First Measurement of the $^{64}Ni(\gamma,n)^{63}Ni$ Cross Section

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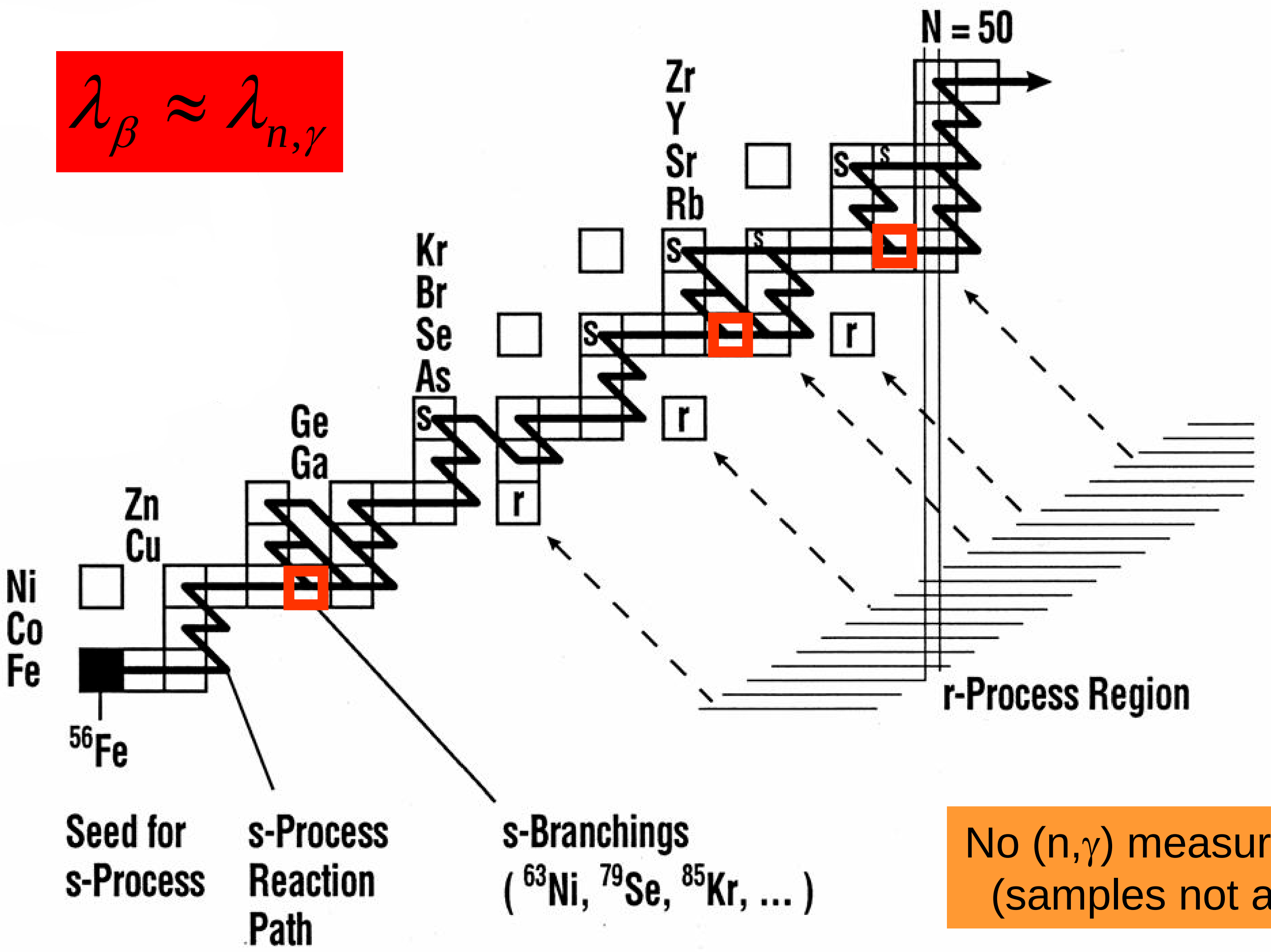
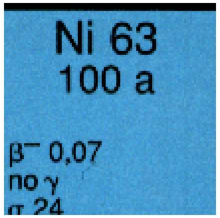
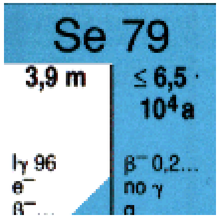
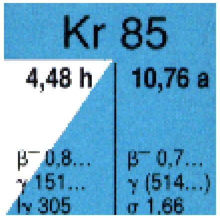
The weak s process and its branching points

$\lambda_\beta \approx \lambda_{n,\gamma}$



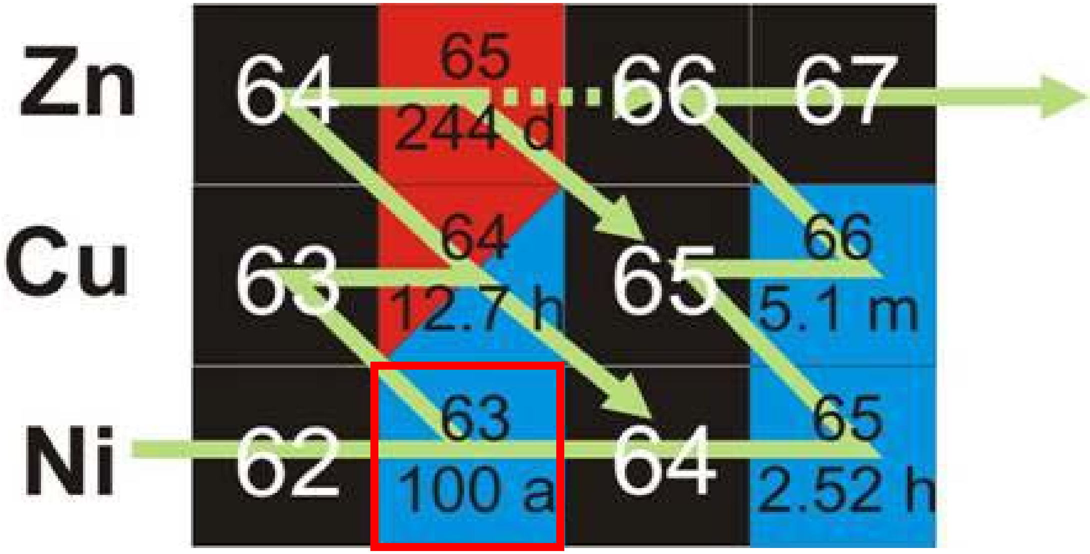






No (n,γ) measurement yet
(samples not available)

Branching ratio



$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n}$$

Branching ratio

f_β~0 : neutron capture
f_β~1: beta decay

Branchings can be
- neutron density monitors or
- stellar thermometers

But: temperature-dependence of $t_{1/2}$ and cross section should be known!

^{63}Ni: first branching ⇨ low cross section, bottleneck!

Propagation effects

Weak s-process

No equilibrium ($\sigma \cdot N_s \neq$ const.):
sensitive to low xs (<150 mb)
⇨**“propagation effects”** up to A~90

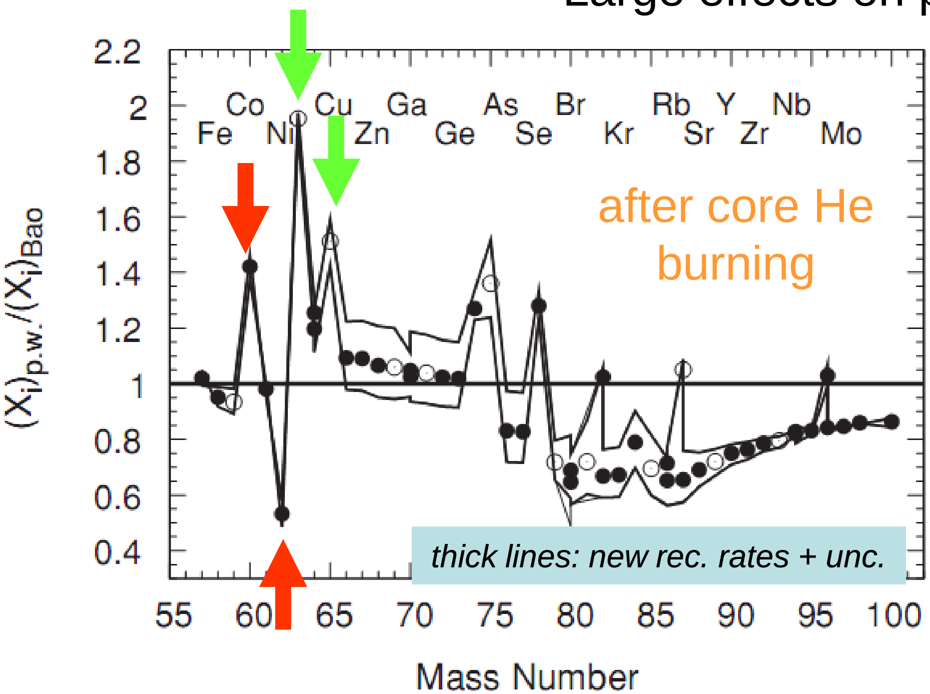
^{60}Ni(n,γ): -16% (Corvi et al, 2002)

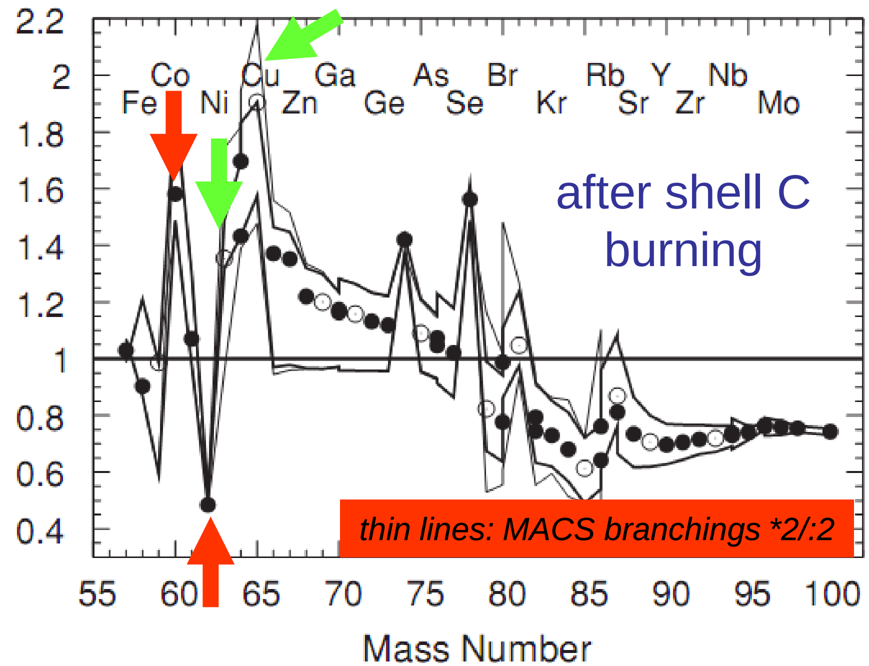
^{62}Ni(n,γ): +88% (Nassar et al. 2005, Walter 2008, Alpizar-Vicxente et al. 2008)

^{63}Cu(n,γ): -40% (Heil et al. 2008)

^{65}Cu(n,γ): -27% (Heil et al. 2008)

Large effects on production factors:

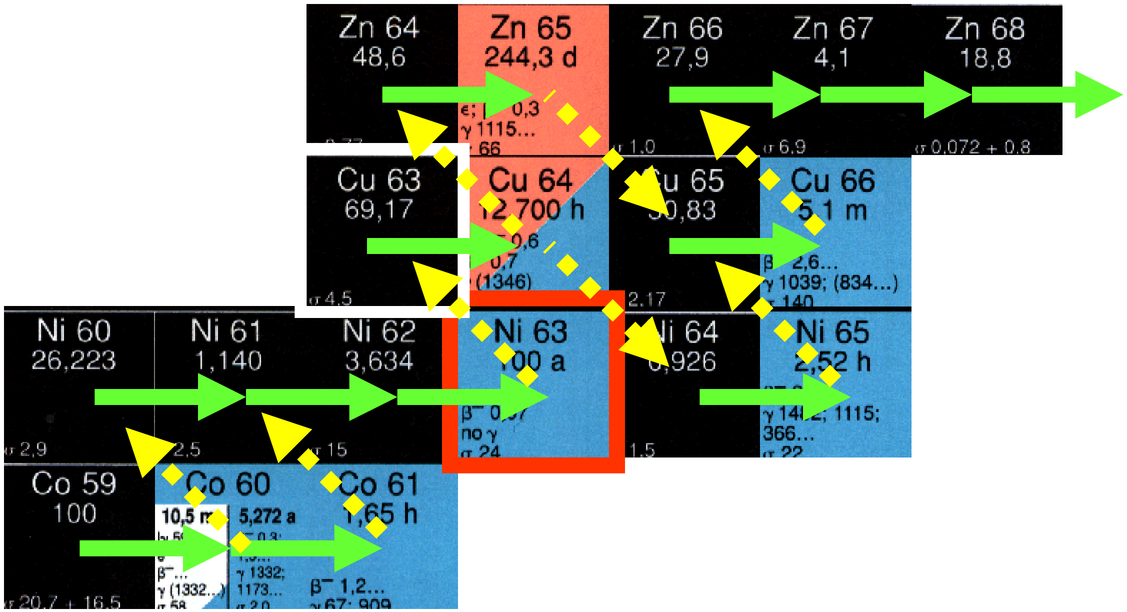




M. Pignatari et al., ApJ 710 (2010) 1557
Z.Y. Bao et al., ADNDT 76 (2000) 1

Reaction paths

During core He burning: mean $n_n = 1.1 \cdot 10^6$ cm^{-3}



- **f_β=0.91** ⇨ β-decay to ^{63}Cu
- Change in ^{63}Ni(n,γ)^{64}Ni MACS has **no influence**

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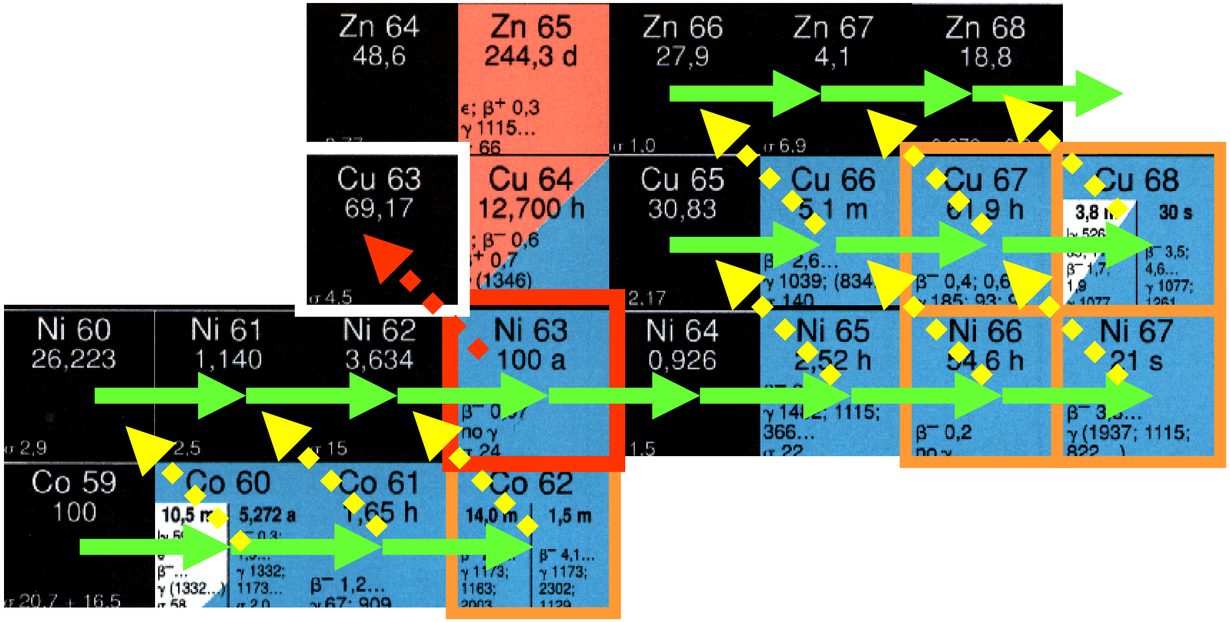
Reaction paths

During shell C burning: mean $n_n=(2.0 – 50)\cdot 10^{11}$ cm^{-3}



- **f_β=0.02** ⇨ ^{63}Ni(n,γ)^{64}Ni dominates and has influence on reaction flow
- ^{63}Cu produced (significantly) by radiogenic decay
- Amount of ^{63}Cu depedent on ^{63}Ni(n,γ) cross section (low: bottleneck)

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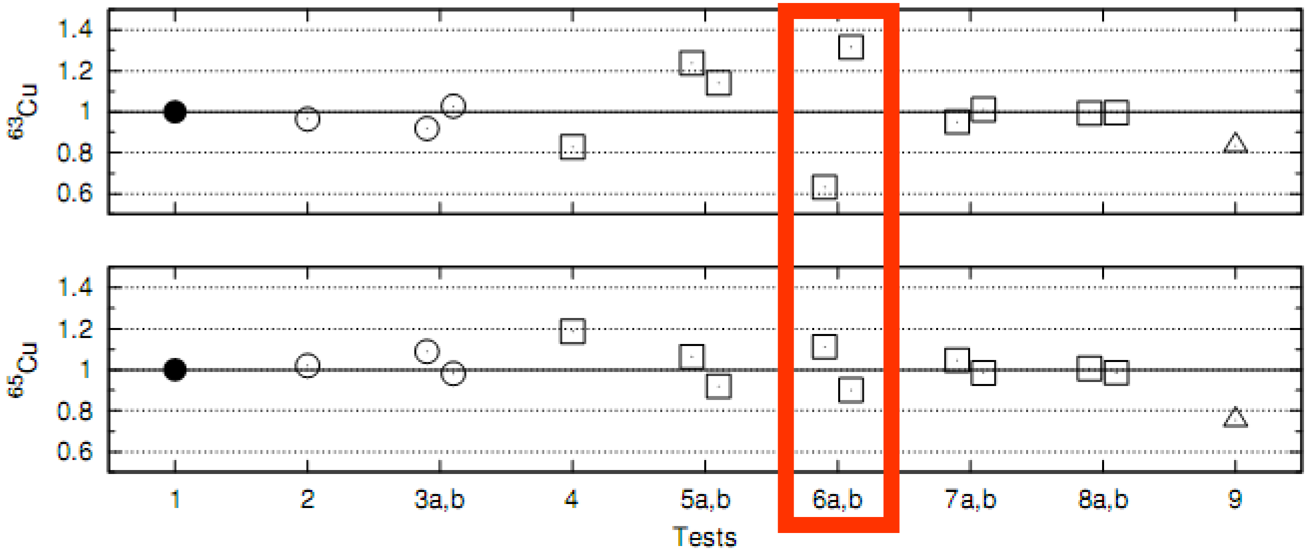
Influence on production of $^{63,65}Cu$



1: Standard case
2: constant T
3a: C shell burning T=1.0 GK
3b: C shell burning T=1.1 GK
4: $^{22}Ne(\alpha,n)^{25}Mg$ (NACRE)

5a,b: New MACS of $^{63,65}Cu$
6a: $^{63}Ni(n,\gamma)^{64}Ni$: MACS *2
6b: $^{63}Ni(n,\gamma)^{64}Ni$: MACS :2
7a,b: $t_{1/2}(^{63}Ni)$ *2 and :2
8a,b: MACS of $^{64}Cu(n,\gamma)$ *2 and :2
9: Solar abundances by Lodders (2003)

„The $^{63}Ni(n,\gamma)^{64}Ni$ MACS is crucial for the s abundance of ^{63}Cu… An experimental determination of the ^{63}Ni MACS is required for a further improvement of the abundance prediction of copper."

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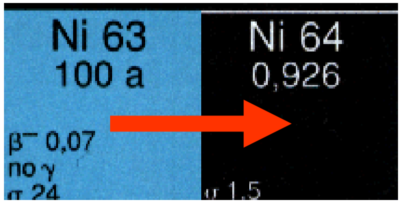
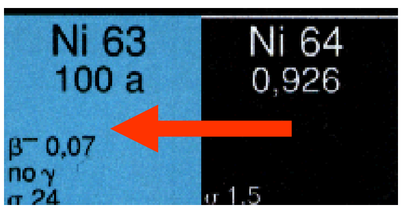
Theoretical predictions: $^{63}Ni(n,\gamma)$ and $^{64}Ni(\gamma,n)$

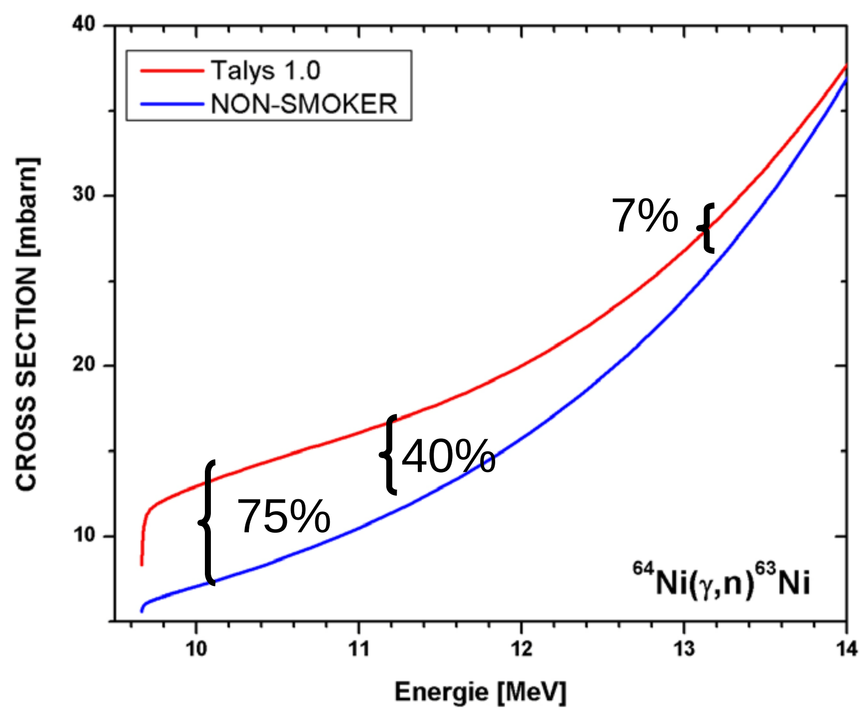


Stellar neutron capture cross section at kT=30 keV

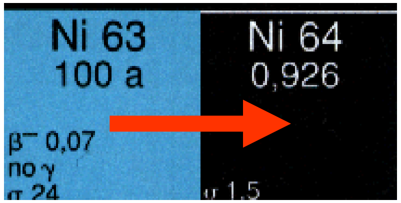
Bao et al. comp. (2000):	$<\sigma>_{30keV}$= 31 (6) mbarn
Woosley (1978):	$<\sigma>_{30keV}$= 24 mbarn
NON-SMOKER (2000):	$<\sigma>_{30keV}$= 34 mbarn
MOST (2005):	$<\sigma>_{30keV}$= 42 mbarn



E_{thresh}=9.659 MeV

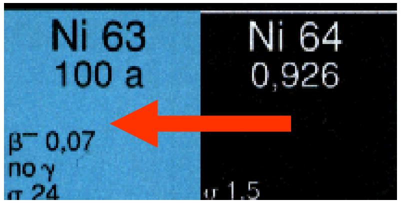


Experimental status $^{63}Ni(n,\gamma)$ and $^{64}Ni(\gamma,n)$



• Thermal cross section: σ_{th}=24.4 ± 3.0 barn

• „Stellar“ cross section:
TOF measurement at DANCE in Los Alamos performed in November 2009, analysis in progress

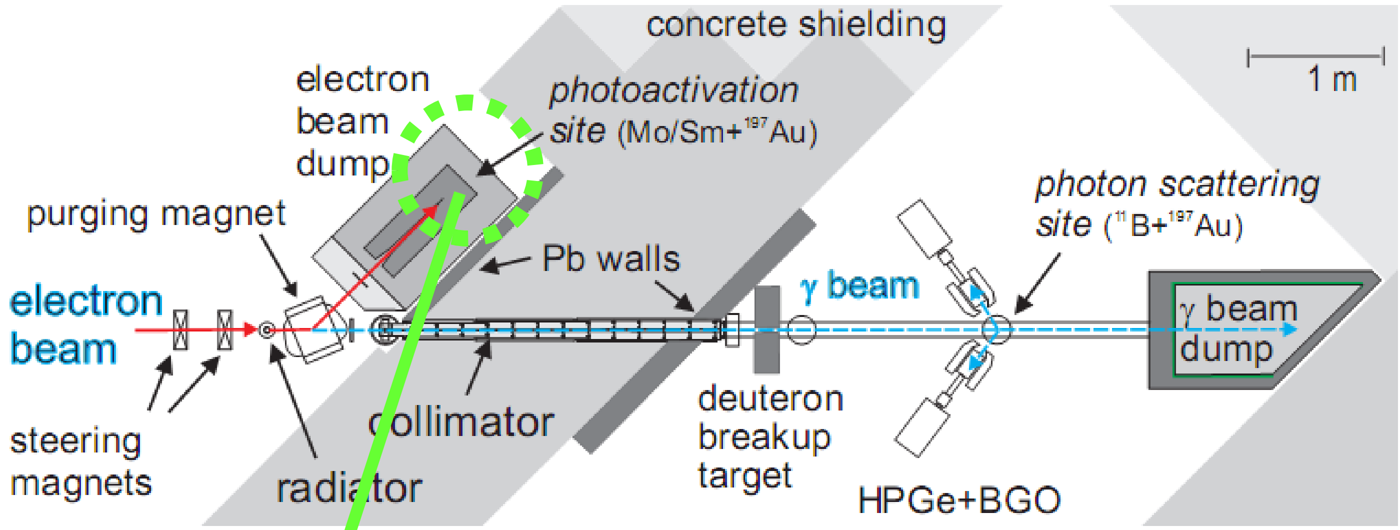


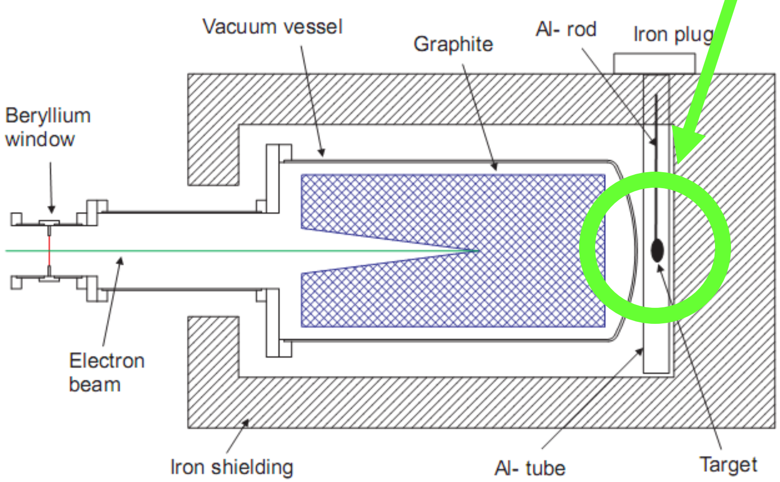
Photodissociation:

NO DATA!

Activation: $^{64}Ni(\gamma,n)^{63}Ni$ at ELBE

Electron
Linac of high
Brilliance and low
Emittance
at FZ Dresden-Rossendorf

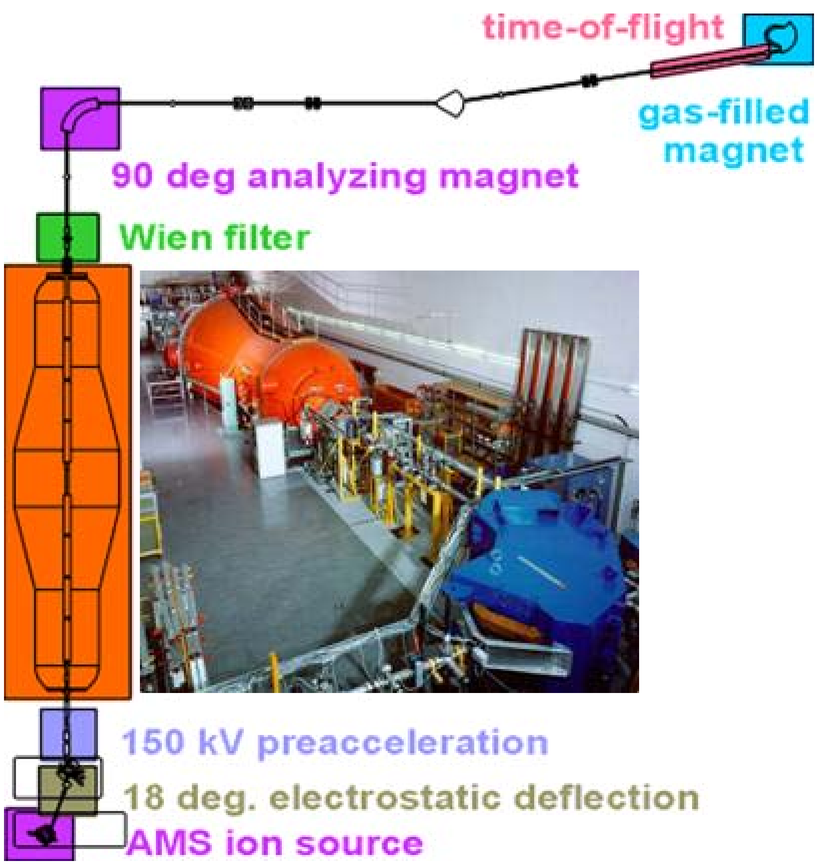


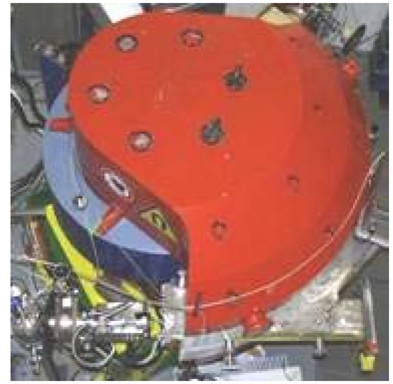


- Enriched ^{64}Ni samples
- 3 activations: E_0= 10.3 MeV (84h), 11.5 MeV (17h), and 13.4 MeV (18h)
- Photon flux: $\Phi_\gamma \sim 10^{10}$ s^{-1} cm^{-2} MeV^{-1}
- Endpoint energy via D breakup
- Absolute photon flux via $^{11}B(\gamma,\gamma')$
- Relative photon flux via $^{197}Au(\gamma,n)$

Measurement: ^{63}Ni at the AMS facility in Garching

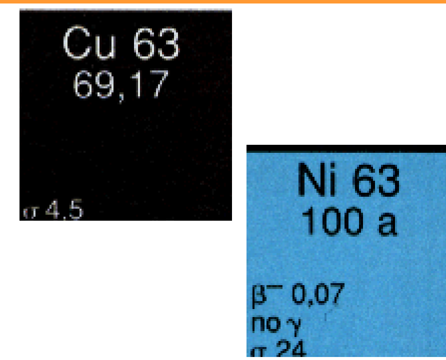
14 MV MP Tandem + GAMS: Ultrasensitive detection of long-lived radionuclides

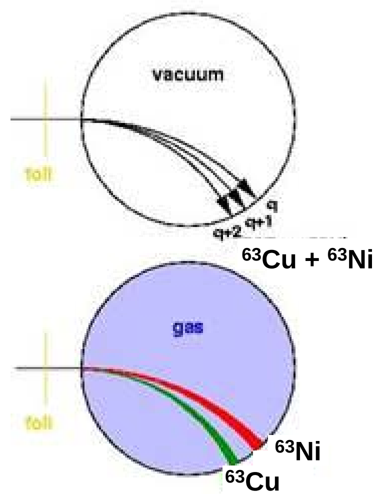




^{63}Ni/Ni ratios down to 10^{-14}

Suppression factor of stable ^{63}Cu: 10^9





Isobaric separation in **Gas-filled Analyzing Magnet System**

Detection in multi-ΔE ionization chamber

Preliminary results: $^{64}Ni(\gamma,n)^{63}Ni$

Sample 1 (E_0= 13.4 MeV):

$^{63}Ni/^{64}Ni$= $\mathbf{(1.5 \pm 0.4)\cdot 10^{-12}}$

previous measurement: $^{63}Ni/^{64}Ni = (1.1^{+0.5}_{-0.4})\cdot 10^{-12}$

Ph.D. thesis S. Walter, Universität Karlsruhe (2008)

Background = $8.1\cdot 10^{-14}$

Sample 2 (E_0= 11.5 MeV):

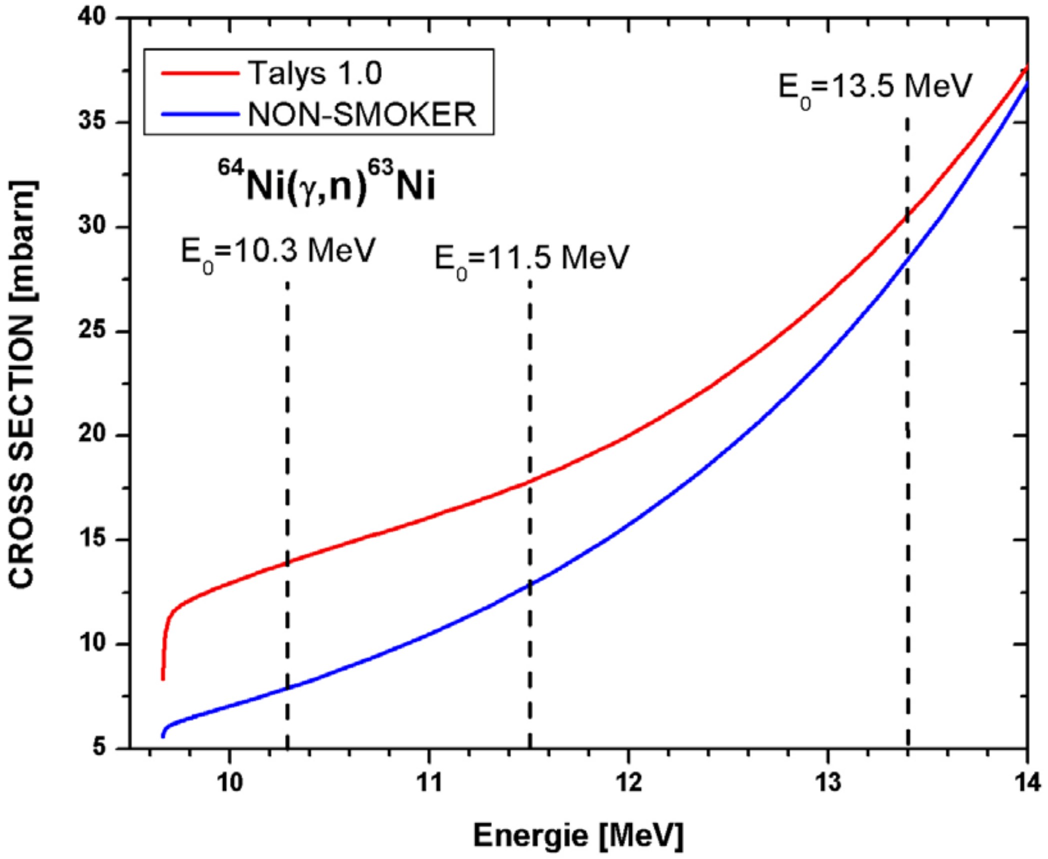
$^{63}Ni/^{64}Ni$ = $\mathbf{(3.7 \pm 2.1)\cdot 10^{-13}}$

Background < $1.35\cdot 10^{-13}$

Sample 3 (E_0= 10.3 MeV): analysis in progress

Background ~10^{-12} ☹

Preliminary results: $^{64}Ni(\gamma,n)^{63}Ni$



$k_{norm} = Y_{act}(AMS)/Y_{act}(theo)$

Talys

k_{norm}(13.4 MeV)= 0.21 ± 0.06

k_{norm}(11.5 MeV)= 0.33 ± 0.19

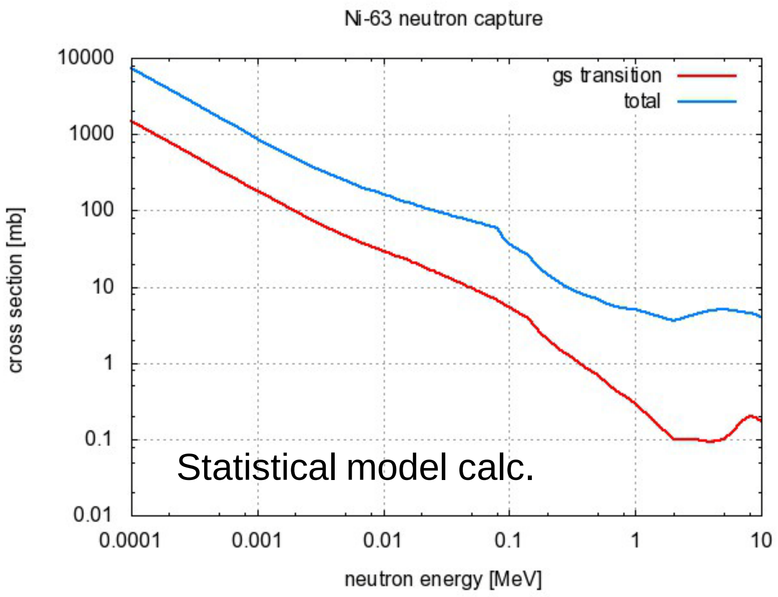
⇨ Better agreement with NON-SMOKER: PhD S. Walter: $k_{norm}=0.45\ (^{+0.20}_{-0.16})$ for E_0=13.4 MeV

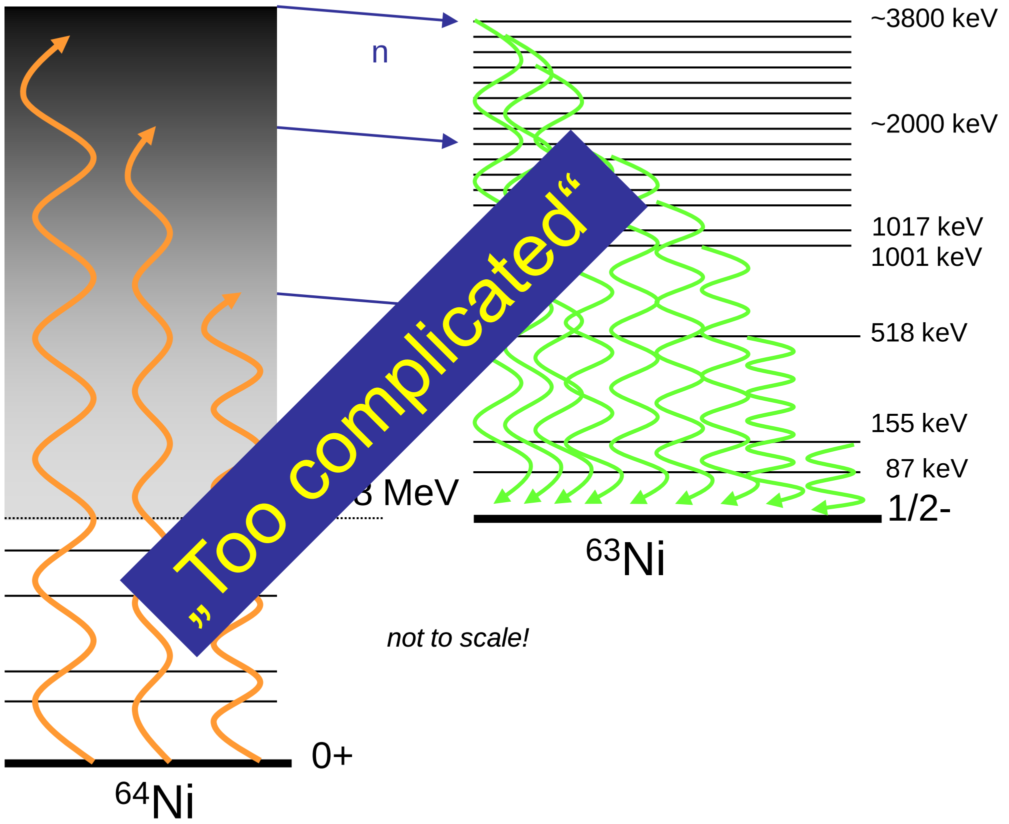
To do: E_0=10.3 MeV sample

First time combination of photoactivation and AMS

First measurement of $^{64}Ni(\gamma,n)^{63}Ni$ cross section

What can we deduce for $^{63}Ni(n,\gamma)$?



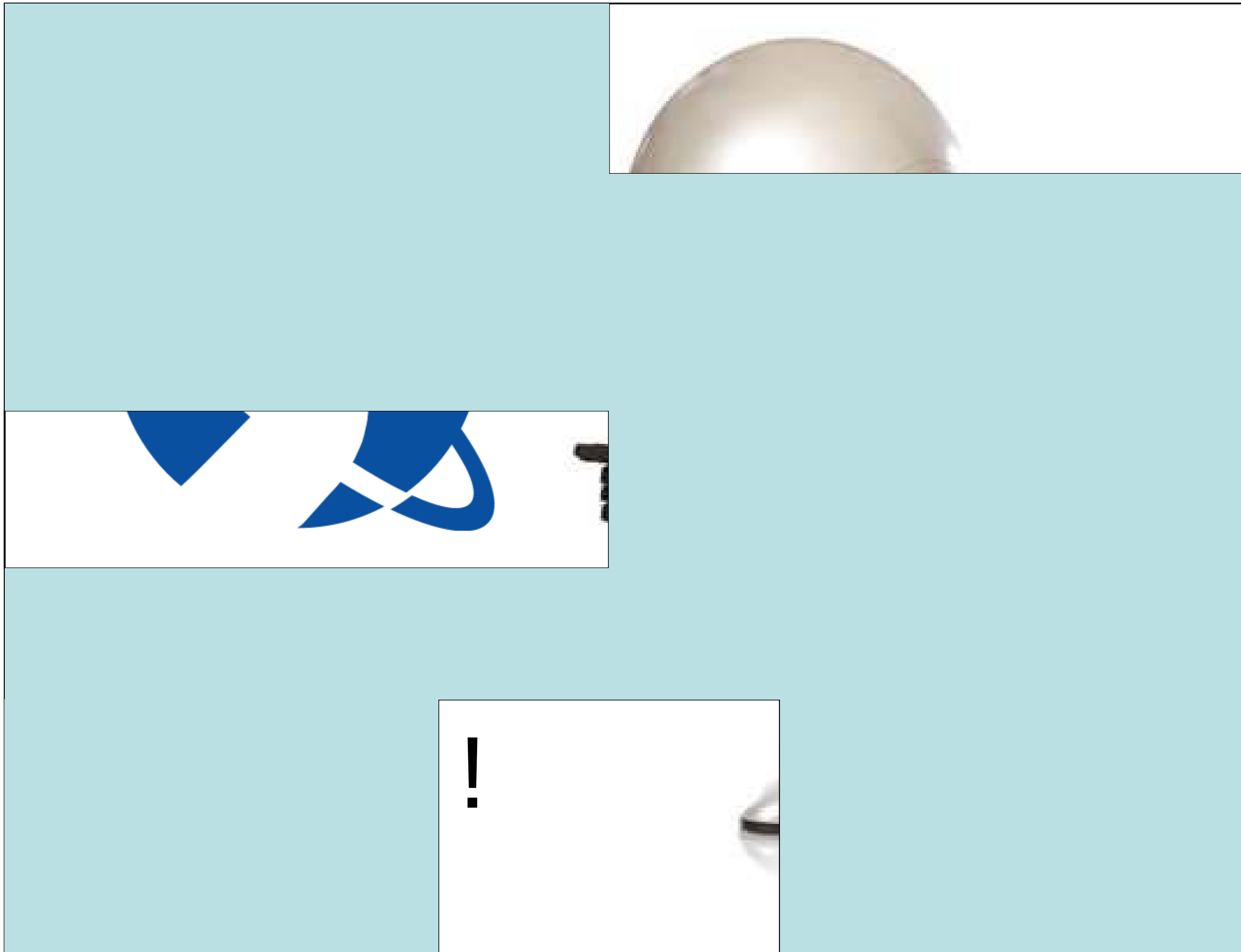


Ratio g.s./total @ 30 keV ~ 15%

Experimental information from the (γ,n) on ^{64}Ni is still valuable because the HFSM calculation need to be normalized

$^{63}Ni(n,\gamma)^{64}Ni$: What we knew before

$^{64}Ni(\gamma,n)^{63}Ni$: What we have measured



not to scale!

How theory can help us

not to scale!

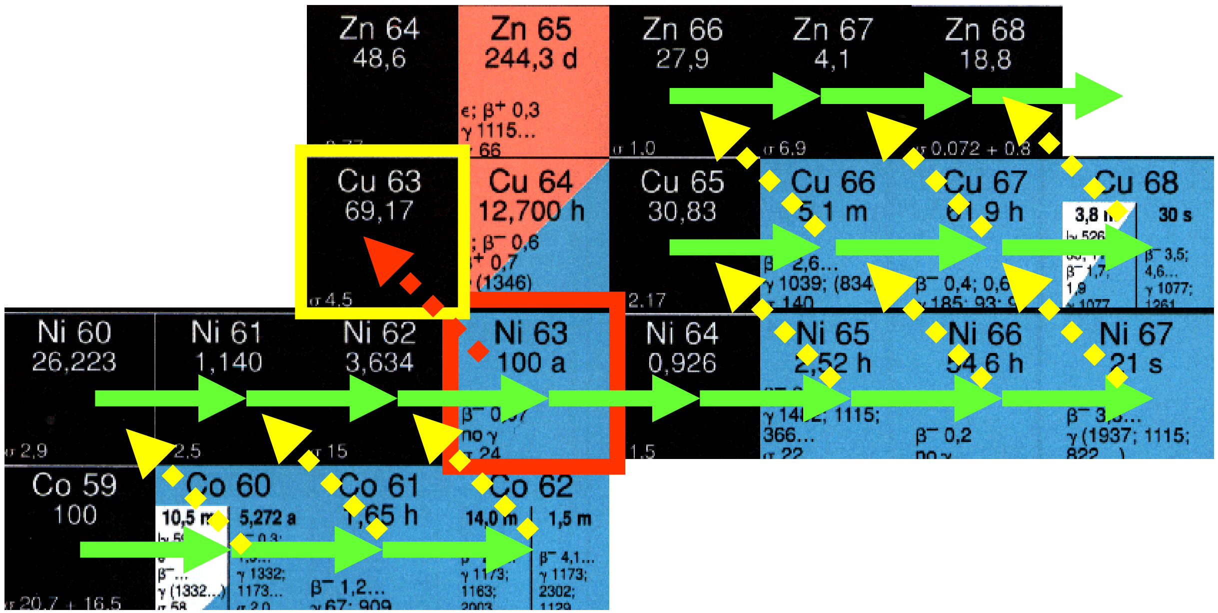
But the full picture needs the direct way: $^{63}Ni(n,\gamma)$

not to scale!

If ^{63}Ni(n,γ)^{64}Ni is lower than predicted...

Consequences for the weak s-process reaction flow

- During core He burning: no influence (β-decay to ^{63}Cu)
- During shell C burning:



- Lower ^{63}Ni(n,γ)^{64}Ni ⇨ another bottleneck, influence on all heavier isotopes up to A=90 (propagation effect)

⇨ More ^{63}Cu and less ^{65}Cu:

if ^{63}Ni(n,γ) :2

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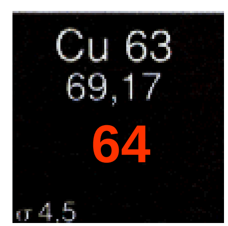
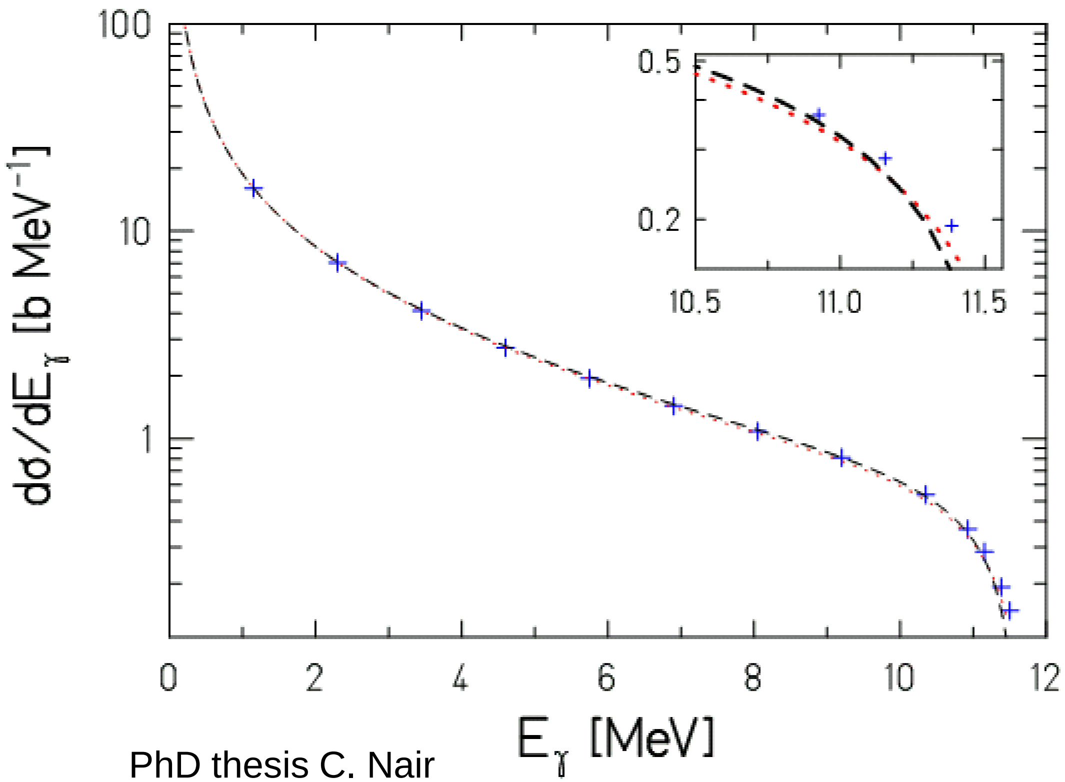


Activation yield

$$Y_{\mathrm{act}}(\mathrm{Sm}) = \Phi_\gamma(E_\gamma^{\mathrm{X}}, E_0) \cdot \int_{E_{\mathrm{thr}}}^{E_0} \sigma_{\gamma,\mathrm{x}}^{sim}(E) \cdot \frac{\Phi_\gamma^{\mathrm{sim}}(E_\gamma, E_0)}{\Phi_\gamma^{\mathrm{sim}}(E_\gamma^{\mathrm{X}}, E_0)}\, dE$$

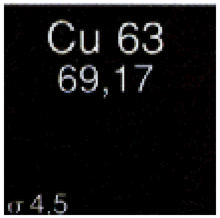
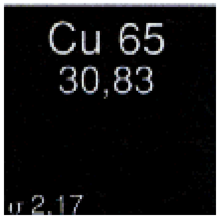
normalization to fluence at 7.29 MeV and 8.9 MeV



PhD thesis C. Nair

$$Y_{act}(AMS) = \frac{^{63}Ni}{^{64}Ni} \frac{10^{24}}{\Phi_\gamma}$$

Solar ^{63}Cu and ^{65}Cu

Solar		
After core He burning	31%*	69%*
After shell C burning	56%*	44%*
If ^{63}Ni(n,γ) x2	41%*	59%*
If ^{63}Ni(n,γ) :2	**64%***	**36%***

* Only 25 $M_{\odot}$ star

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