High Resolution Spectroscopy in Nuclear Astrophysics

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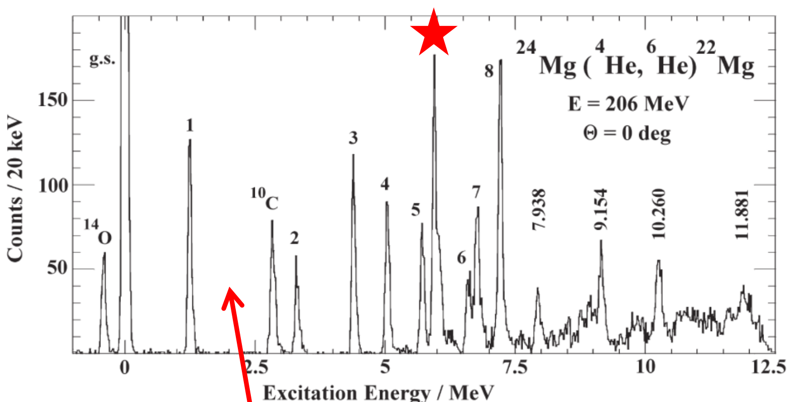
University of Notre Dame & JINA

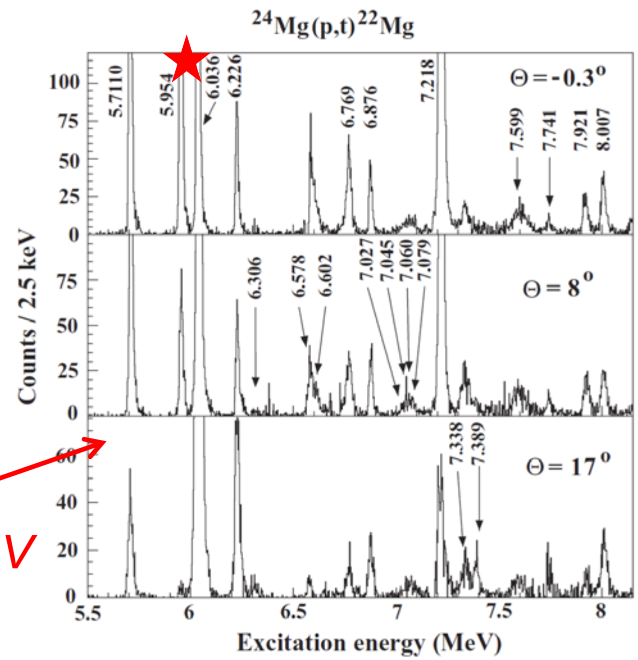
Nuclear Astrophysics Studies at RCNP

Osaka – Notre Dame – Groningen

Started in 2002 (Georg @ RCNP) with a series of (p,t) reactions

explosive H burning in X-ray bursts in the αp-process
indirect study of (α,p) reactions on the “waiting points” ^{18}Ne, ^{22}Mg, and ^{26}Si

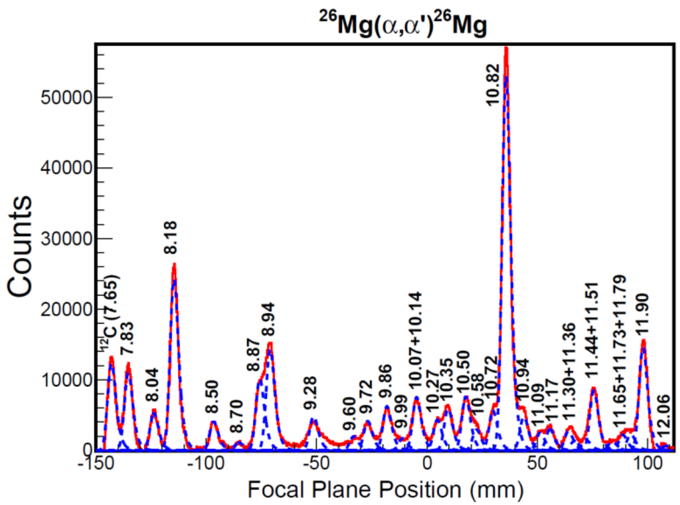


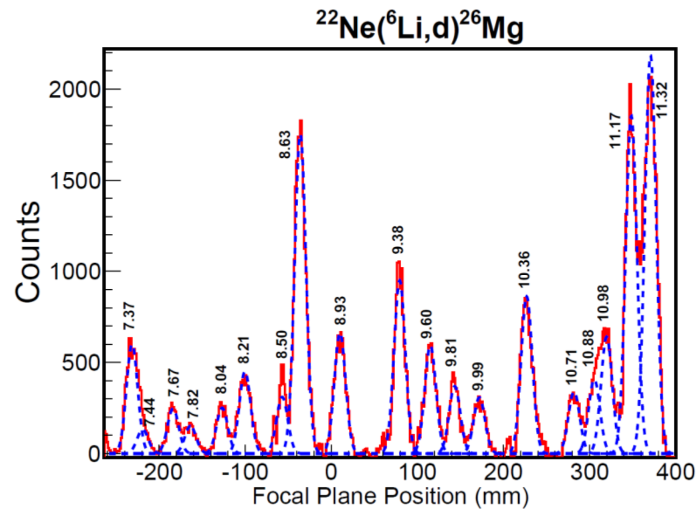


75 keV energy resolution *13 keV*

Since 2009:

focus on the ^{22}Ne neutron source for the s-process
indirect study of ^{22}Ne(α,n) (s-process): (α,α'), (^{6}Li,d) and ^{25}Mg(d,p)





Program very successful

2 Master Theses (RCNP)
so far 3 PhD Theses!
2 more coming up

Collaborators

Osaka	H. Fujita	*Groningen*
Y. Fujita	T. Adachi	A. Matic
K. Hatanaka	Y. Shimbara	A. van der Berg
A. Tamii	K. Miki	M.N. Harakeh

A. Matic (IBA Particle Therapy) S. O'Brien (US Federal Gov.) R. Talwi (ANL)

Neutron sources for ~~the~~ s-process

Main Component A>100

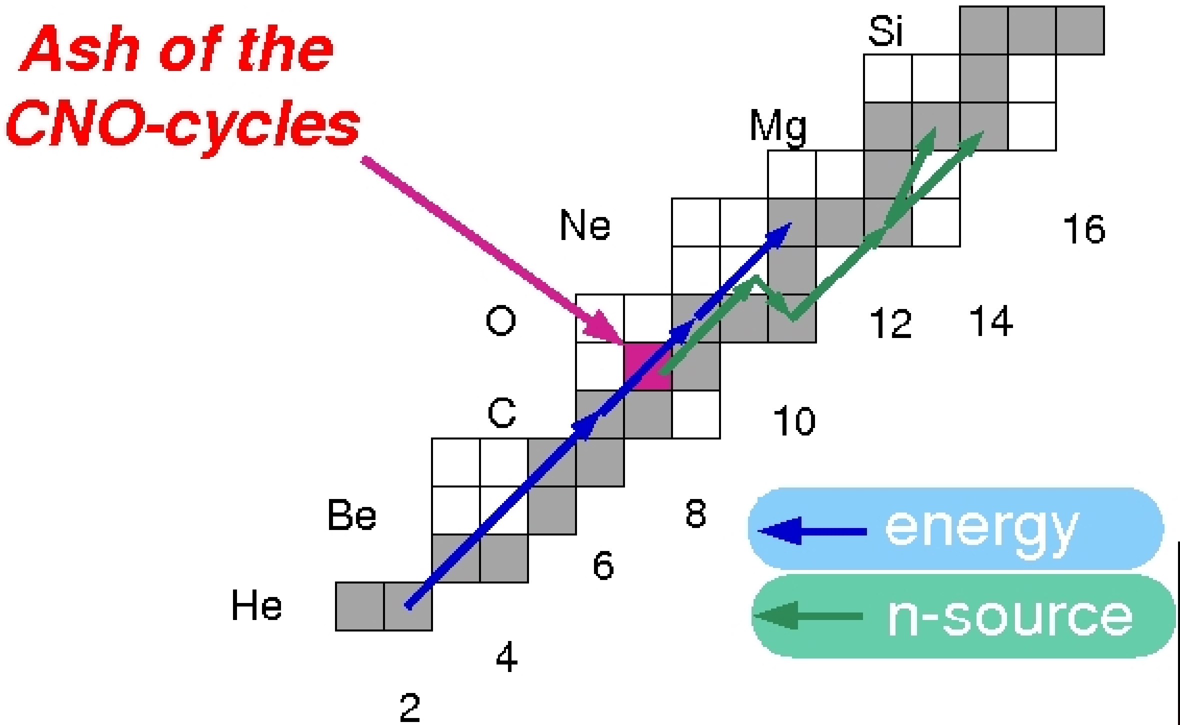
low mass AGB stars
T= 0.1 GK
$N_n \sim 10^7$ /cm^{-3}
s-process at kT=8 keV
Time scale:
a few 10,000 years
^{13}C(α,n) & ^{22}Ne(α,n)

Weak Component A< 100

core He burning in massive stars
T=0.3 GK
$N_n \sim 10^6$ /cm^{-3}
s-process at kT=25 KeV
Time scale:
Last few 10,000 years
^{22}Ne(α,n)

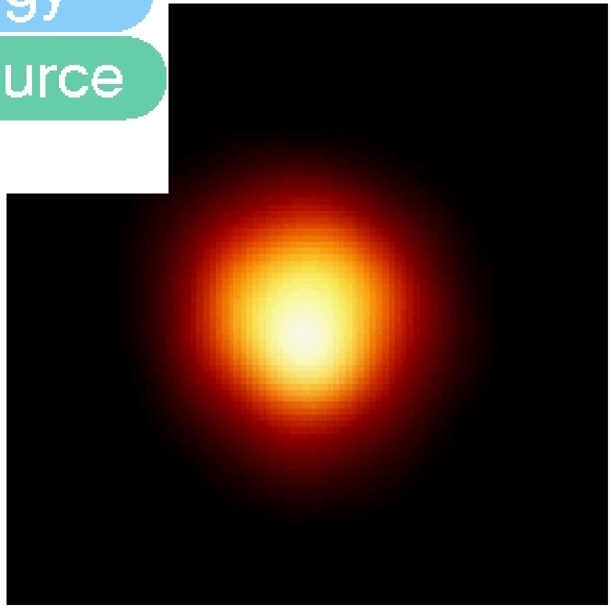
Shell C burning in massive stars
T=1 GK
$N_n \sim$ up to 10^{12} /cm^{-3}
s-process at kT=90 KeV
Time scale: 1 year
(not the "typical" s-process)
^{22}Ne(α,n)

Core Helium Burning

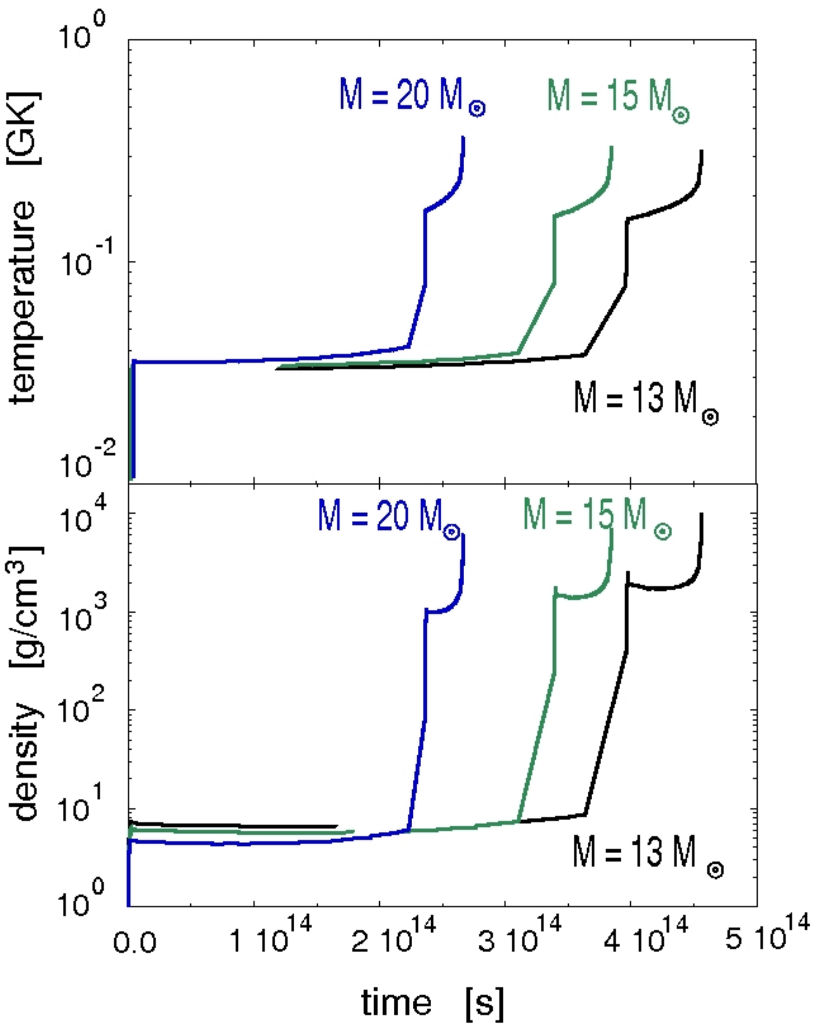


weak component
of s-Process
A<100

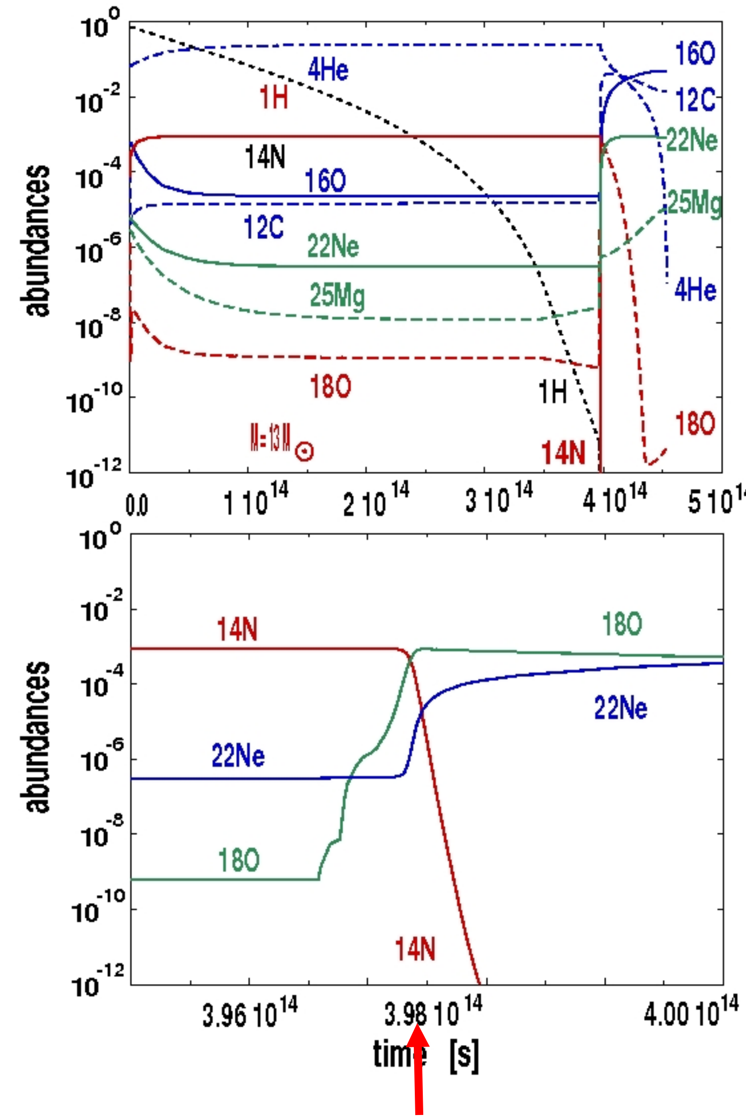
Hubble Space Telescope
Betelgeuse



Simple "1-Zone" Model



Courtesy Alessandro Chieffi



12.6 million years

Shell Carbon Burning

burns on the ashes of He-Burning
^{12}C, ^{16}O, $^{20,22}Ne$ and $^{25,26}Mg$

main energy source: $^{12}C+^{12}C$

$$^{12}C+^{12}C \rightarrow \begin{cases} ^{20}Ne+\boldsymbol{\alpha} \\ ^{23}Na+\mathbf{p} \end{cases}$$

!

p/α-ratio

main neutron source: $^{22}Ne(\alpha,n)$

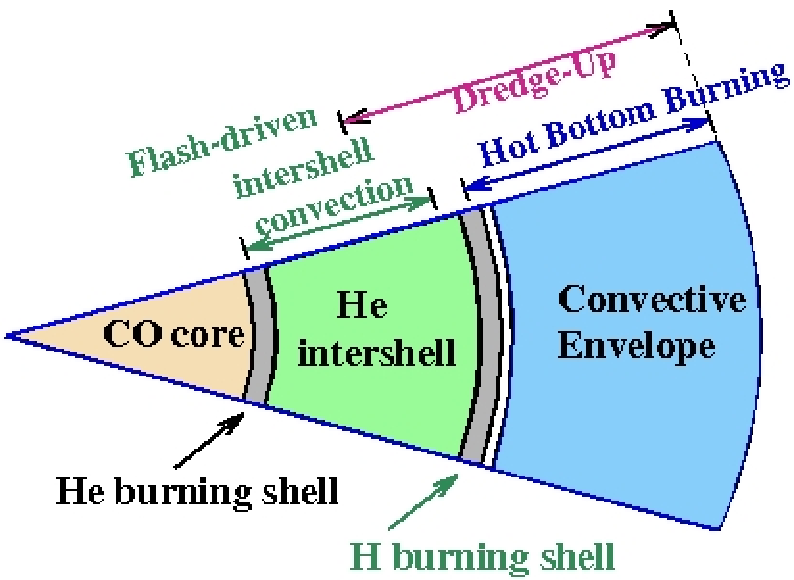
well known at 1GK
residual from He burning
→how much is left at end of He burning?
Small production branch:
$^{20}Ne(p,\gamma)^{21}Na(\beta^+)^{21}Ne(p,\gamma)^{22}Na(\beta^+)$
^{22}Ne poison: $^{22}Ne(p,\gamma)$

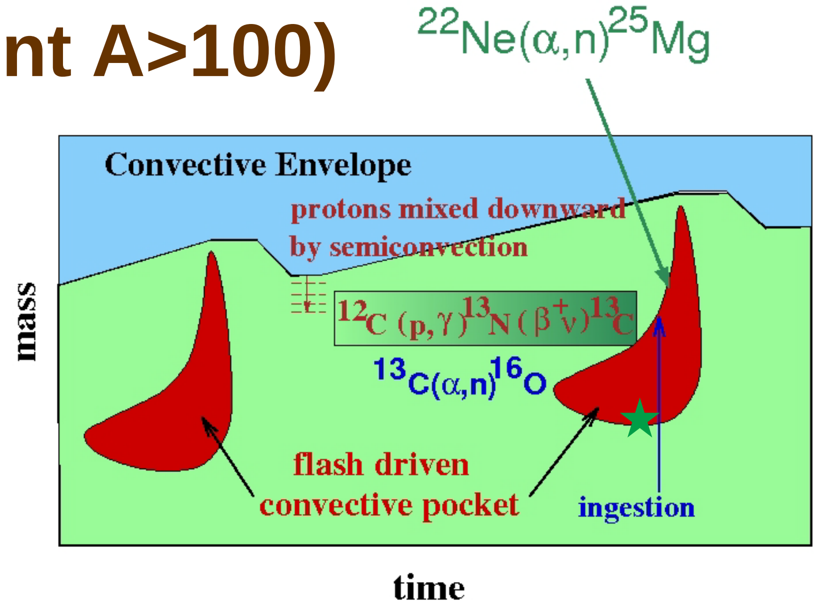
possible neutron source at end of burning: $^{25,26}Mg(\alpha,n)$

Most abundant isotopes at end of burning:
^{16}O, ^{20}Ne, ^{23}Na and ^{24}Mg

s-Process (Main Component A>100)

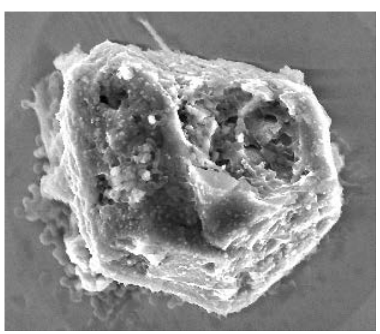
TP-AGB Stars



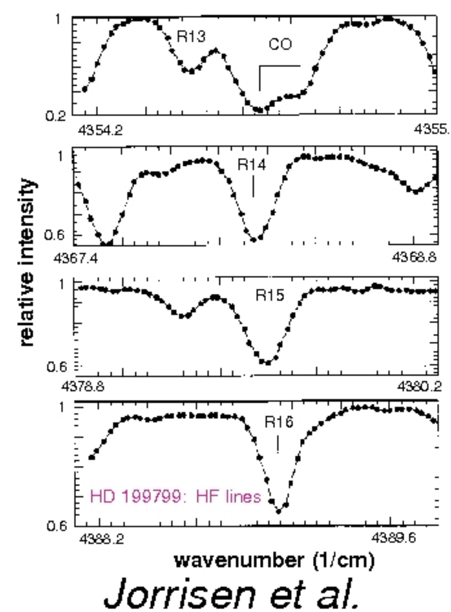


Large Mass Loss ➡ Chemical Evolution

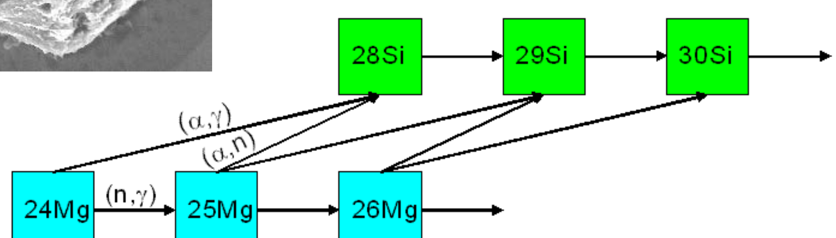
meteorite inclusions



Fluorine Lines Observed On Surface of AGB Star



^{29,30}Si isotope ratios

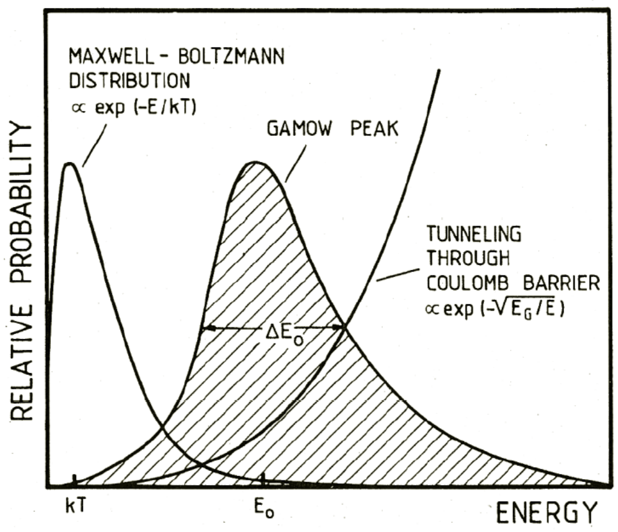


Reaction Rates

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE$$

non-resonant reaction

S(E) ≈ constant



Gamow Peak

resonant reaction

S(E) ≈ Breit-Wigner

Resonance Strength:

$$\omega\gamma = \omega \frac{\Gamma_a \Gamma_b}{\Gamma}.$$

!

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T}\right)^{3/2} \hbar^2 (\omega\gamma)_R \exp\left(-\frac{E_R}{kT}\right)$$

$\Gamma_p(E << E_C) \sim \exp(-k \cdot E_R^{-1/2})$!

Indirect approach

$$\omega\gamma = \omega \frac{\Gamma_\alpha \cdot \Gamma_n}{\Gamma_\alpha + \Gamma_\gamma + \Gamma_n} \approx \omega\, \Gamma_\alpha = \omega\, S_\alpha\, \Gamma_\alpha^{sp}$$

assuming $\Gamma_\alpha, \Gamma_{\gamma/n} << \Gamma_{n/\gamma}$

need to know:

Spin and parity (natural J^π? ω)

excitation energy (see above)

Γ_α or S_α from transfer reaction

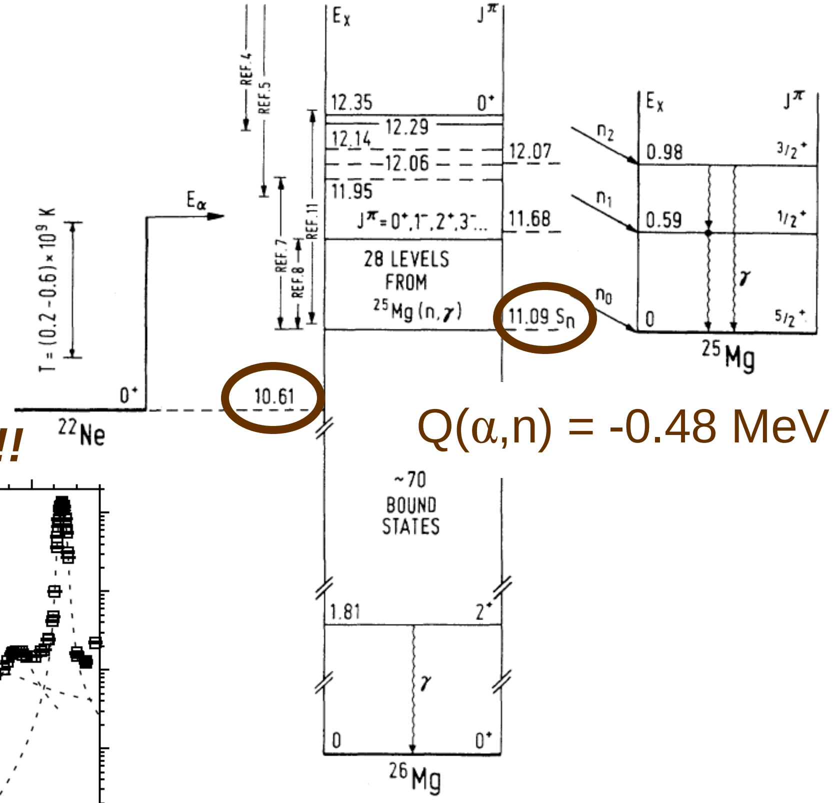
Γ_n/Γ_γ if both channels are open

S_α and Γ_α^{sp} are model dependent

if Γ_α is known, only relative value are needed! (see example later on)

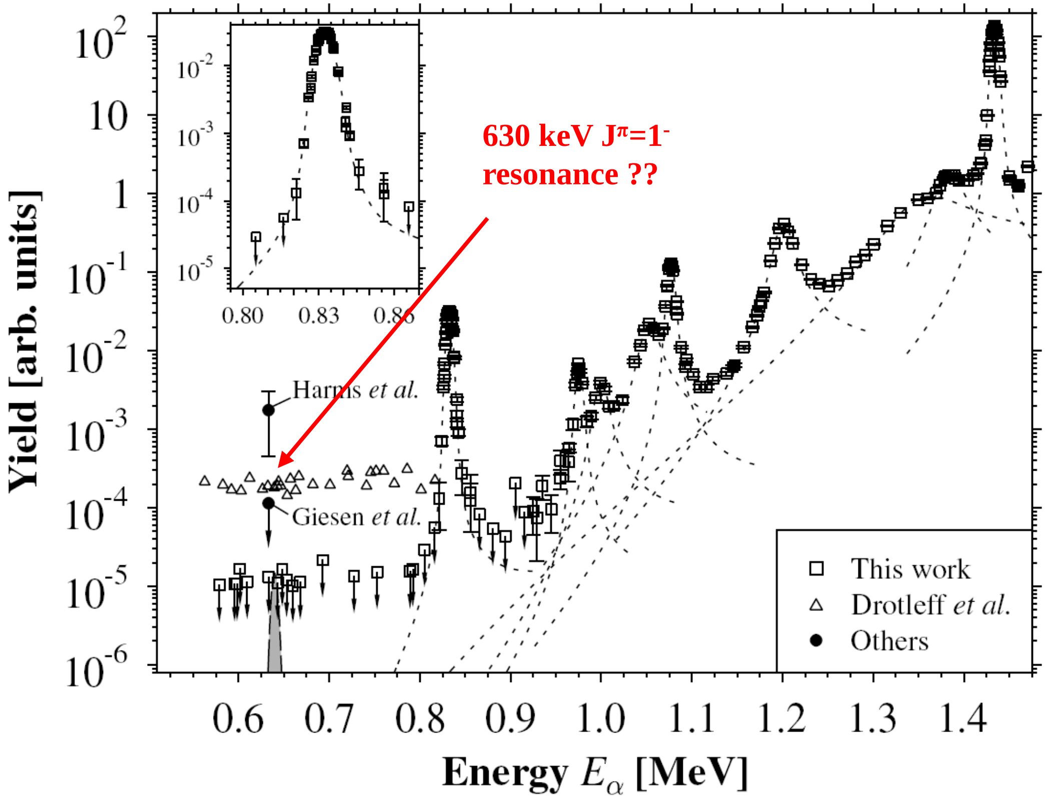
^{22}Ne(α,n) neutron source

competition between **(α,n)** & **(α,γ)** reaction channels



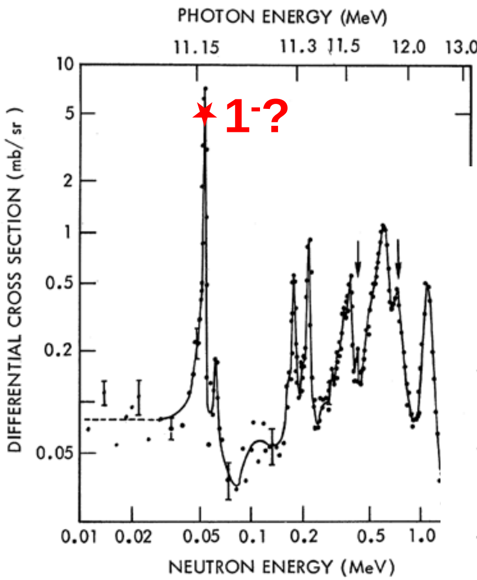
Q(α,n) = -0.48 MeV

NO (α,γ) below 832 keV resonance ***!!***

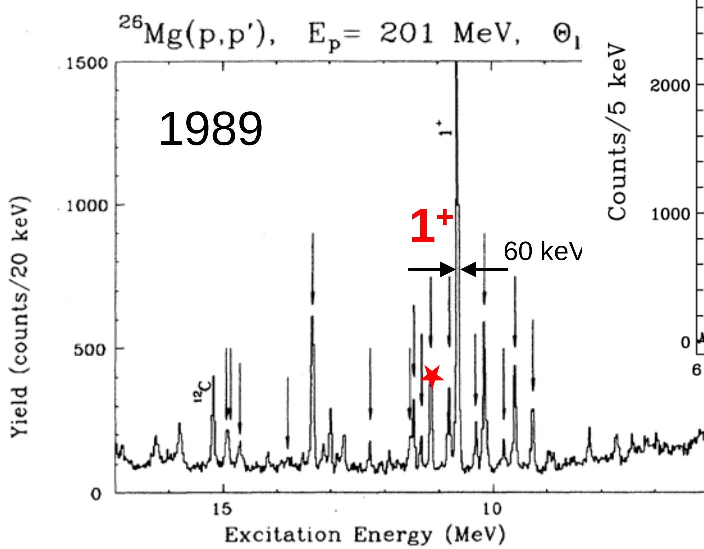


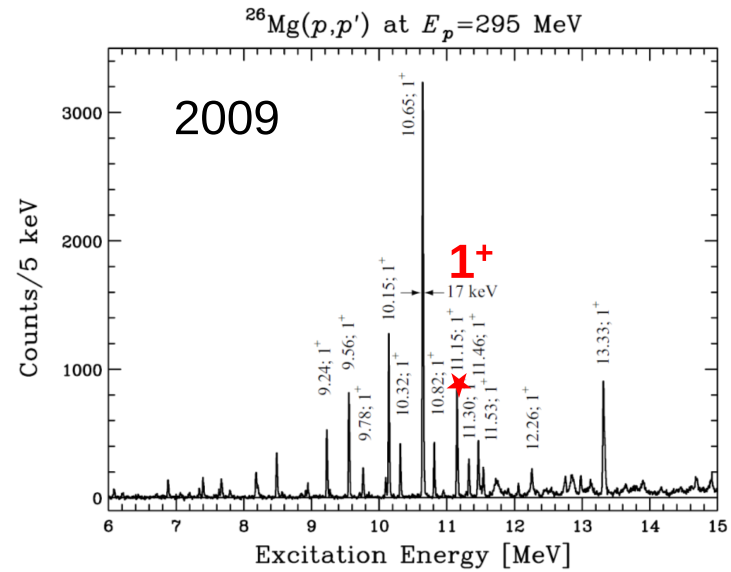
Jaeger et al., PRL 87, 202501 (2001)

present upper limit: < 60 neV



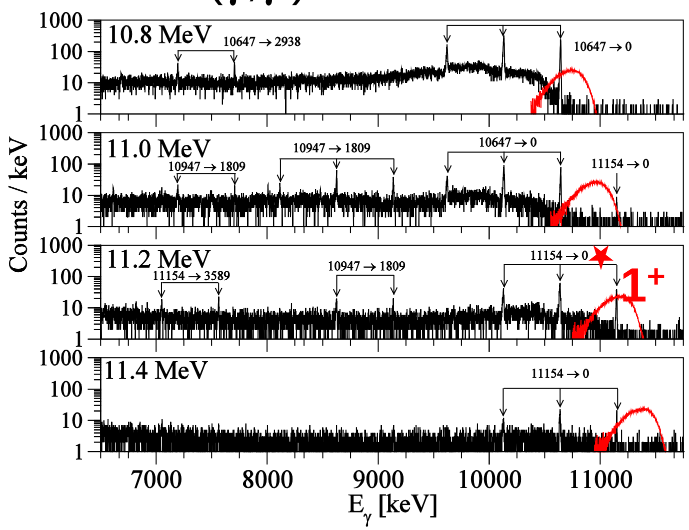
^{26}Mg(γ,n) 1969





Shown by Yoshi at a seminar on the occasion of his visit to Notre Dame !!

(γ,γ') 2009



Surprisingly enough:

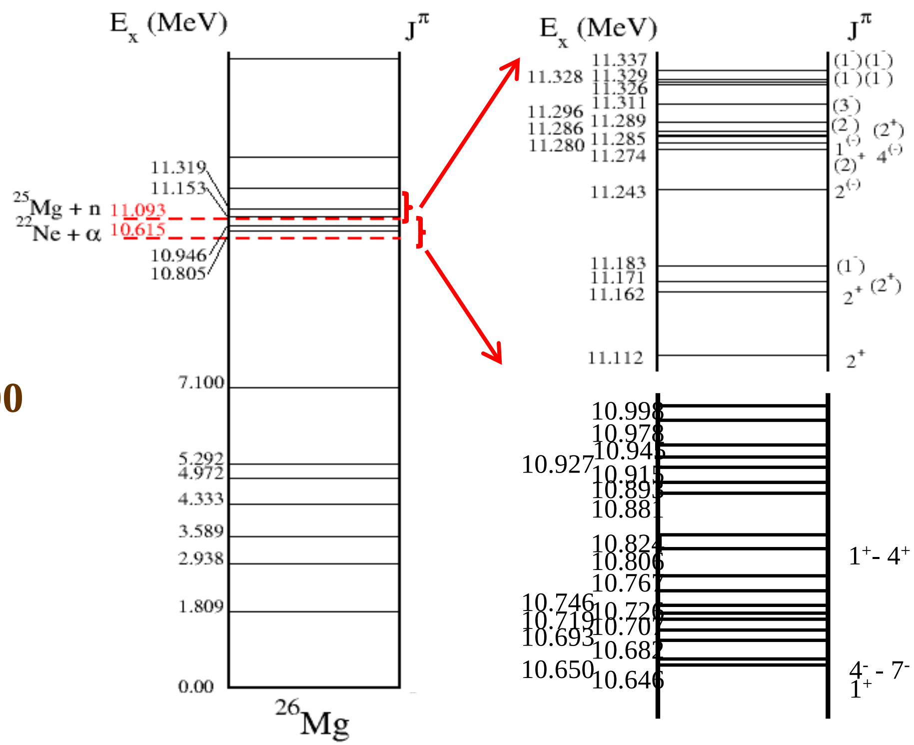
Latest compilation (NNDC 1998) still shows state without spin assignment

^{25}Mg+n: new n-tof data

E_n (keV)	J^π	Γ_γ (eV)	Γ_n (eV)
−154.25	2+	6.5	30 000
19.86 ± 0.05	2+	1.7 ± 0.2	2310 ± 30
62.727 ± 0.003	1+[a]	4.1 ± 0.7	28 ± 5
72.66 ± 0.03	2+	2.5 ± 0.4	5080 ± 80
79.29 ± 0.03	(3+)	3.3 ± 0.4	1560 ± 80
81.117 ± 0.001	(2)+	3 ± 2	0.8 ± 0.7
93.60 ± 0.02	(1−)	2.3 ± 2	0.6 ± 0.2
100.03 ± 0.02	3+	1.0 ± 0.1	5240 ± 40
[101.997 ± 0.009]	[2−]	[0.2 ± 0.1]	[4 ± 3]
[107.60 ± 0.02]	[3+]	[0.3 ± 0.1]	[2 ± 1]
156.34 ± 0.02	(2−)	6.1 ± 0.4	5520 ± 20
188.347 ± 0.009	(2)+	1.7 ± 0.2	590 ± 20
194.482 ± 0.009	4(−)	0.2 ± 0.1	1730 ± 20
200.20 ± 0.03	1−	0.3 ± 0.3	1410 ± 60
200.944 ± 0.006	(2+)	3.0 ± 0.3	0.7 ± 0.7
203.878 ± 0.001	(2−)	0.8 ± 0.3	2 ± 1
[208.27 ± 0.01]	[1−]	[1.2 ± 0.5]	[230 ± 20]
211.14 ± 0.05	(2−)[d]	3.1 ± 0.7	12400 ± 100
226.255 ± 0.001	(1−)	4 ± 3	0.4 ± 0.2
242.47 ± 0.02	(1−)	6 ± 4	0.3 ± 0.2
244.60 ± 0.03	1−	3.5 ± 0.6	50 ± 20
245.552 ± 0.002	(1−)	2.3 ± 2	0.5 ± 0.2
253.63 ± 0.01	(1−)	3.1 ± 2.7	0.1 ± 0.1
261.84 ± 0.03	4(−)	2.6 ± 0.4	3490 ± 60
279.6 ± 0.2	(2+)	1.9 ± 0.7	3290 ± 50
311.57 ± 0.01	(5+)	(0.84 ± 0.09)	(240 ± 10)
362.04 ± 0.02	4+[c]	2.2 ± 0.2	2020 ± 40
387.57 ± 0.04	(5−)[c]	(1.7 ± 0.3)	(8910 ± 80)
423.43 ± 0.01	(1−)[c]	(20 ± 10)	(25 ± 10)
451.24 ± 0.06	(3−)[c]	(6.6 ± 0.8)	(3000 ± 100)
514.88 ± 0.03	(2−)	(8.6 ± 0.8)	(1800 ± 100)
536.0 ± 0.02	(4−)	(2.7 ± 0.3)	(840 ± 40)

211.14 ± 0.05
226.255 ± 0.001
242.47 ± 0.02
244.60 ± 0.03

20 keV average spacing of states



Γ_n/Γ_γ : from 1000 to 1/10

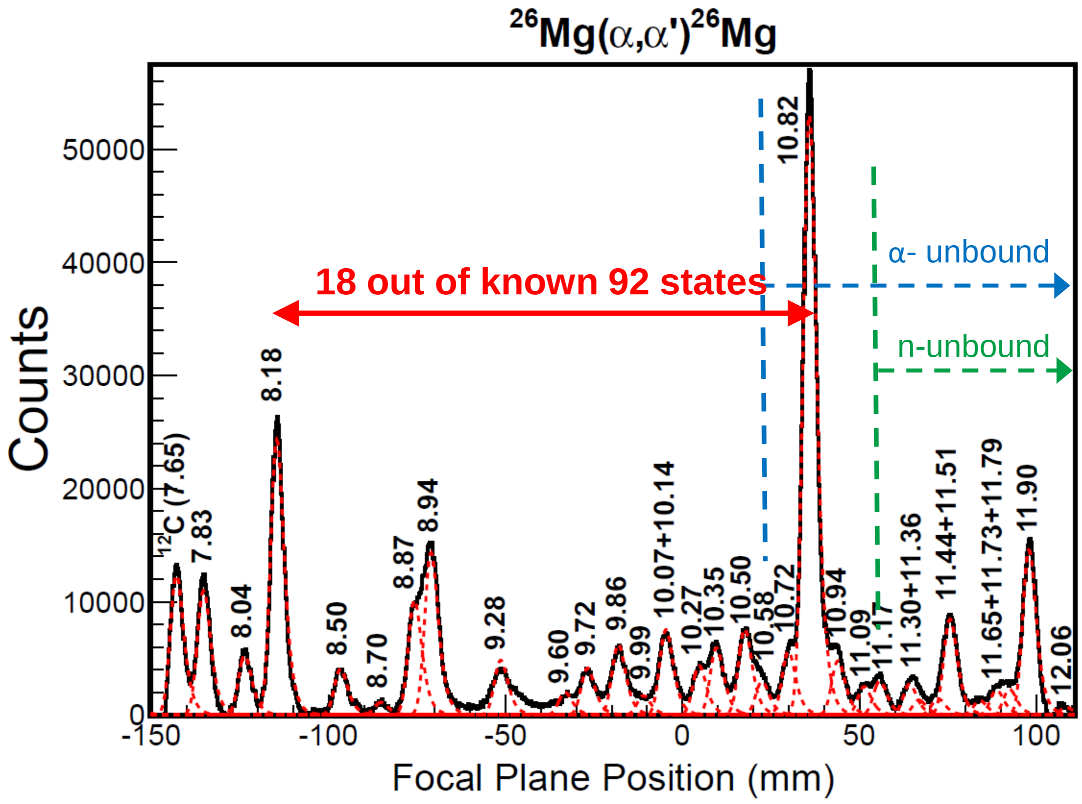
Below n-threshold:
no widths and nearly no spins are known

234±2 keV = last known resonance at 831 keV

Massimi et al 2012

First step: ^{26}Mg(α,α') @ 206 MeV

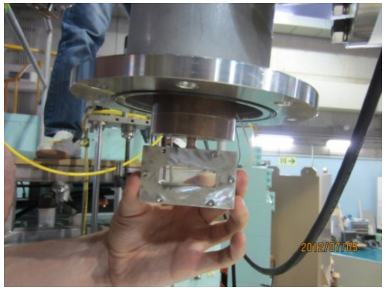
Going to 206 MeV to learn about 206 keV

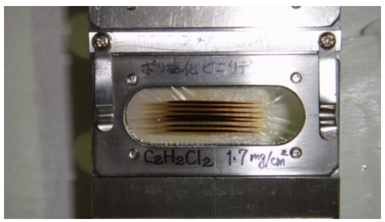


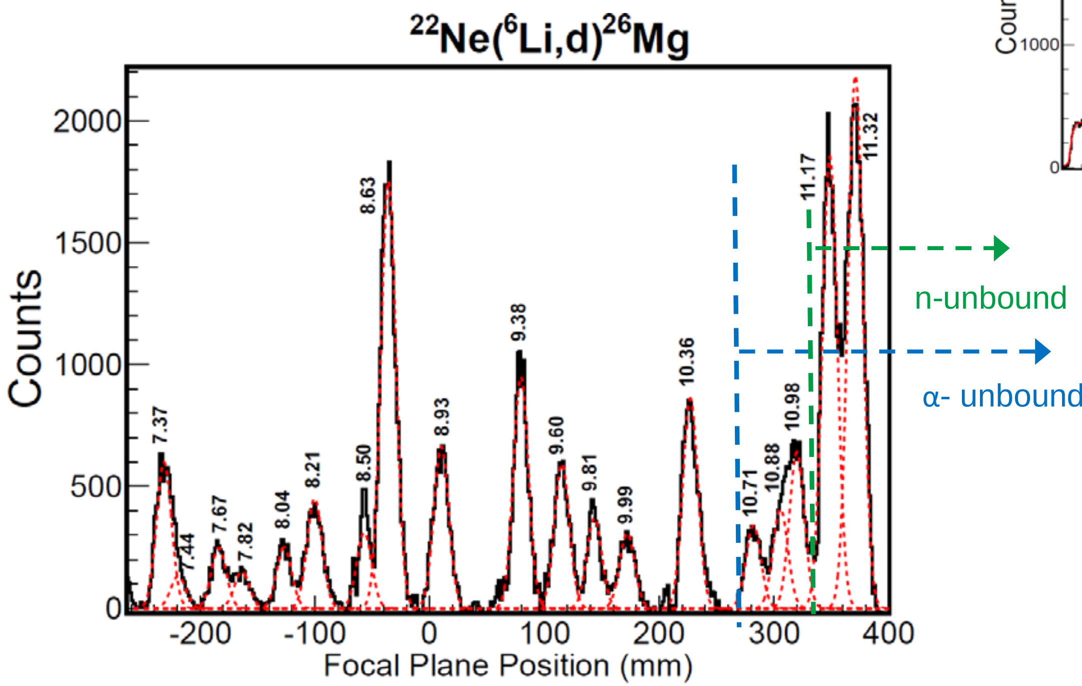
(α,α') populates preferentially natural parity states

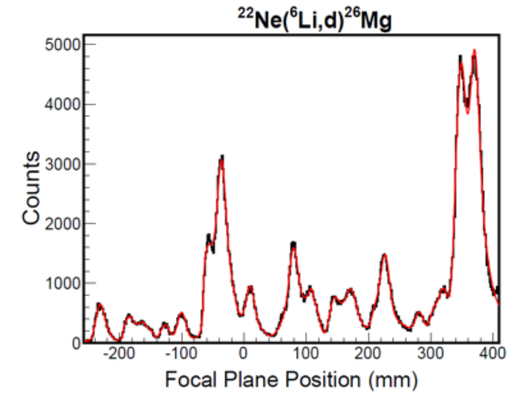
no unnatural parity state observed below **α**-threshold

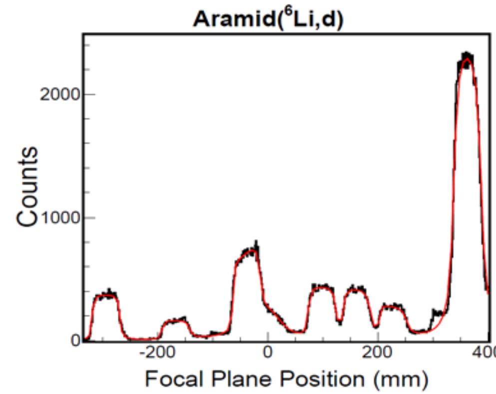
Second step: ^{22}Ne(^{6}Li,d) @ 80 MeV











Result:

E_x (keV)	$E_R^{c.m.}$ (keV)	J^π	S_α	Γ_{sp} (eV)	Γ_α (eV)	Γ_γ^a (eV)	Γ_n^a (eV)	$\omega\gamma_{(\alpha,\gamma)}$ (eV)	$\omega\gamma_{(\alpha,n)}$ (eV)
10717 (9)	102	1^-	0.07	3.78×10^{-35}	$2.8\ (2)\times10^{-36}$			$8.5\ (5)\times10^{-36}$	
		2^+	0.14	6.00×10^{-36}	$9\ (2)\times10^{-37}$			$4\ (1)\times10^{-36}$	
10822[b] (10)	207	1^-	≤0.07	$\leq2.99\times10^{-20}$	$\leq1.97\times10^{-21}$			$\leq5.92\times10^{-21}$	
10951 (21)	336	1^-	0.16	5.68×10^{-13}	$9\ (3)\times10^{-14}$			$2.8\ (8)\times10^{-13}$	
11085[b] (8)	471	2^+	≤0.07	$\leq7.01\times10^{-11}$	$\leq4.71\times10^{-12}$			$\leq2.36\times10^{-11}$	
		3^-	≤0.07	$\leq9.77\times10^{-12}$	$\leq7.06\times10^{-13}$			$\leq4.95\times10^{-12}$	
n-threshold									
11167 (8)	553	1^-	0.40	5.00×10^{-07}	$2.0\ (1)\times10^{-07}$	2 (2)	0.6 (0.2)	$5.5\ (4)\times10^{-07}$	6×10^{-08} [c]
11317 (18)	702	1^-	0.48[f]	1.05×10^{-04}	$5.0\ (3)\times10^{-05}$ [e]			$3.7\ (4)\times10^{-05}$ [d]	$1.2\ (1)\times10^{-04}$ [d]

lowest known resonance

calculated from Γ_α

calculated from $\omega\gamma$

experimental resonance strengths

Result:

from n-tof experiment

E_x (keV)	$E_R^{c.m.}$ (keV)	J^π	S_α	Γ_{sp} (eV)	Γ_α (eV)	Γ_γ^a (eV)	Γ_n^a (eV)	$\omega\gamma_{(\alpha,\gamma)}$ (eV)	$\omega\gamma_{(\alpha,n)}$ (eV)
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11317 (18)	702	1^-	0.48[f]	1.05×10^{-04}	$5.0\ (3)\times10^{-05}$ [e]			$3.7\ (4)\times10^{-05}$ [d]	$1.2\ (1)\times10^{-04}$ [d]

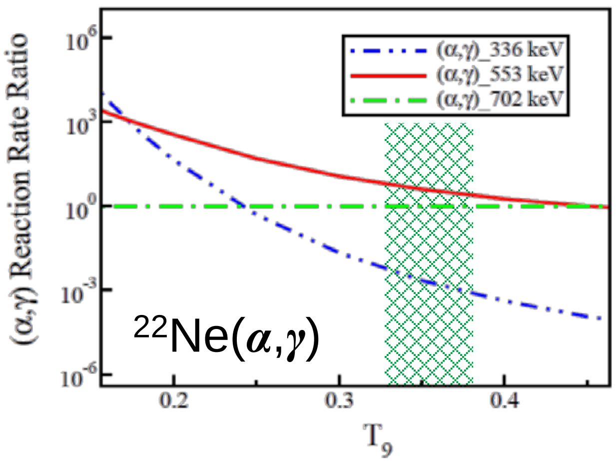
n-threshold (dashed line between the 11085 and 11167 rows)

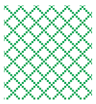
upper limit from Jaeger

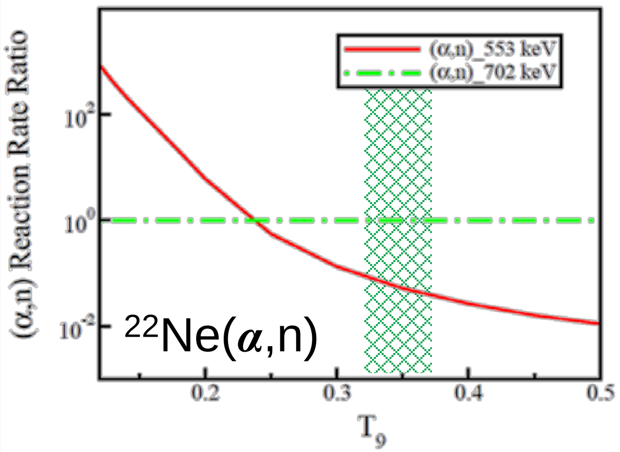
$\omega\gamma_{\alpha\gamma}$**= 0.5 μeV !**

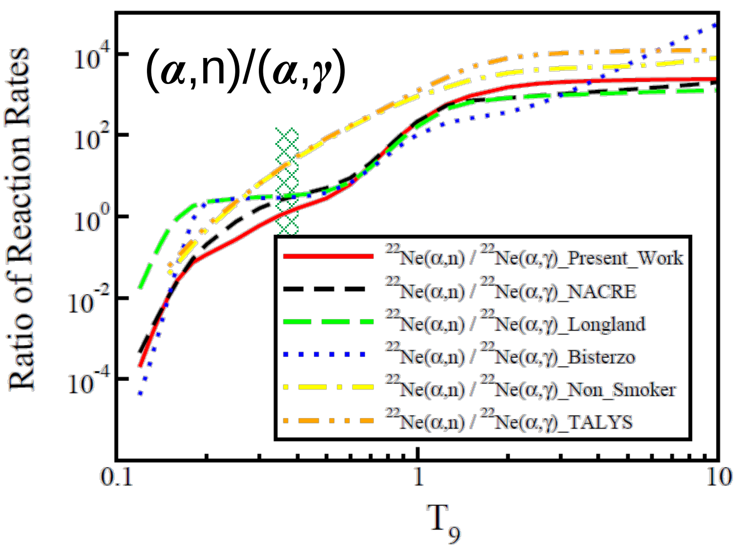
within experimental reach

Reaction Rates:



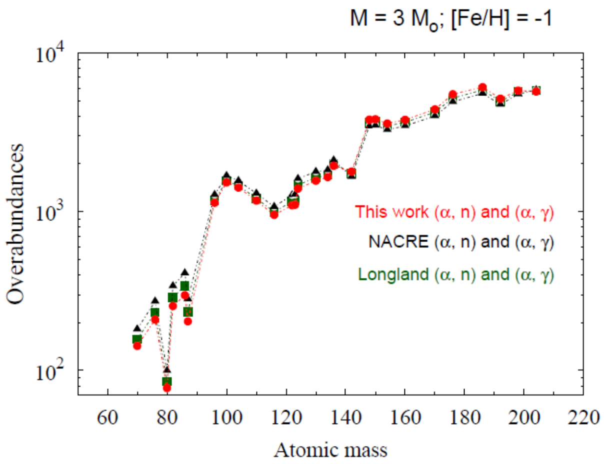


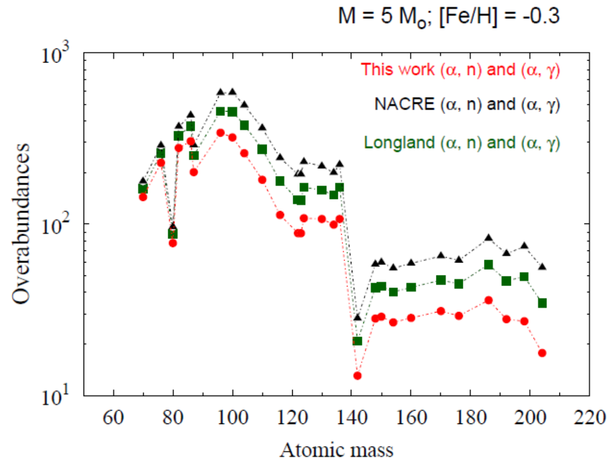


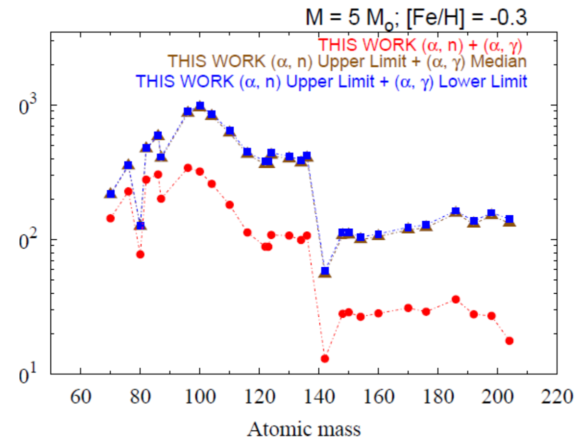


General Impact:
reduction of s-process synthesis
but
significant uncertainties remain

ABG Nucleosynthesis:

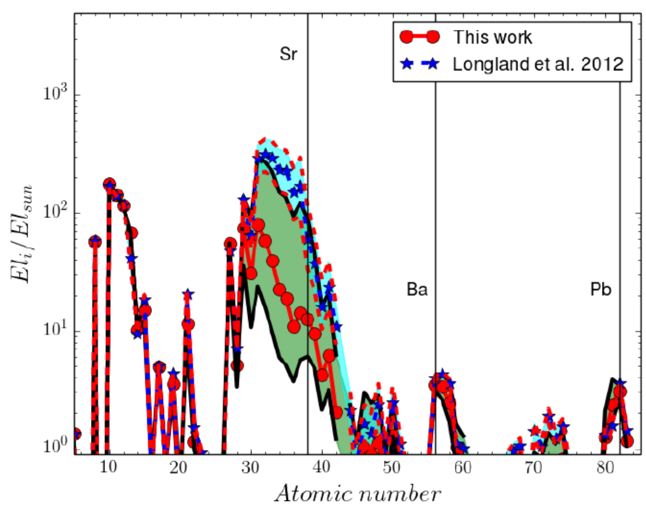






Massive Stars

(25 solar mass)



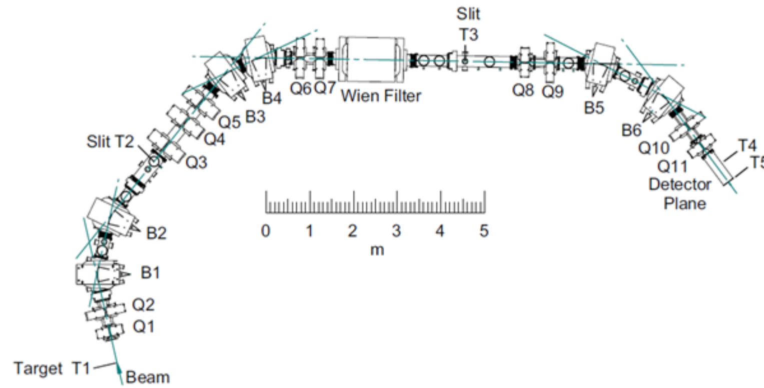
Thanks to:

S. Bisterzo

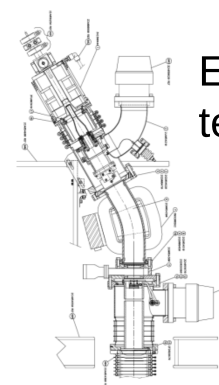
M. Pignatari

Low Energy Alpha Capture Experiments @ Notre Dame

St. George Recoil Separator



Design Parameters				
	Brho(min)	=	0.1 Tm	
	Brho(max)	=	0.45 Tm	
	Momentum accept	= +/-	3.7 %	
		= +/-	2.3 deg	40 mrad



ECR in terminal

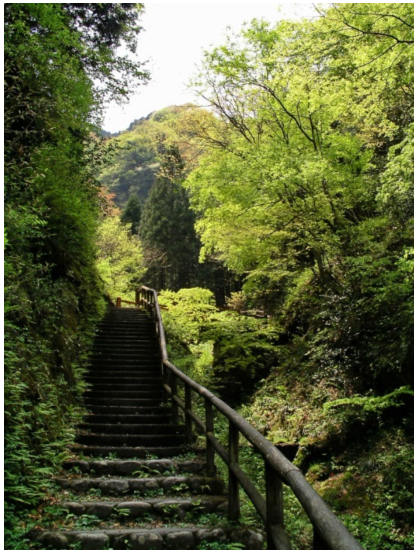
experiments are time consuming

knowledge from indirect search are very helpful

single ended 5 MV vertical accelerator

A Trip with Yoshi To Minoh Waterfall

Yoshi's
"small" walk



The "easy" way
from Minoh station