Neutron capture cross-section of ^{93}Zr

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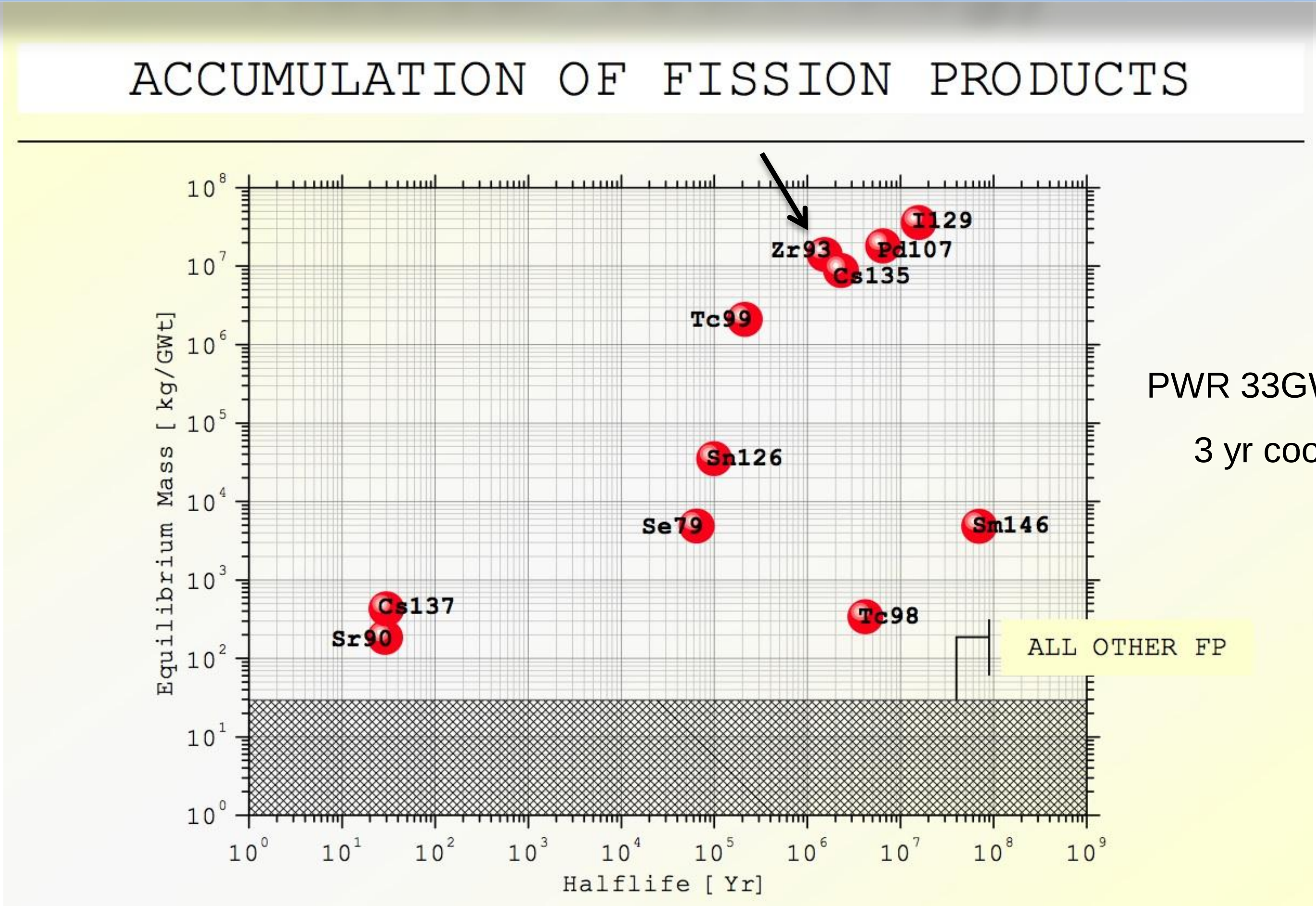
Scientific Motivations

- Nuclear Technology

- Nuclear Astrophysics

Nuclear Technology



PWR 33GWtd THM^{-1} burnup

3 yr cooling spent fuel

Nuclear Technology

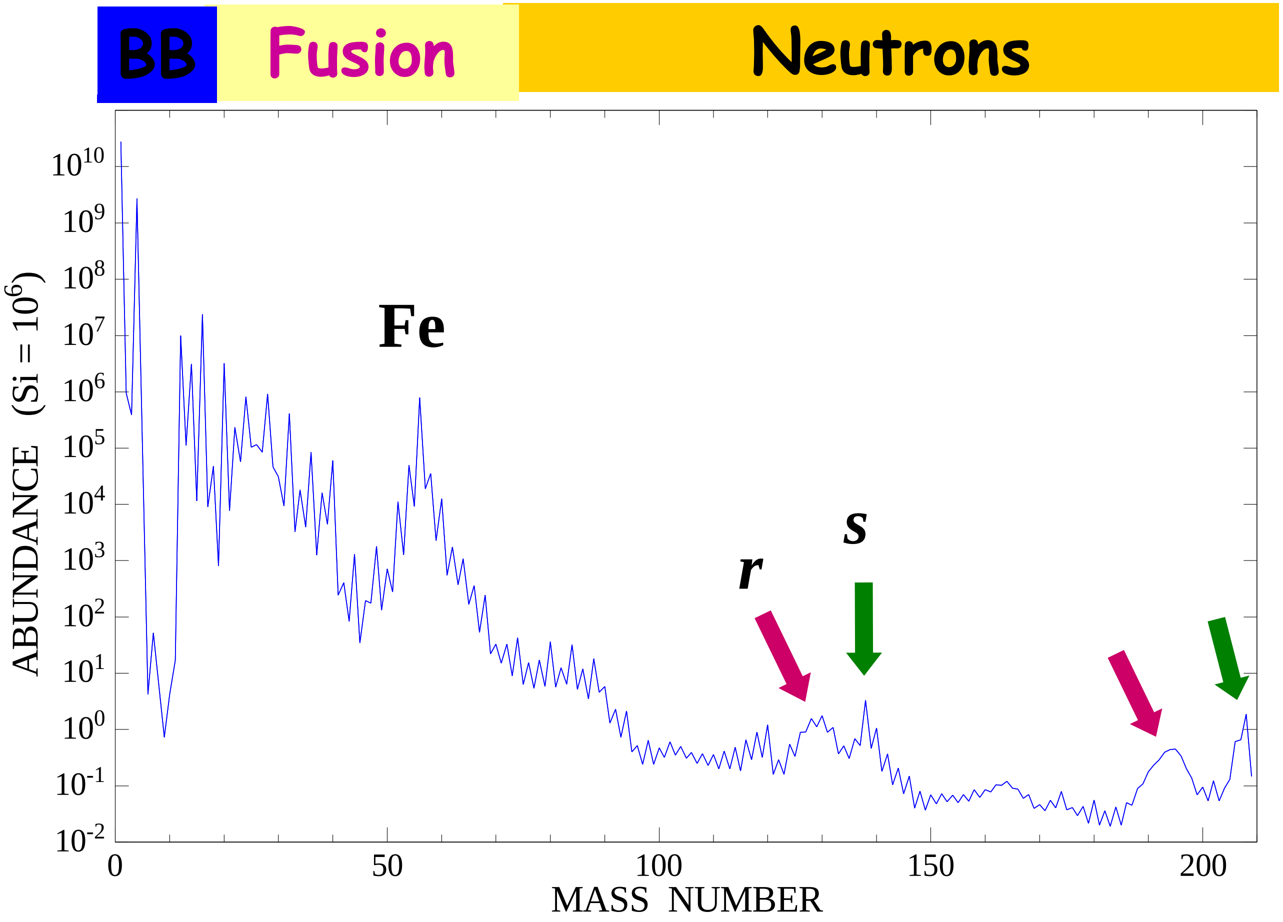
- Partitioning and transmutation of nuclear wastes should make possible to reduce both the size of the repository for nuclear wastes and the long term risk. Fission products, such as ^{93}Zr , are considered as candidates for transmutation otherwise their very long half-lives necessitate storage in a repository for extremely long times.

- Neutron capture cross section of ^{93}Zr, as well as other long-lived fission products, is required for transmutation studies, as well as for nuclear reactor design purposes.

- Formal requests have been made for 5% uncertainties on capture cross sections of ^{93}Zr.

Nuclear Astrophysics

Abundances beyond Fe–ashes of stellar burning

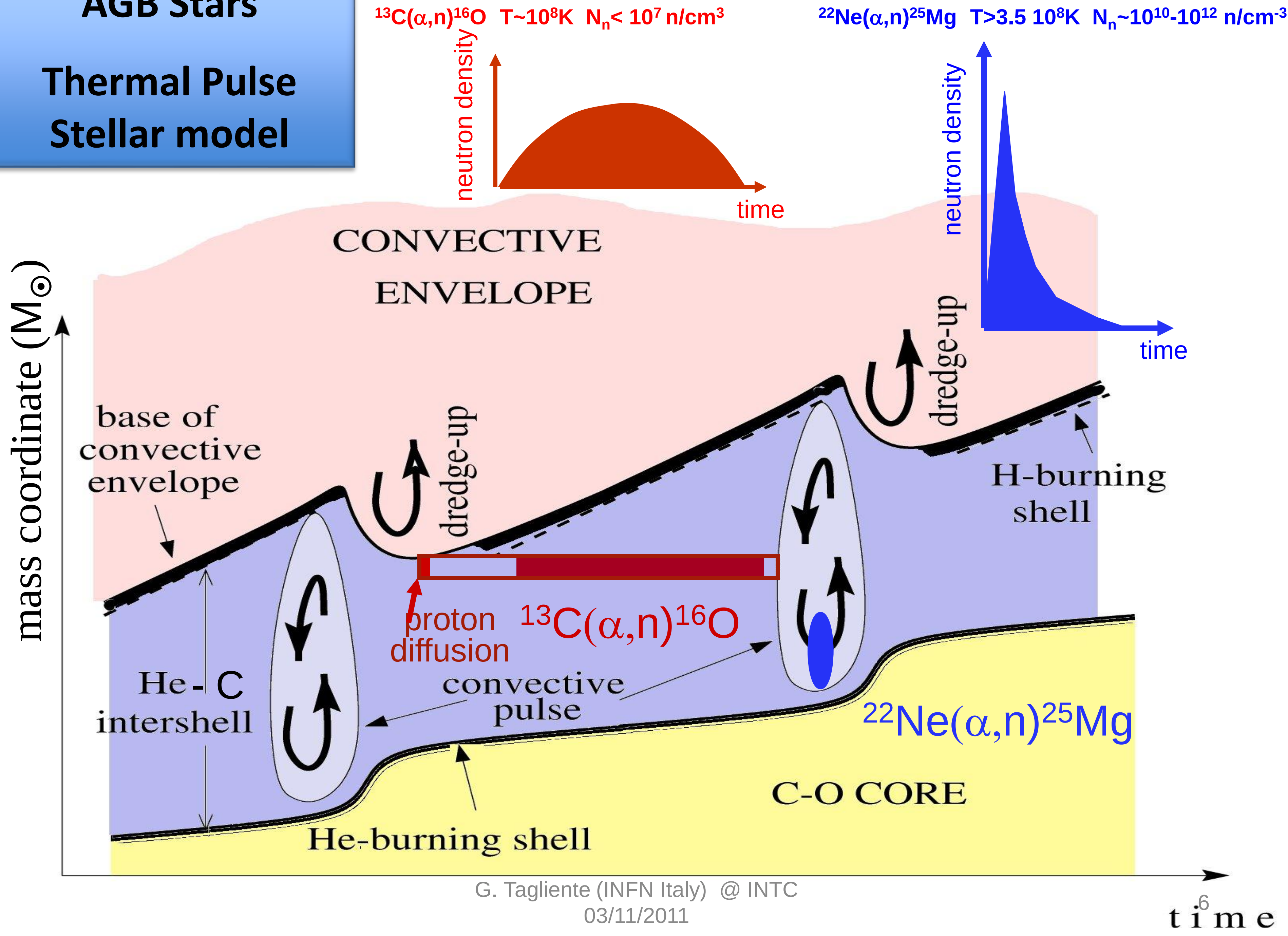


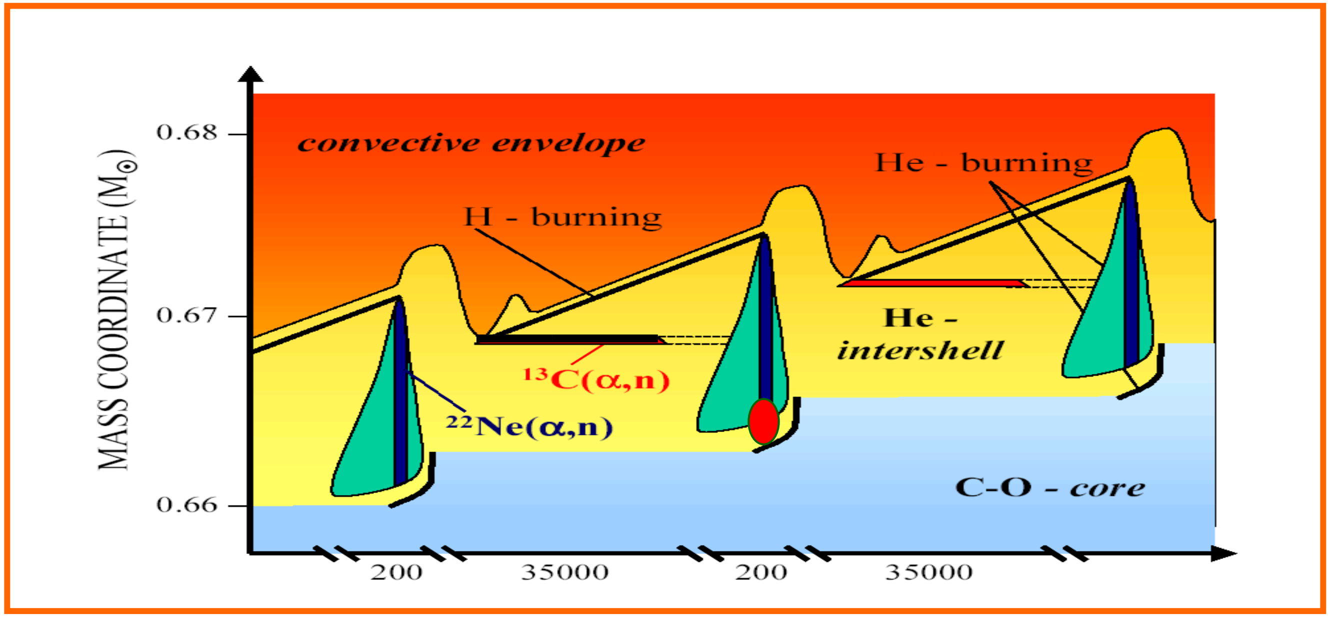
s-processes $n_n \sim 10^{10}$ n/cm^3
site: low mass AGB stars

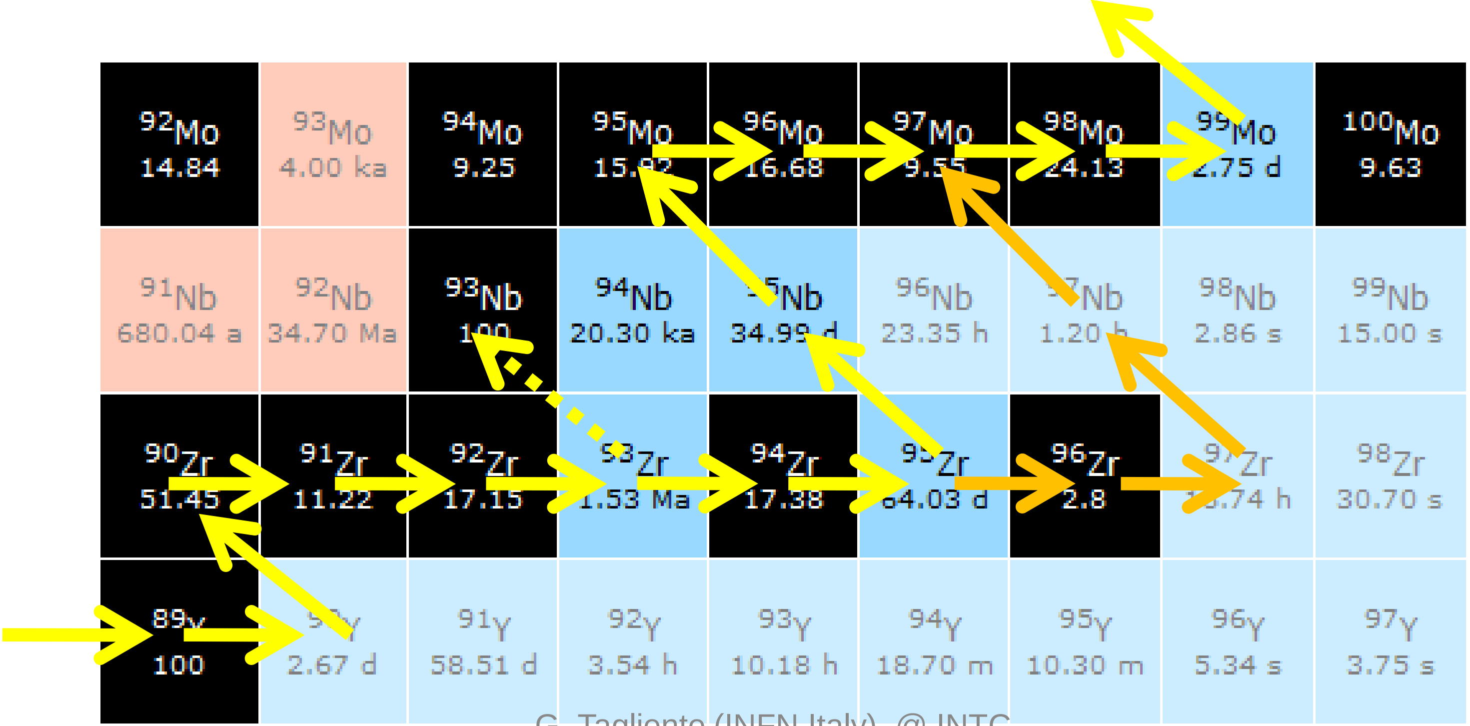
r-processes $n_n \sim 10^{22}$ n/cm^3
site: supernovae explosions

AGB Stars

Thermal Pulse Stellar model







^{92}Mo 14.84	^{93}Mo 4.00 ka	^{94}Mo 9.25	^{95}Mo 15.92	^{96}Mo 16.68	^{97}Mo 9.55	^{98}Mo 24.13	^{99}Mo 2.75 d	^{100}Mo 9.63
^{91}Nb 680.04 a	^{92}Nb 34.70 Ma	^{93}Nb 100	^{94}Nb 20.30 ka	^{95}Nb 34.99 d	^{96}Nb 23.35 h	^{97}Nb 1.20 h	^{98}Nb 2.86 s	^{99}Nb 15.00 s
^{90}Zr 51.45	^{91}Zr 11.22	^{92}Zr 17.15	^{93}Zr 1.53 Ma	^{94}Zr 17.38	^{95}Zr 64.03 d	^{96}Zr 2.8	^{97}Zr 16.74 h	^{98}Zr 30.70 s
^{89}Y 100	^{90}Y 2.67 d	^{91}Y 58.51 d	^{92}Y 3.54 h	^{93}Y 10.18 h	^{94}Y 18.70 m	^{95}Y 10.30 m	^{96}Y 5.34 s	^{97}Y 3.75 s

The Thermal Pulse Stellar model: the Zr case

There is some inconsistency using the TP stellar model to calculate the N_s abundances with values of the Zr cross sections before n_TOF.

Nucleus	$N_{\odot}$ Normalized to $N(Si)=10^6$ atoms	$N_s/N_{\odot}$
^{90}Zr	**5.546**	**0.789**
^{91}Zr	**1.21**	**1.066**
^{92}Zr	**1.848**	**1.052**
^{94}Zr	**1.873**	**1.217**
^{96}Zr	**0.302**	**0.842**

he uncertainty on the $N_{\odot}$ is 10%

he uncertainty on Zr cross sections

anges from 5% to 20% (depending on the isotopes).

here are discrepancies up to 50% on the results of some measurements

New measurements with high accuracy needed !

Zr measurements:INTC 2002-034/P163

Zr isotope samples

	Isotopic content (%)					
Sample	^{90}Zr	^{91}Zr	^{92}Zr	^{93}Zr	^{94}Zr	^{96}Zr
^{90}Zr	97.7	0.87	0.6	-	0.67	0.16
^{91}Zr	5.43	89.9	2.68	-	1.75	0.24
^{92}Zr	4.65	1.62	91.4	-	2.03	0.3
^{93}Zr*	*1.5*	*19.0*	*20.0*	*20.0*	*20.0*	*19.0*
^{94}Zr	4.05	1.18	1.93	-	91.8	1.04
^{96}Zr	19.41	5.21	8.2	-	8.68	58.5

Admixture: Hf, Na, Mg, Al ...

* Radio isotope ($T_{1/2}$ =1.5x10^{6} year)

Zr measurements:INTC 2002-034/P163

	^{90}Zr	^{91}Zr	^{92}Zr	^{93}Zr	^{94}Zr	^{96}Zr	^{197}Au	Pb
Mass (g)	2.717	1.404	1.349	4.88	2.015	3.398	1.871	3.895
Thickness (cm)	0,127	0,065	0,062	0,37	0,091	0,151	0.025	0.09
Chemical form	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2	Metal	Metal
Enrichment (%)	97.7	89.9	91.4	*20.0*	91.8	58.5	100	Nat.

Samples 2.2 cm in diameter, 1 mm thick
Stable Zr isotopes encapsulated in 0.2 mm Al can
^{93}Zr isotope encapsulated in 0.2 mm Al + 0.2 mm Ti

Chemical form:ZrO_2

^{93}Zr isotope activity 92.5 MBq

Zr (INTC 2002-034/P163) publications

Neutron capture cross section of ^{90}Zr: bottleneck in the s-process reaction flow: G. Tagliente et al., PRC 77(2008)

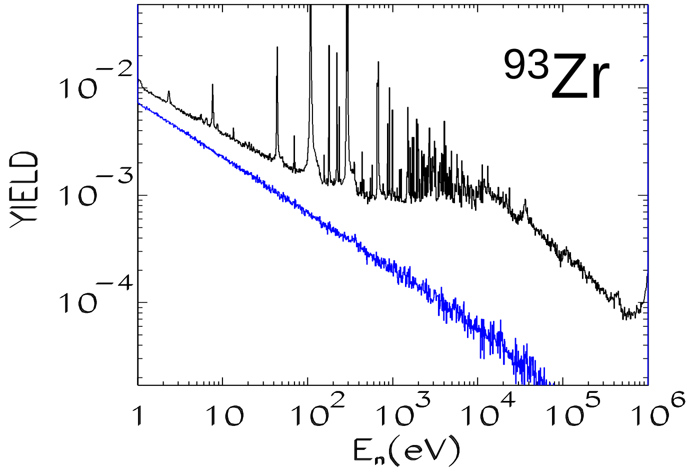
Study of the ^{91}Zr(n, γ) reaction up to 26 keV: G. Tagliente et al., PRC 78(2008)

The ^{92}Zr(n,γ) reaction and its implications on stellar nucleosynthesis: G. Tagliente et al., PRC 81(2010)

Neutron capture on ^{94}Zr: Resonance parameters and Maxwellian-averaged cross sections: G. Tagliente et al., PRC 84(2011)

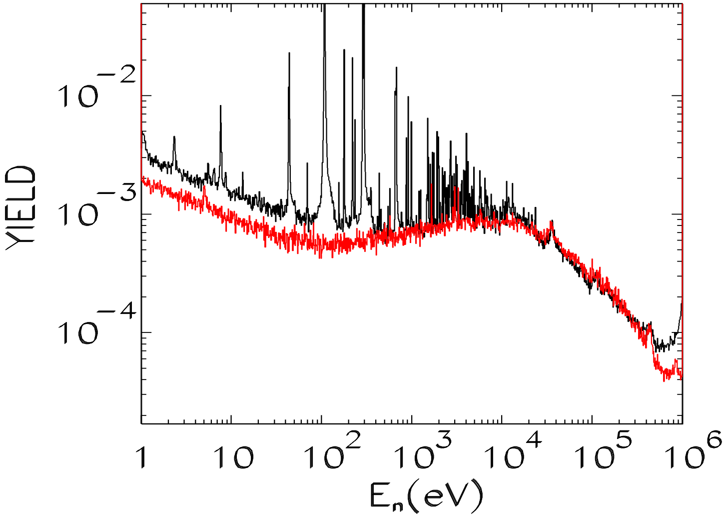
^{96}Zr(n, γ) measurement at the n_TOF facility at CERN: G. Tagliente et al., PRC accepted

Results - ^{93}Zr yield



raw Yield

Natural radioactivity of the sample

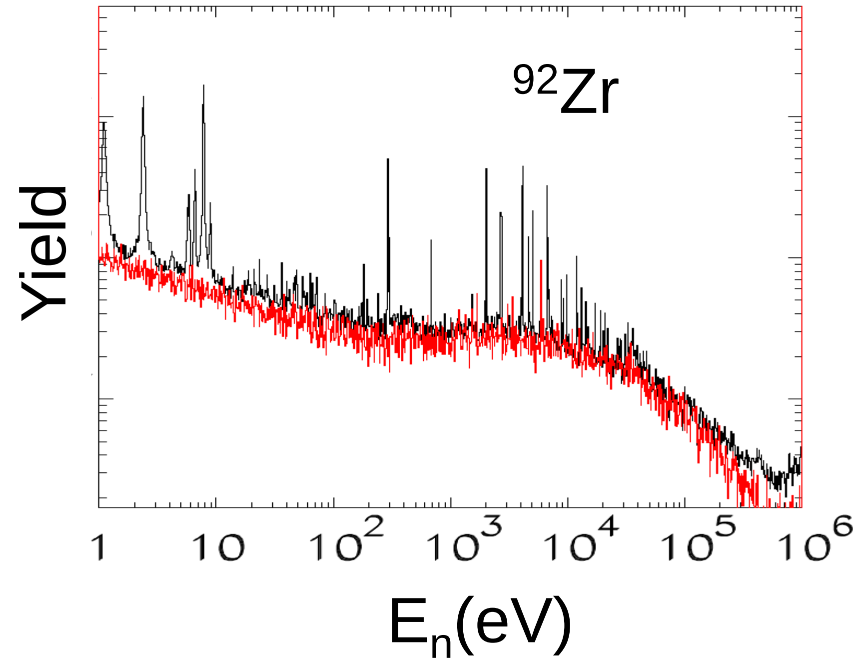


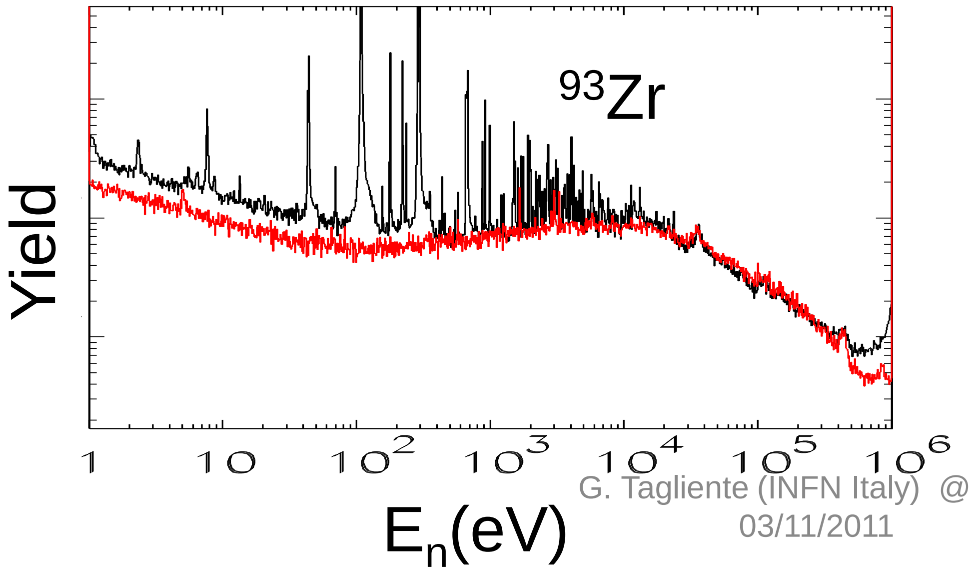
Yield – nat. radioactivity of the sample

overall background

Results : MACS & experimental energy ranges

Maxwellian Averaged Cross Sections(MACS)



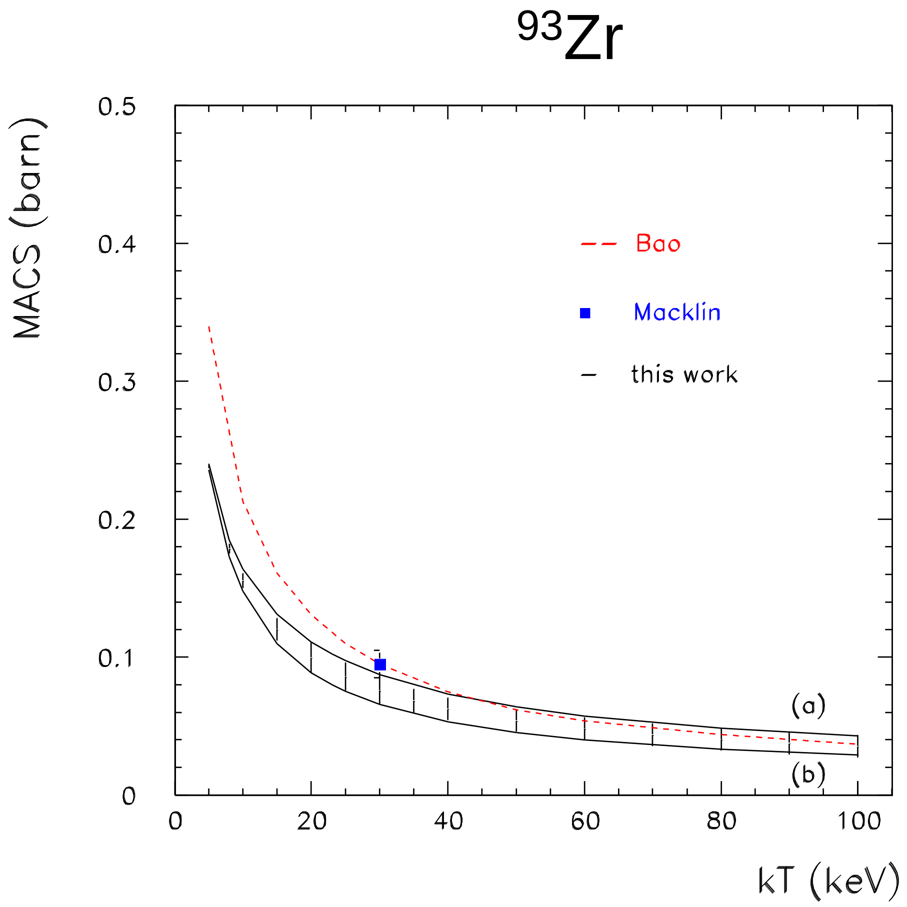


	Energy range (keV) **n_TOF**
^{90}Zr	0.01 - 66
^{91}Zr	0.01 - 26
^{92}Zr	0.01 – 40
^{93}Zr	**0.01 – 8**
^{94}Zr	0.01 – 60
^{96}Zr	0.01 – 37

The n_TOF data have to be complemented with a data library Jendl 3.3 and ENDF IV

MACS: results

The ^{93}Zr cross sections measured at n_TOF are 35% lower than the previous measurements

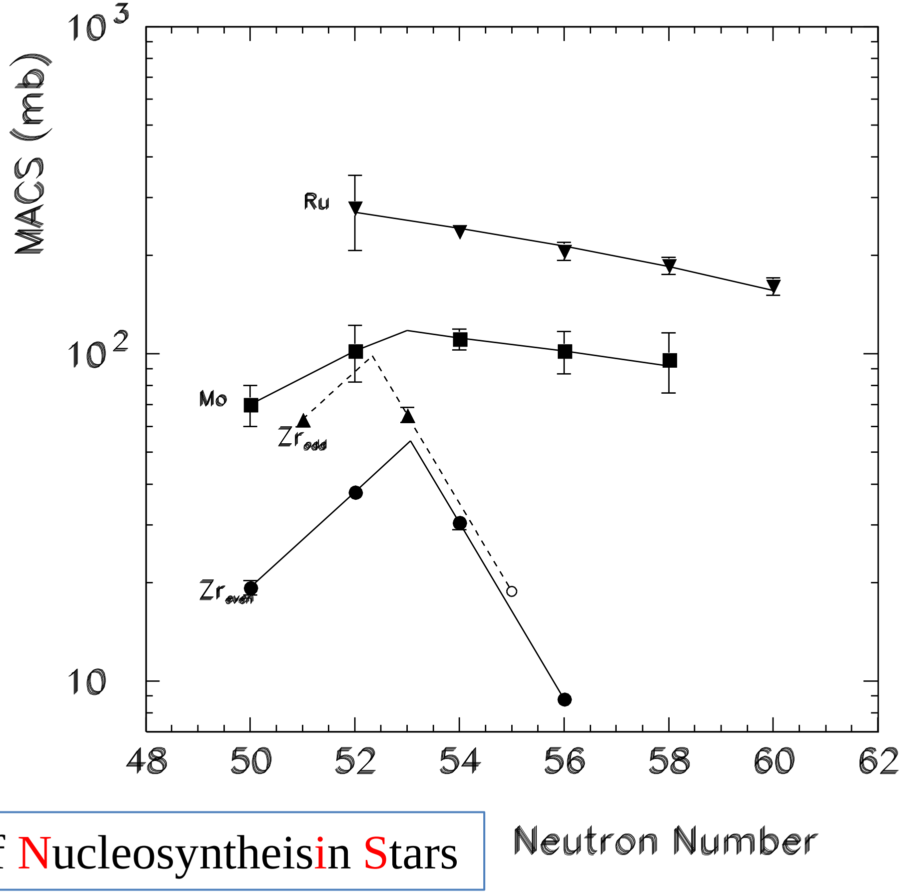


Prelimiary

MACS:@ 30 keV

MACS in mbarn

Isotope	KADoNiS	n_TOF
^{90}Zr	21 ± 2	19.3 ± 0.9
^{91}Zr	60 ± 8	63 ± 4
^{92}Zr	34 ± 6	38 ± 3
^{93}Zr	95 ± 10	**65.1 ± 3**
^{94}Zr	26 ± 1	30.5 ± 2
^{95}Zr	79	**18.9 ± 0.9**
^{96}Zr	10.7 ± 0.5	8.9 ± 0.5



KADoNIS: Karlsruhe Astrophysical Database of Nucleosyntheisin Stars

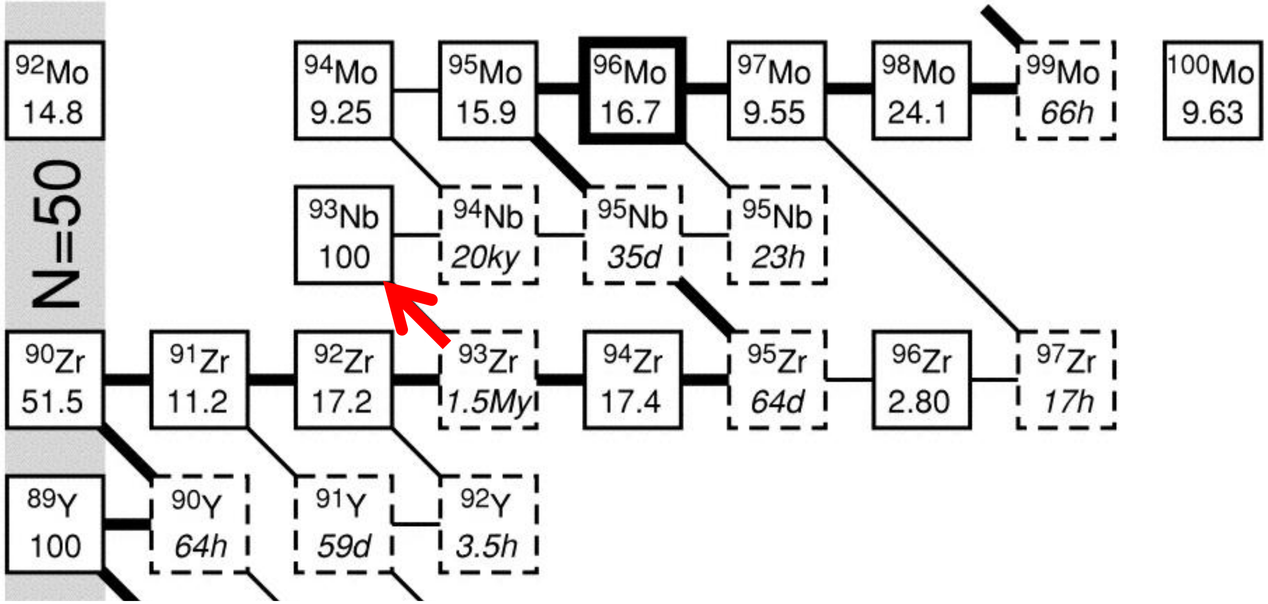
Astrophysical implication: Abundances

Nucleus	$N_\odot$ Normalized to $N(Si)=10^6$ atoms	$N_s/N_\odot$ % Old MACS	$N_s/N_\odot$ % n_TOF MACS
^{90}Zr	5.546	0.789	0.844
^{91}Zr	1.21	1.066	1.024
^{92}Zr	1.848	1.052	0.981
^{94}Zr	1.873	1.217	1.152
^{96}Zr	0.302	0.842	0.321

Solar abundances, $N_\odot$, from Lodders 2009, accuracy 10%

The s-abundances, N_s, are calculated using the TP stellar model for low mass AGB star (1.5 - 3 $M_\odot$), accuracy 8%.
Old MACS are from the KADoNiS data base 2008. Since 2009 the databases has been update at the new n_TOF data, as the new data are relased.

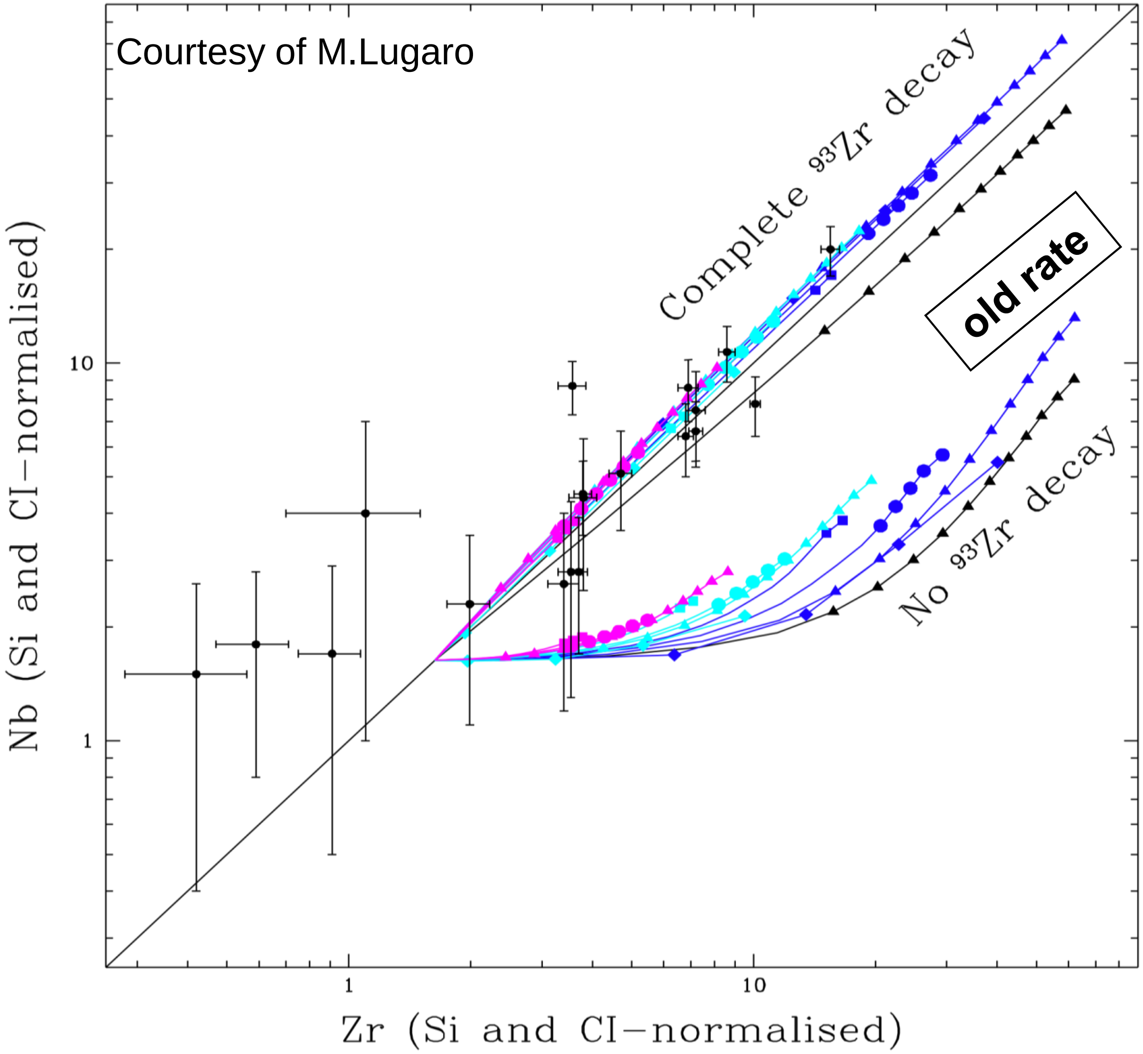
Astrophysical implication: Zr/Nb



A lower ^{93}Zr(n,γ) value means that more ^{93}Zr is produced. After radiogenic decay of ^{93}Zr more Nb will result.

The final result is ~50% more Nb!

Elemental Nb and Zr abundances in SiC


Courtesy of M.Lugaro

Mass, Metallicity

◇ 1.8, 0.01 ~ 0.7 $Z_\odot$

△ 3, 0.01 ~ 0.7 $Z_\odot$

○ 3, 0.02 ~ 1.5 $Z_\odot$

□ 3, 0.03 ~ 2 $Z_\odot$

$M_{mix}(M_\odot)$

🟦 0.002

🟩 0.0005

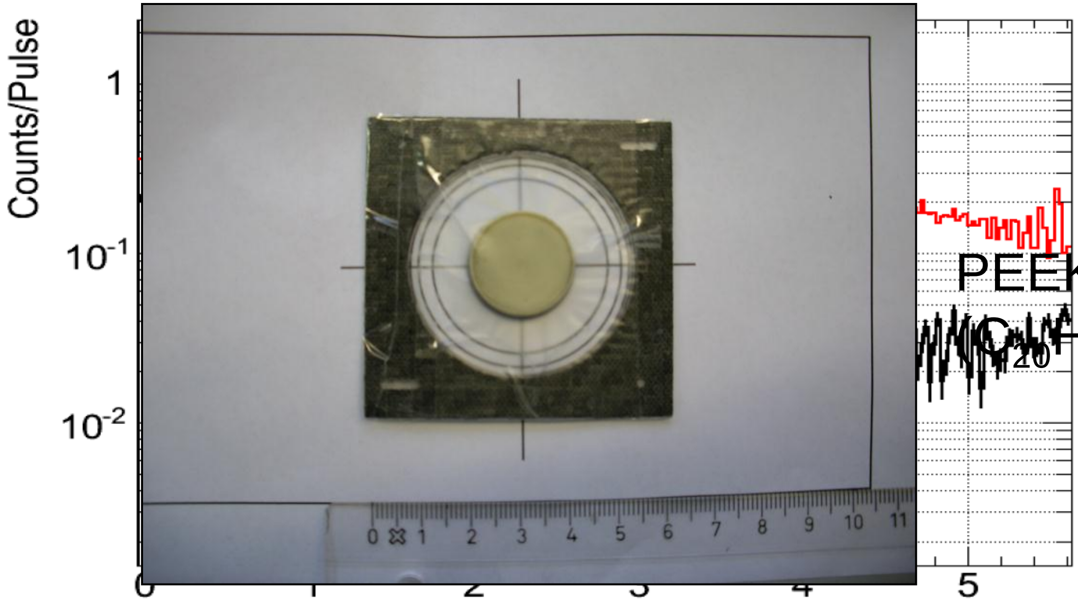
🟪 0.0002

With the new ^{93}Zr(n,γ) cross section the problem is solved.

BUT!!!

The data, specially for the ^{93}Zr, have to be confirmed with new data in a wider neutron energy range

New ^{93}Zr capture measurement @ n_TOF

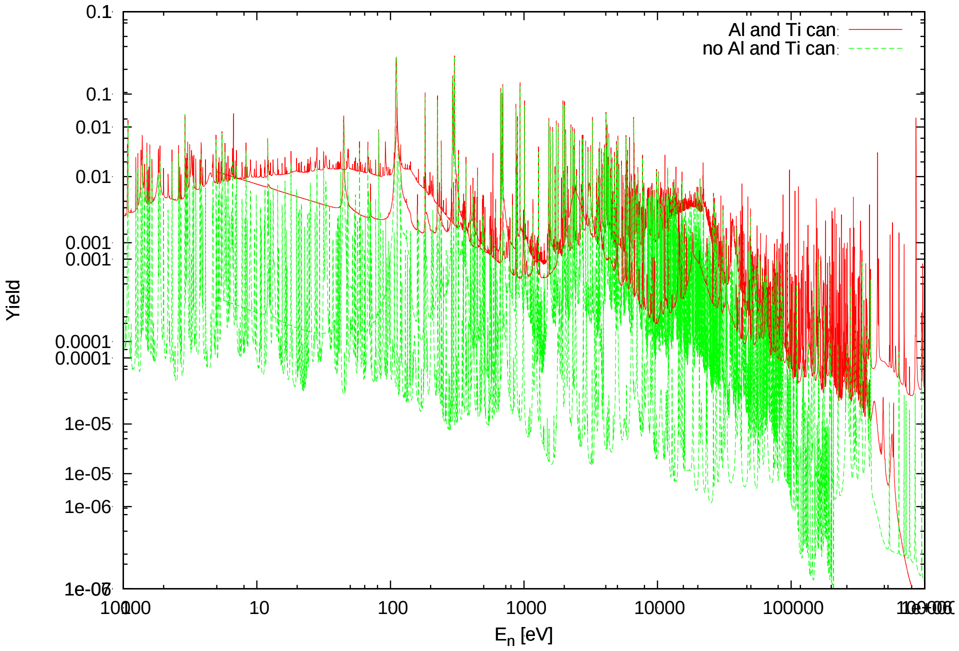


2009 ne H_3BO_3):
lower bac

PEEK container ($C_{20}H_{12}O_3$)

2010 Up r of class A:
easier to ^{63}Ni measurement (CERN-INTC 2010-067/INTC-P-283)

New ^{93}Zr capture measurement @ n_TOF



New ^{93}Zr capture measurement @ n_TOF

- Detectors: C_6D_6
- Samples
  - ^{93}Zr
  - Pb, empty ^{93}Zr container: background
  - Au, ^{92}Zr : normalization

- Goal: extend the measured cross section up to En ≈ 100 keV with an accuracy < 5%

- Number of protons required : 3×10^{18}