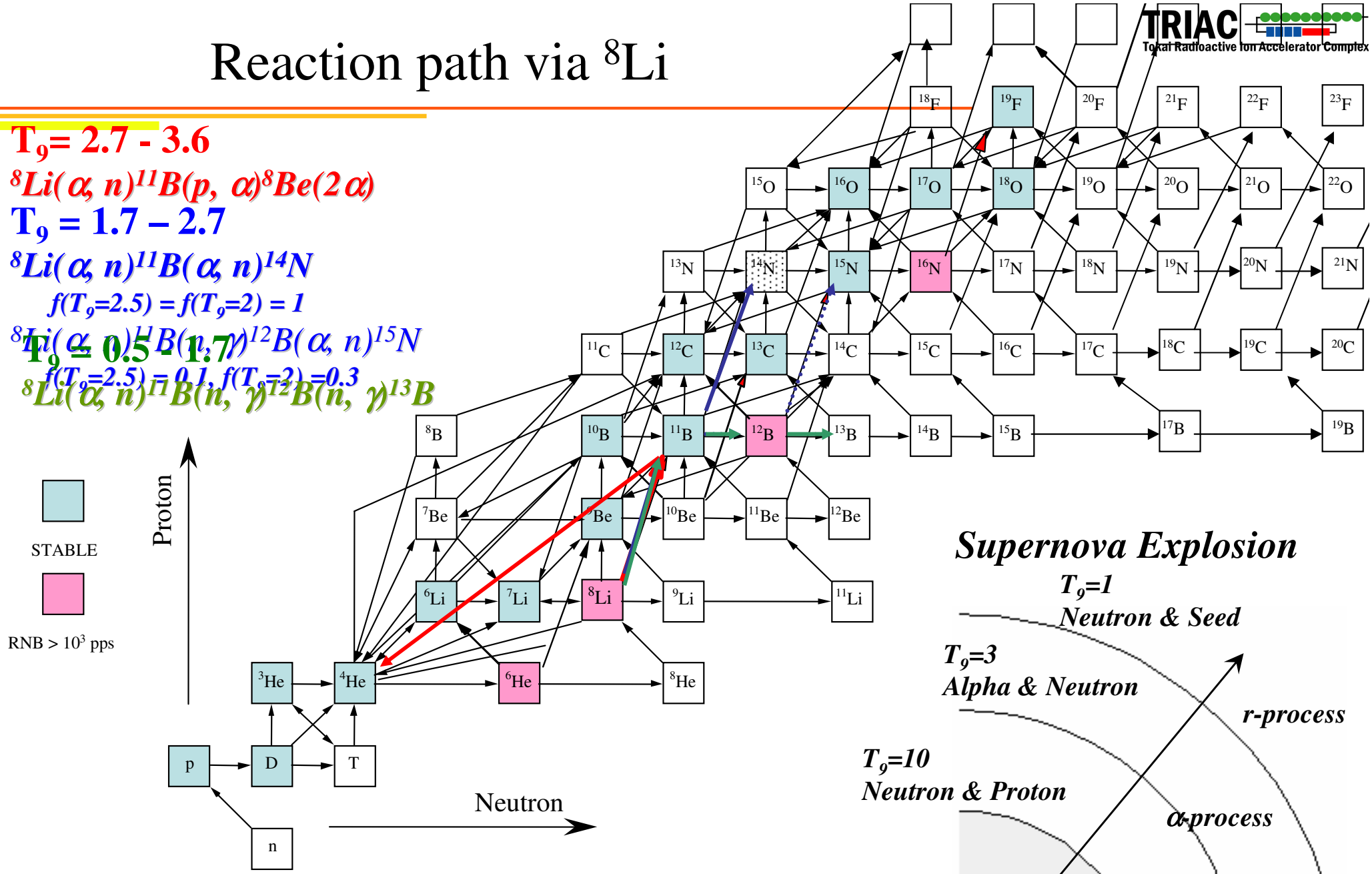
$f(T_9=2.5) = f(T_9=2) = 1$

^{8}Li(α, n)^{11}B(n, γ)^{12}B(α, n)^{15}N

T_9 = 0.5 - 1.7

$f(T_9=2.5) = 0.1$, $f(T_9=2) = 0.3$

^{8}Li(α, n)^{11}B(n, γ)^{12}B(n, γ)^{13}B



fast steady state flow model for the neutrino driven wind (K. Otsuki priv. comm.)

@ dynamical expansion timescale: τ_{dyn} = 50 ms

entropy: s/k = 200

electron fraction: Y_e = 0.45

Summary

- Reactions around unstable mass gap A=5, 8 are important to study r-process scenarios.

- Revised ^{8}Li(α, n) reaction rate reproduces r-process elemental abundance pattern even under the long dynamical expansion time scale (50 ms) in the neutrino driven wind.

- Excitation function of the ^{8}Li(d, t) reaction in the low energy region shows a large resonance like structure at E_{cm}=0.8 MeV corresponding to the 22.4 MeV state in ^{10}Be.

- Dominant reaction path related to ^{8}Li was estimated based on the measured data as a function of the temperature.

TRIAC
Tokai Radioactive Ion Accelerator Complex

Collaborator

T. Hashimoto[2], Y. X. Watanabe[1], H. Miyatake[1,2],
M. H. Tanaka[1], Y. Hirayama[1], N. Imai[1], Y. Fuchi[1], S. C. Jeong[1],
I. Katayama[1], T. Nomura[1], S. Mitsuoka[2], A. Osa[2], T. Sato[2],
K. Nishio[2], M.Matsuda[2], S. Ichikawa[2], H. Ikezoe[2], S. K. Das[3],
Y. Mizoi[3], T. Fukuda[3], T. Shimoda[4], K. Otsuki[5], J.F. Lara[6],
T. Kajino[7]

[1]IPNS KEK, [2]JAEA, [3]Osaka Electro-Communication Univ.,
[4]Osaka Univ., [5]Univ. of Chicago, [6]Clemeson Univ., [7]NAO