Nuclear Astrophysics – Direct Methods

Cross section measurements of capture reactions relevant to p-process nucleosynthesis

Sotirios V. Harissopulos

Tandem Accelerator Laboratory,

Institute of Nuclear and Particle Physics, NCSR “Demokritos”,

Athens, Greece

The 4th Azarquiel School of Astronomy, Portopalo di Capo Passero - Syracuse, Italy11-16 June 2017

NCSR Demokritos

2015

HR data

Total : 964

Scientists: 691

Administration: 87

Technicians: 142

Auxiliary: 44

FR data

Total income: 30,396 k€

Public grants: 11,196 k€

Income: 19,236 k€ (EC + Services +other)

2015

PhD theses: 21

Master's theses: 22

Diploma theses: 26

Training reports: 63

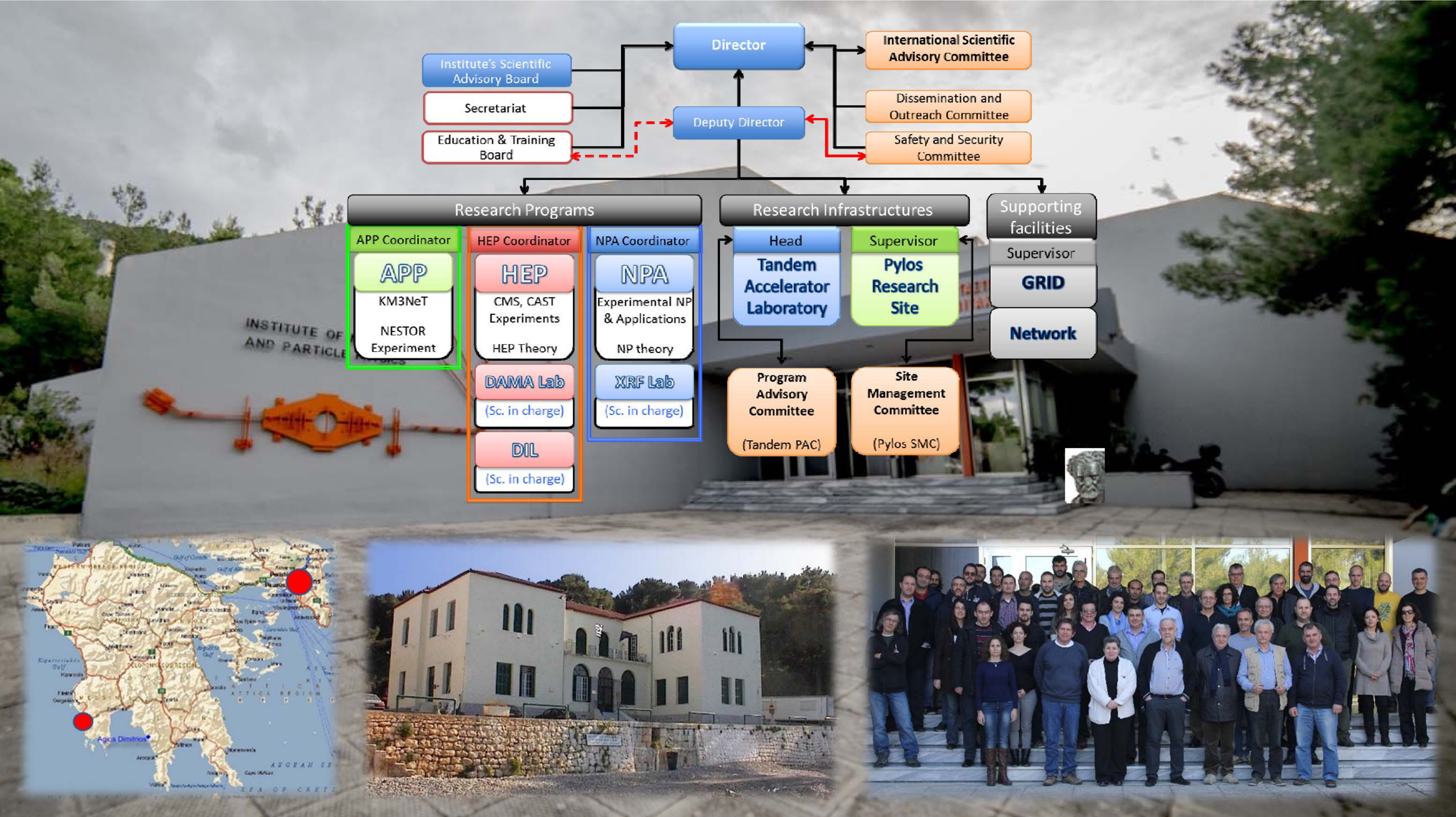
2015

Peer-rev. publications: 526

Citations: 15.840

Conf. Proceedings: 564

Patents: 21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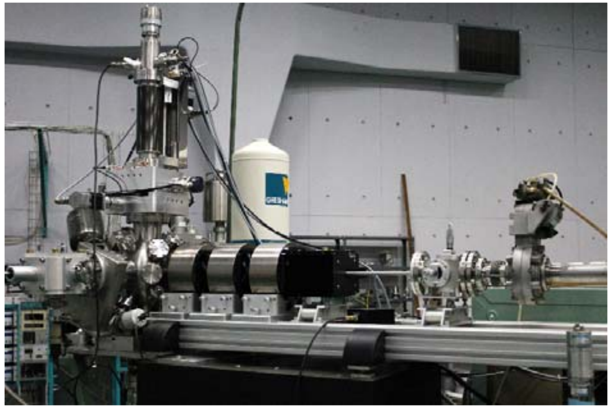
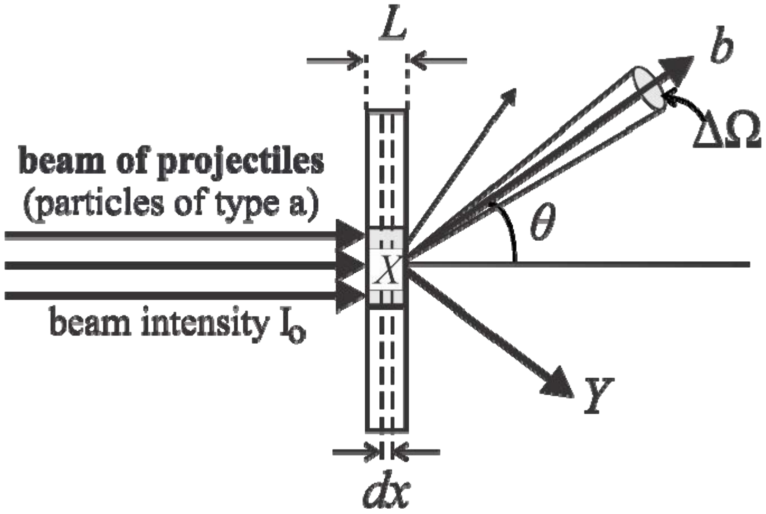


reaction cross section σ : a very basic nuclear physics quantity

$$a + X \longrightarrow Y + b$$



$$\sigma = \frac{\textit{reactions per time}}{(\textit{projectiles per area per time}) \times (\textit{target nuclei})}$$

$$\sigma = \frac{A\, N_b}{N_a\, N_A\, \rho\, L} = \frac{A\, N_b}{N_A\, N_a\, \xi}$$

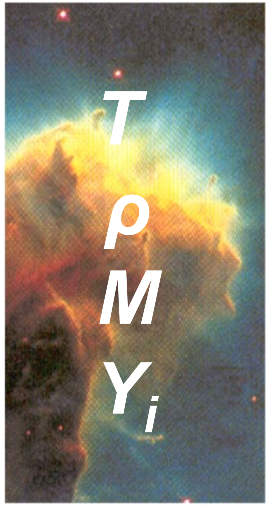
1 b = 10^{-24} cm^2

A := target's atomic weight (*g/mol*)
N_A := Avogadro's number (*at/mol*)
ξ := *target radial density (g/cm²)*
N_a := number of projectiles *a*
N_b := number of ejectiles *b*

$^{12}C(\alpha,\gamma)^{16}O$
$^{13}C(\alpha,n)^{16}O$
$^{13}N(\alpha,p)^{16}O$
$^{16}O(\alpha,\alpha)^{16}O$

measures the probability that a certain reaction takes place at a given "projectile" energy E

=> $\sigma(E)$



$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j$$ decays, *e* captures, …

$$+ \sum_{j,k} N^i_{j,k} \rho N_A \langle \sigma v \rangle_{j,k} Y_j Y_k$$ two-particle fusion reactions

$$+ \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A^2 \langle \sigma v \rangle_{j,k,l} Y_j Y_k Y_l$$ three-particle reactions

two successive captures with an intermediate particle-unstable nucleus

number of species *i* created or destroyed

$$N^i_j = N_j$$

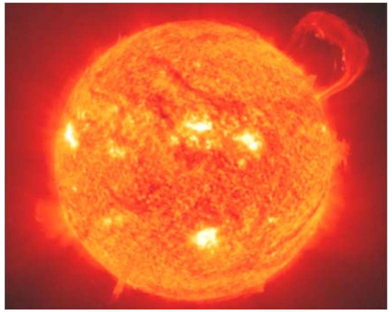
$$N^i_{j,k} = N_i / (N_j!\ N_k!)$$

decay constant $\lambda = 1/\tau$

reaction rate: *reactions / sec / cm³*

$$< \sigma\upsilon > = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE$$

SUN: The pp chain



I (86%) $p(p,e^+\nu)d$ II (14%)

$d(p,\gamma)^3He$

$^3He(^3He,2p)\,^4He$

$^3He(^4He,\gamma)\,^7Be$

IIa (≈14%)

IIb (0.02%)

$^7Be(p,\gamma)^8B(e^+,\nu)\,^8Be^*(\alpha)\,^4He$

$^7Be(e^-,\nu)^7Li(p,\alpha)\,^4He$

$$\frac{d(H)}{dt} = -2<\sigma v>_{11}\frac{(H)^2}{2} - <\sigma v>_{12}(H)(D) + 2<\sigma v>_{33}\frac{(^3He)^2}{2} - <\sigma v>_{17}(H)(^7Be) - <\sigma v>^*_{17}(H)(^7Li)$$

$$\frac{d(D)}{dt} = <\sigma v>_{11}\frac{(H)^2}{2} - <\sigma v>_{12}(H)(D)$$

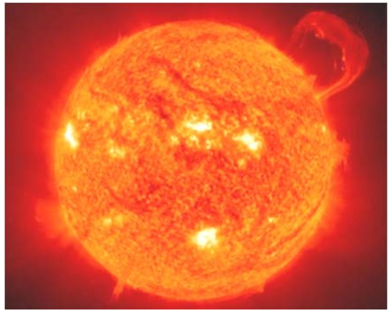
$$\frac{d(^3He)}{dt} = <\sigma v>_{12}(H)(D) - 2<\sigma v>_{33}\frac{(^3He)^2}{2} - <\sigma v>_{34}(^3He)(^4He)$$

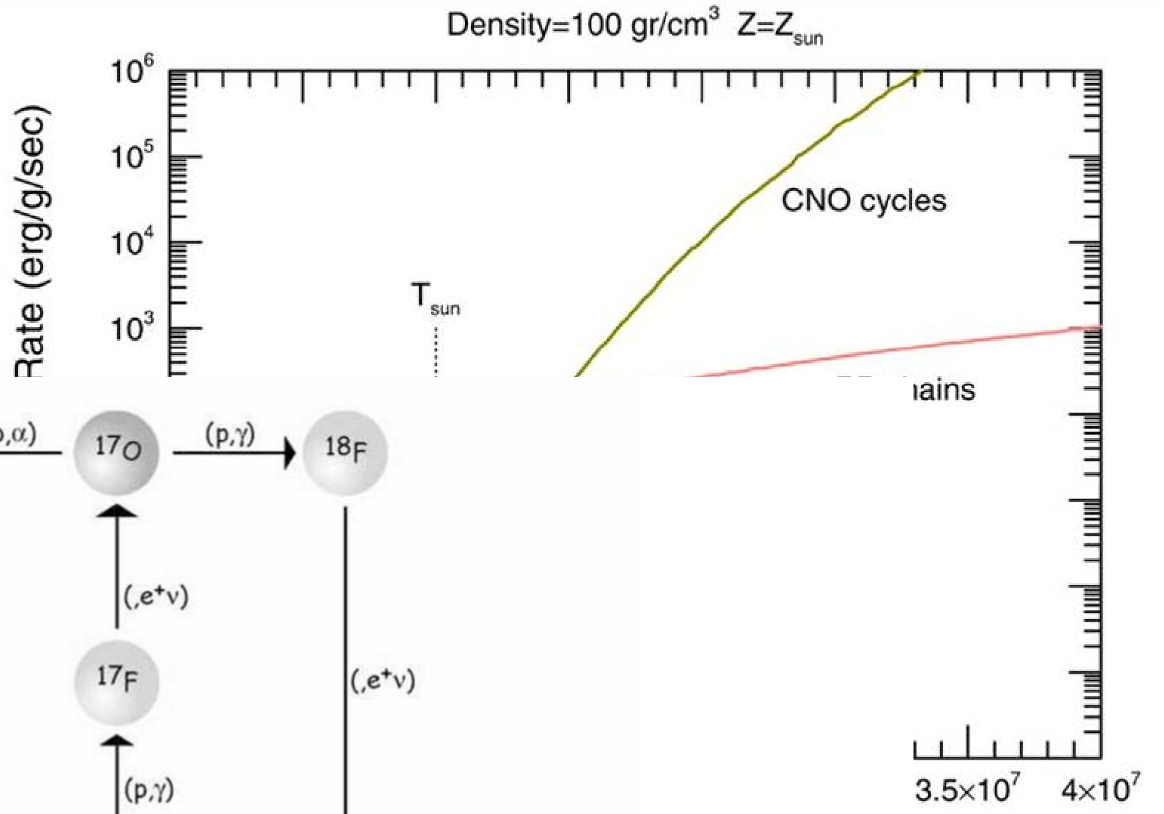
$$\frac{d(^4He)}{dt} = <\sigma v>_{33}\frac{(^3He)^2}{2} - <\sigma v>_{34}(^3He)(^4He) + 2<\sigma v>_{17}(H)(^7Be) + 2<\sigma v>^*_{17}(H)(^7Li)$$

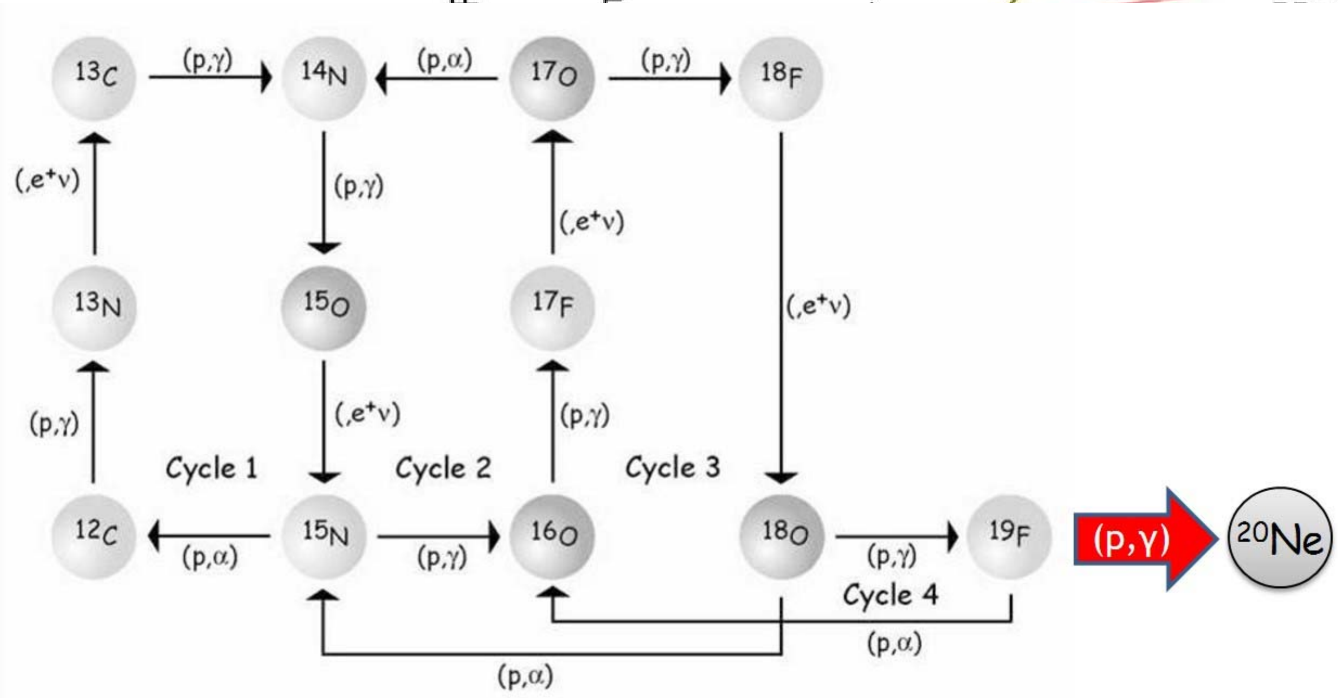
$$\frac{d(^7Be)}{dt} = <\sigma v>_{34}(^3He)(^4He) - <\sigma v>_{e7}\,n_e(^7Be) - <\sigma v>_{17}(H)(^7Be)$$

$$\frac{d(^7Li)}{dt} = <\sigma v>_{e7}\,n_e(^7Be) - <\sigma v>^*_{17}(H)(^7Li)$$

SUN: The pp chain



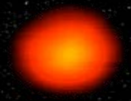




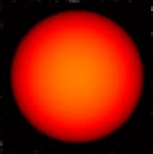
Astrophysical environments

Big Bang
(primordial
nucleosynthesis)

Main sequence
(e.g. Sun)



Red giant stars, stars of the
Asymptotic branch



Super giant stars,
Wolf-Rayet stars and
Pre-supernovae

Novae, supernovae,
X-ray bursts

AGB stars,
supernovae II,
Neutrons stars

Nuclear processes

Reactions between the lightest elements
p, d, He, Be, Li

Hydrogen burning
proton-proton chain, CNO cycle,
Ne-Na cycle, Mg-Al cycle

Helium burning
3a-process, $^{12}C(a,\gamma)^{16}O$
Other (a,γ) and (a,n) reactions

Advance burning stages
Reactions of C, O, N, Ne, Si…

Explosive burning
Hot CNO cycle
Rapid proton capture (rp process)

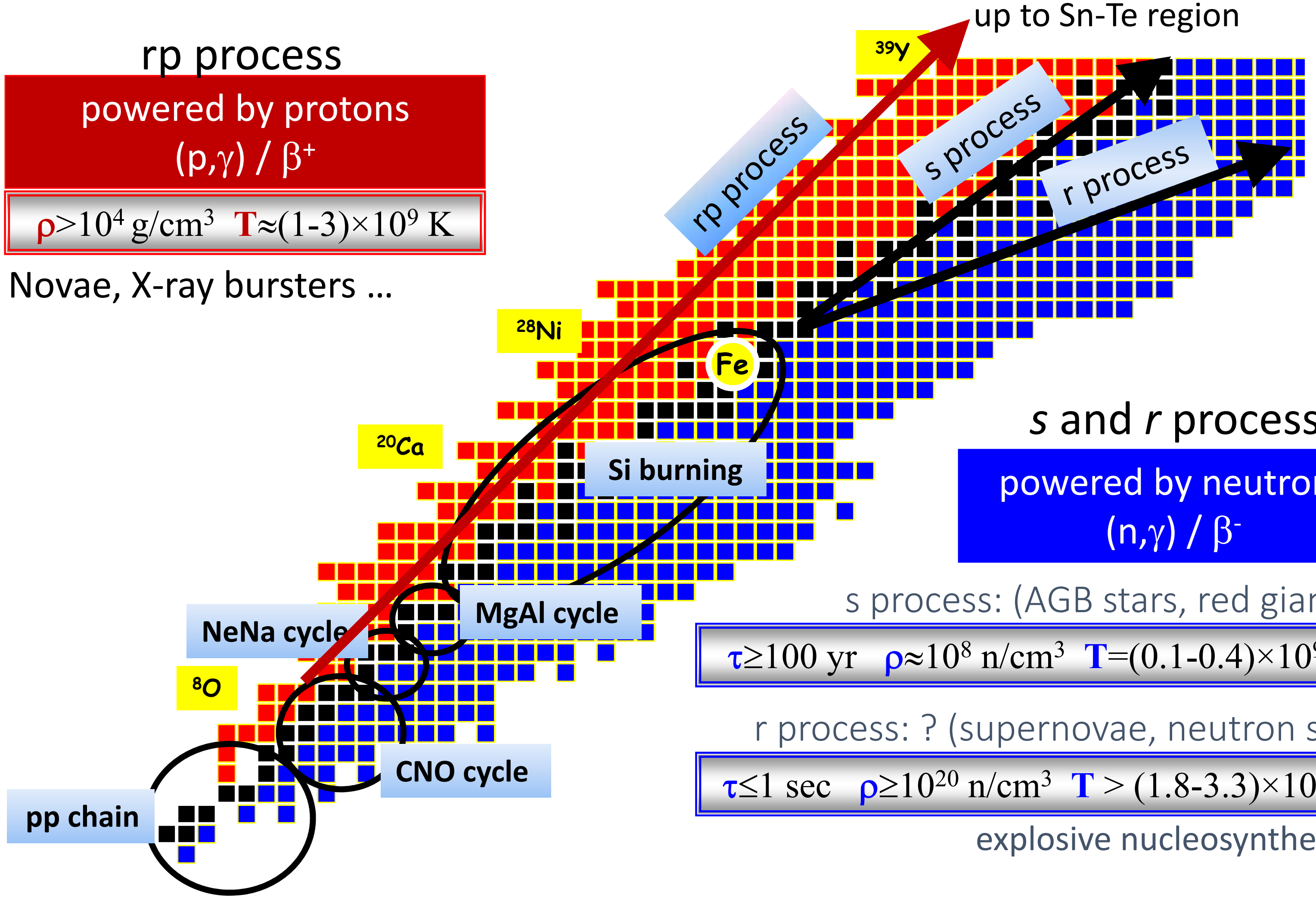
Nucleosynthesis beyond iron
Slow neutron captures (s-process)
Rapid neutron captures (r-process)
photodisintegrations and proton captures (p-process)

rp process

powered by protons
(p,γ) / β^+

$\rho > 10^4$ g/cm^3 $T \approx (1\text{-}3)\times 10^9$ K

Novae, X-ray bursters …



s and *r* processes

powered by neutrons
(n,γ) / β^-

s process: (AGB stars, red giants...)

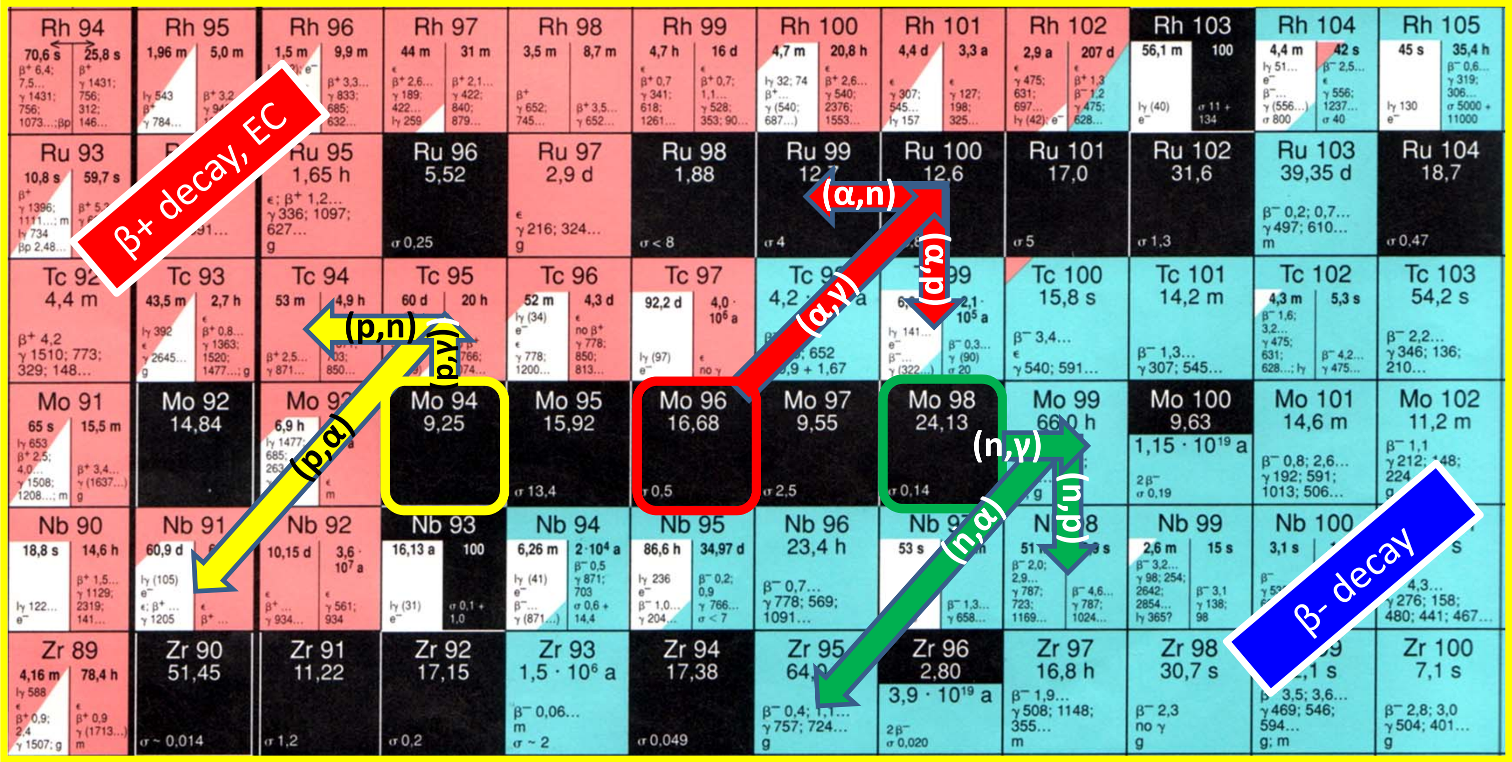
$\tau \geq 100$ yr $\rho \approx 10^8$ n/cm^3 $T = (0.1\text{-}0.4)\times 10^9$ K

r process: ? (supernovae, neutron stars)

$\tau \leq 1$ sec $\rho \geq 10^{20}$ n/cm^3 $T > (1.8\text{-}3.3)\times 10^9$ K

explosive nucleosynthesis !!

moving across the table of isotopes with p-, α-, and n-induced reactions

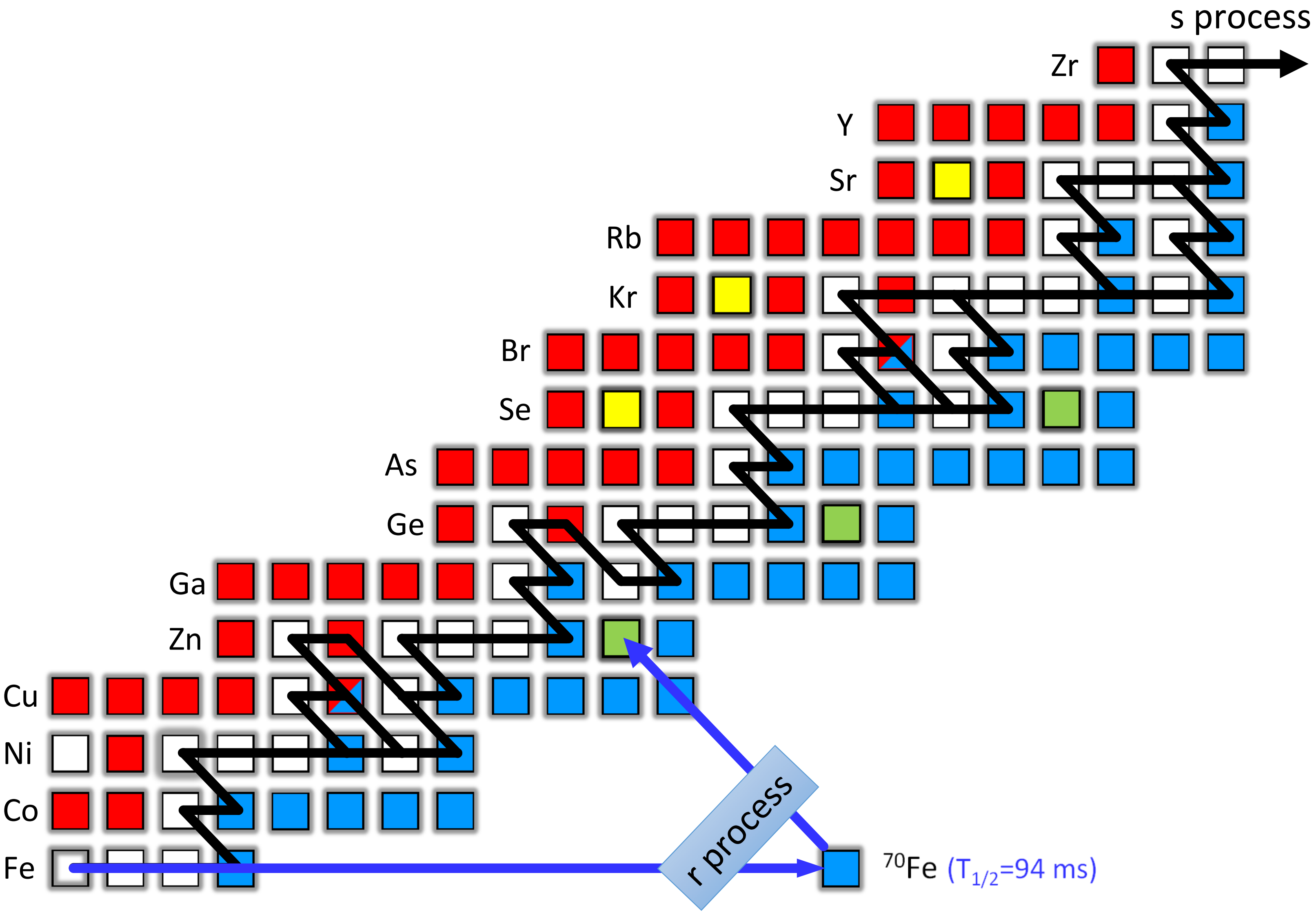


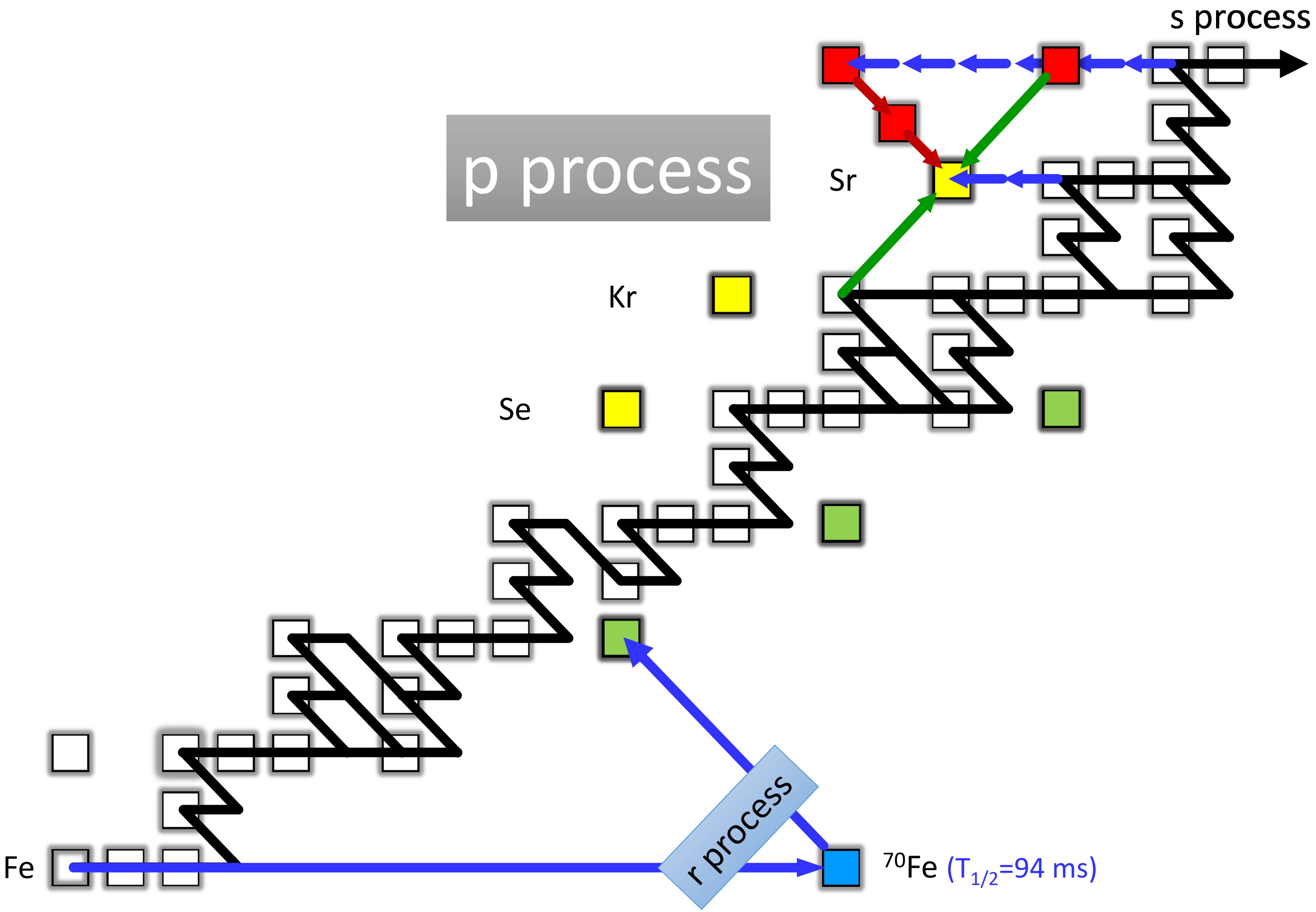
(p,γ) : (Z,N) $\Rightarrow$ (Z+1, N)
(p,n) : (Z,N) $\Rightarrow$ (Z+1, N-1)
(p,α) : (Z,N) $\Rightarrow$ (Z-1, N-2)

(α,γ) : (Z,N) $\Rightarrow$ (Z, N+1)
(α,n) : (Z,N) $\Rightarrow$ (Z-1, N+1)
(α,p) : (Z,N) $\Rightarrow$ (Z-2, N-1)

(n,γ) : (Z,N) $\Rightarrow$ (Z, N+1)
(n,p) : (Z,N) $\Rightarrow$ (Z-1, N+1)
(n,α) : (Z,N) $\Rightarrow$ (Z-2, N-1)

the s- and r-process pathways

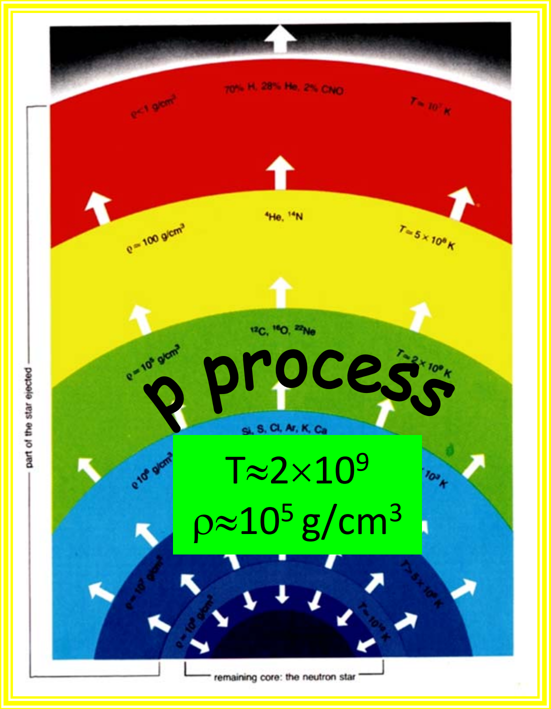



s process
p process
Sr
Kr
Se
Fe
r process
^{70}Fe ($T_{1/2}$=94 ms)

M. Arnould and S. Goriely Phys. Rep. 384, 1 (2003)

CONDITIONS

- Succession of (γ,n), (γ,p), (γ,α) reactions and -partly- inverse processes (n,γ), (p,γ), (α,γ)
- High temperatures T = 2÷3 × 10^9 K
- Short time scales

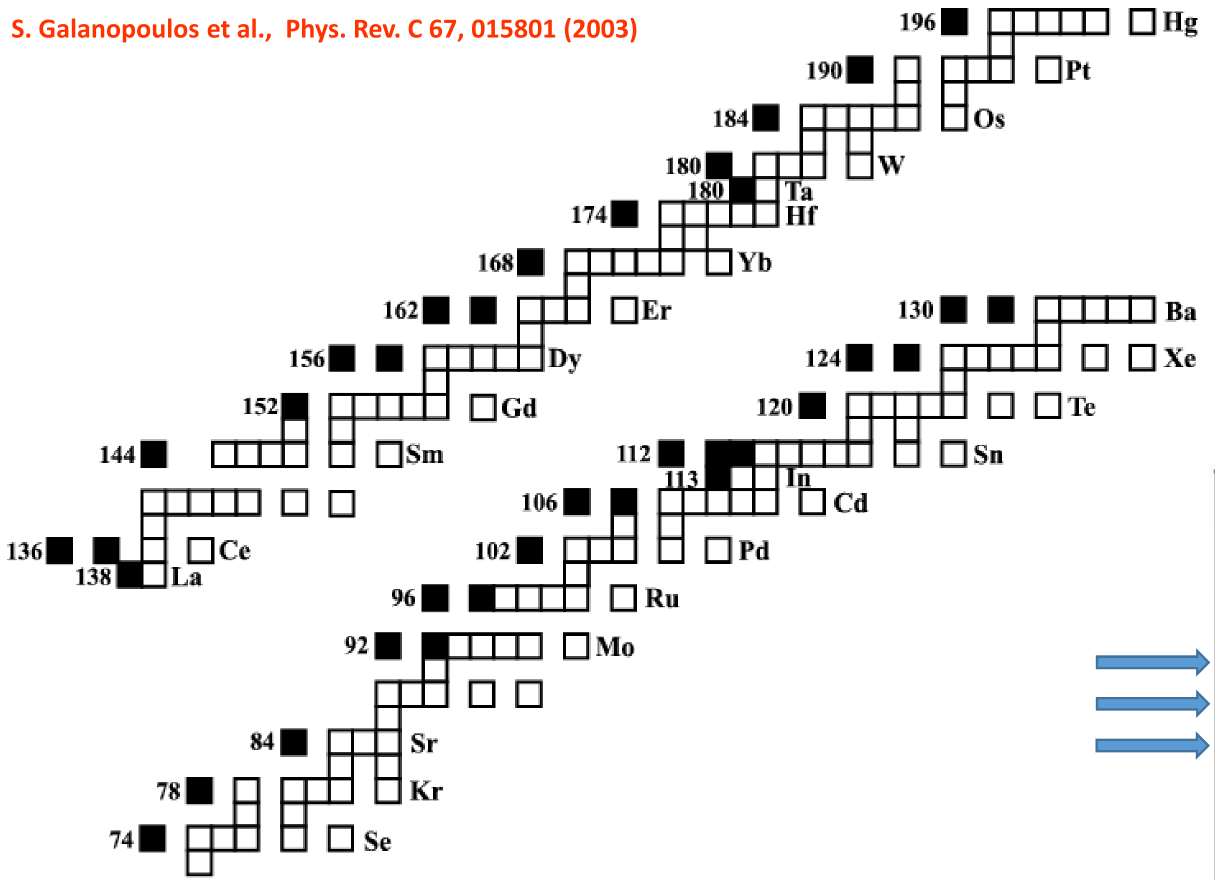


SITES

- SN Explosions
  - *- Pre- and/or Type II-SN explosion of massive stars*
  - *- Type Ia SN explosion of Chandrasekhar-mass WDs*
  - *- Type Ib/Ic and/or pair-creation SN explosion*
- He-detonating sub-Chandrasekhar–mass WDs

p nuclei and their solar-system abundances

S. Galanopoulos et al., Phys. Rev. C 67, 015801 (2003)

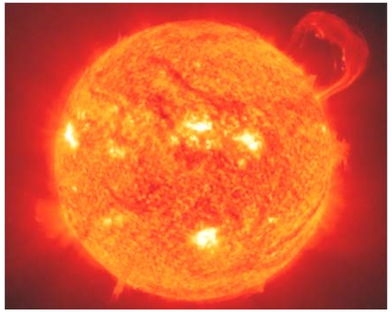


p-nuclei solar abundances

p nucleus	(%)	p nucleus	(%)	p nucleus	(%)
74_Se	0.89	114_Sn	0.65	156_Dy	0.06
78_Kr	0.35	115_Sn	0.34	158_Dy	0.10
84_Sr	0.56	120_Te	0.096	162_Er	0.14
92_Mo	14.84	124_Xe	0.10	164_Er	1.61
94_Mo	9.25	126_Xe	0.09	168_Yb	0.13
96_Ru	5.52	130_Ba	0.106	174_Hf	0.162
98_Ru	1.88	132_Ba	0.101	180_Ta	0.012
102_Pd	1.02	138_La	0.09	180_W	0.13
106_Pd	1.25	136_Ce	0.19	184_Os	0.02
108_Cd	0.89	138_Ce	0.25	190_Pt	0.01
113_In	4.3	144_Sm	3.1	196_Hg	0.15
112_Sn	0.97	152_Gd	0.20		

recall: the basic nuclear reaction network in the sun

SUN: The pp chain



$p(p,e^+\nu)d$

$d(p,\gamma)^3He$

I (86%): $^3He(^3He,2p)\,^4He$

II (14%): $^3He(^4He,\gamma)\,^7Be$

IIa (≈14%): $^7Be(p,\gamma)^8B(e^+,\nu)\,^8Be^*(\alpha)\,^4He$

IIb (0.02%): $^7Be(e^-,\nu)^7Li(p,\alpha)\,^4He$

$$\frac{d(H)}{dt} = -2<\sigma v>_{11}\frac{(H)^2}{2} - <\sigma v>_{12}(H)(D) + 2<\sigma v>_{33}\frac{(^3He)^2}{2} - <\sigma v>_{17}(H)(^7Be) - <\sigma v>^*_{17}(H)(^7Li)$$

$$\frac{d(D)}{dt} = <\sigma v>_{11}\frac{(H)^2}{2} - <\sigma v>_{12}(H)(D)$$

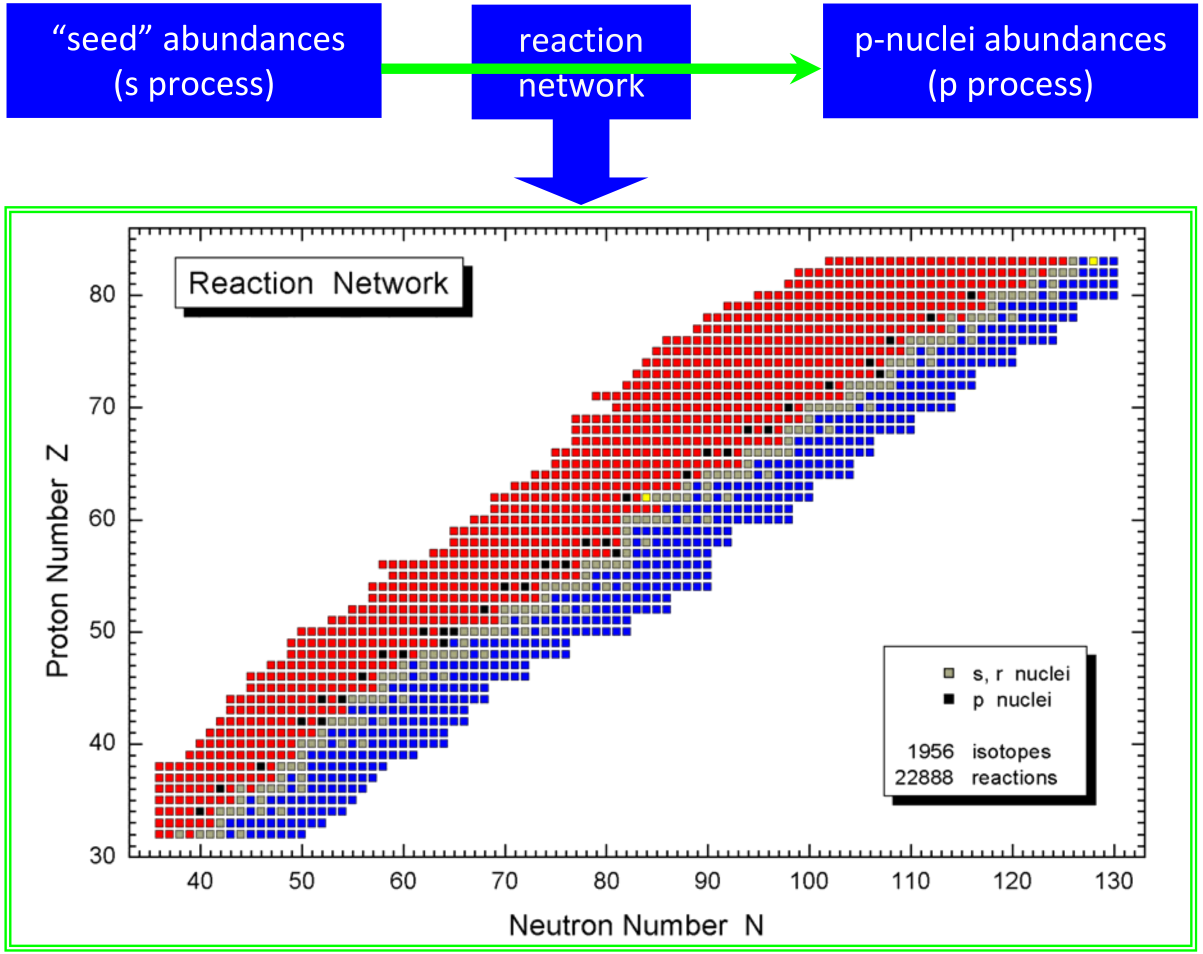
$$\frac{d(^3He)}{dt} = <\sigma v>_{12}(H)(D) - 2<\sigma v>_{33}\frac{(^3He)^2}{2} - <\sigma v>_{34}(^3He)(^4He)$$

$$\frac{d(^4He)}{dt} = <\sigma v>_{33}\frac{(^3He)^2}{2} - <\sigma v>_{34}(^3He)(^4He) + 2<\sigma v>_{17}(H)(^7Be) + 2<\sigma v>^*_{17}(H)(^7Li)$$

$$\frac{d(^7Be)}{dt} = <\sigma v>_{34}(^3He)(^4He) - <\sigma v>_{e7}n_e(^7Be) - <\sigma v>_{17}(H)(^7Be)$$

$$\frac{d(^7Li)}{dt} = <\sigma v>_{e7}n_e(^7Be) - <\sigma v>^*_{17}(H)(^7Li)$$

the p-process nuclear reaction network and the statistical model

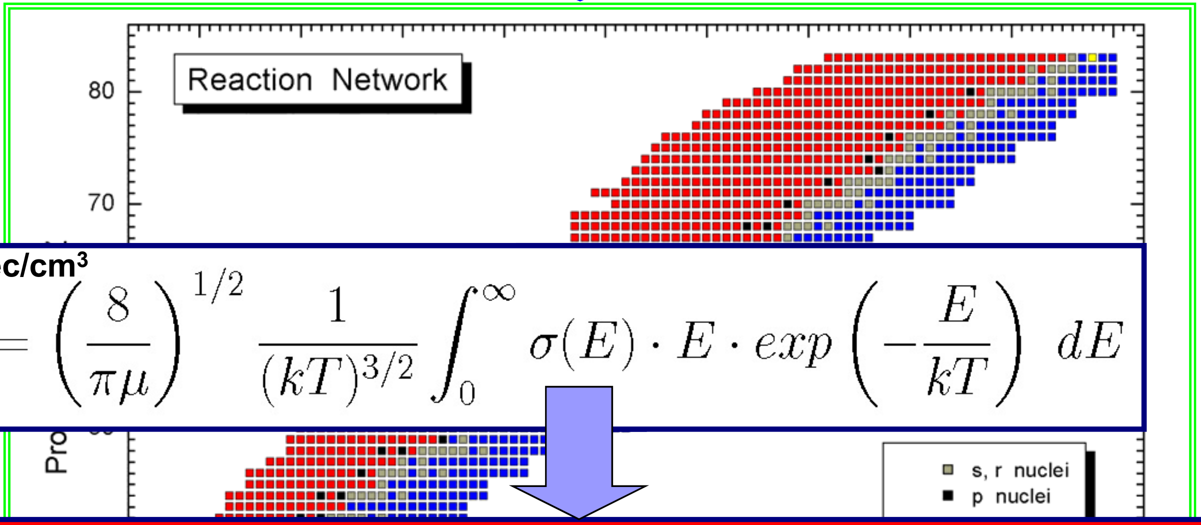


the p-process nuclear reaction network and the statistical model

"seed" abundances
(s process)

reaction
network

p-nuclei abundances
(p process)



reactions/sec/cm^3

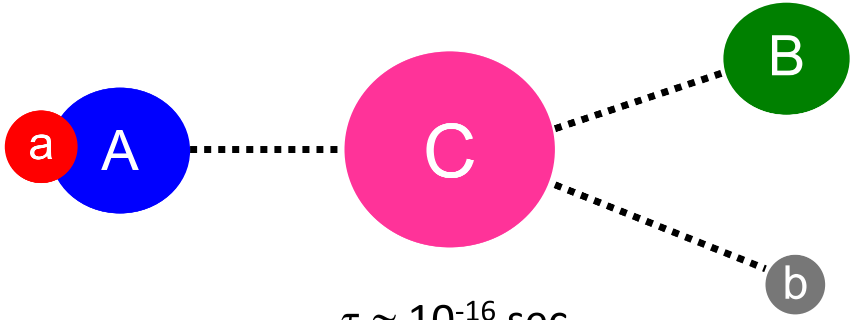
$$< \sigma v > = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) \cdot E \cdot exp\left(-\frac{E}{kT}\right) dE$$

HAUSER-FESHBACH THEORY

Optical Model Potentials - Nuclear Level Densities - γ-Ray Strengths

($32 \leq Z \leq 83$, $36 \leq N \leq 131$)

NEED FOR GLOBAL OMP & NLD MODELS



$\tau \approx 10^{-16}$ sec

$\alpha + A \rightarrow C^{*} \rightarrow (B + b) + (D + d) + \ldots$

$\alpha + A \rightarrow C^{*} \rightarrow C + \gamma$

Capture reaction (via compound nucleus formation)

input parameters entering the Hauser-Feshbach calculations

α + A $\rightarrow$ C^* $\rightarrow$ (B + b) **+** (D + d) + ...

$$\sigma_{bB} = \frac{\pi\lambda^2}{(2J_\alpha + 1)(2J_A + 1)} \sum_{J^\pi} (2J_C + 1)\, T_{\alpha A}^{J^\pi} \frac{T_{bB}^{J^\pi}}{\sum_i T_i^{J^\pi}}$$

$T_{\alpha A}^{J^\pi}$:= probability that **α** will cross the surface of **A** to form a compound state of **C** having spin ***J***. It depends on the orbital momentum of **α**

$T_{bB}^{J^\pi}$:= probability that **b** escapes from a state of the compound nucleus **C** with spin ***J.***

$\sum_i T_i^{J^\pi}$:= sum of probabilities over all exit channels ***i.***

If **γ emission** then *T* from **Giant Dipole de-excitation** **(GDR)**

If **particle emission** then *T* from **Optical Model Potentials** **(OMP)**

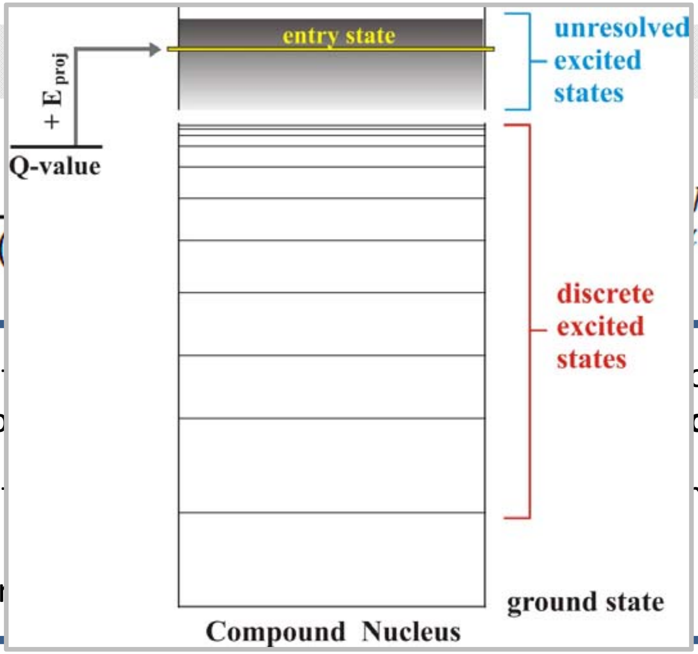
input parameters entering the Hauser-Feshbach calculations

$\sigma_{bB} = \frac{}{(}$ … $T^{J\pi}_{\alpha A}$ $\frac{T^{J\pi}_{bB}}{\sum_i T^{J\pi}_i}$

$T^{J\pi}_{\alpha A}$:= probabilit… having sp… compound state of **C** … **α**

$T^{J\pi}_{bB}$:= probabilit… nd nucleus **C** with spin ***J***.

$\sum_i T^{J\pi}_i$:= sum of pr…



If **γ emission** then *T* from **Giant Dipole de-excitation** (GDR)

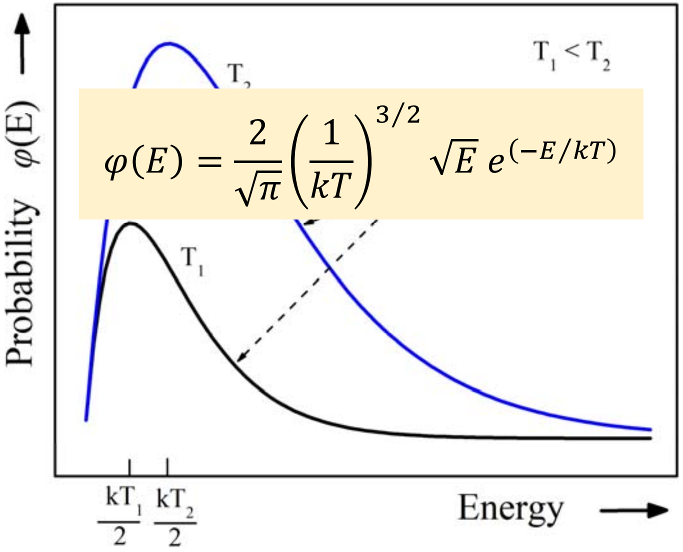
If **particle emission** then *T* from **Optical Model Potentials** (OMP)

CN is excited to continuum => *Ts* have to be averaged

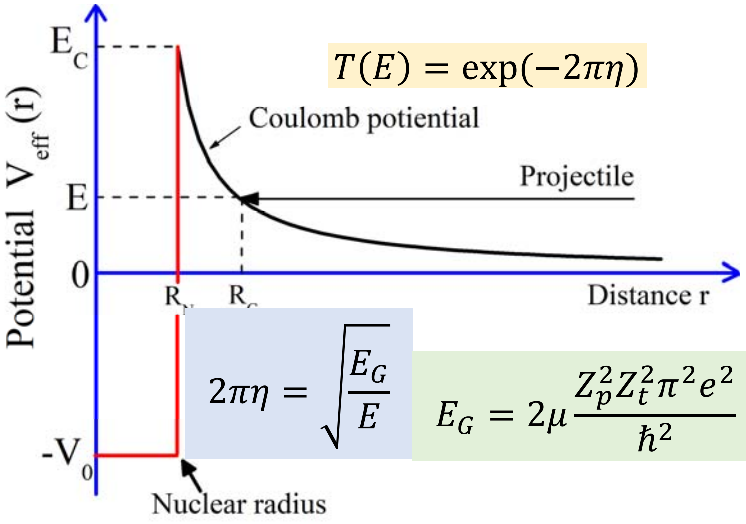
$$\bar{T}_{\alpha A} = \sum_I \int \rho(E_\alpha, I)\, T^I_{\alpha A}(E_\alpha)\, dE_\alpha$$

Nuclear Level Density (NLD)

Gamow peaks and windows: the astrophysical relevant energy regimes



$$\varphi(E) = \frac{2}{\sqrt{\pi}}\left(\frac{1}{kT}\right)^{3/2}\sqrt{E}\,e^{(-E/kT)}$$

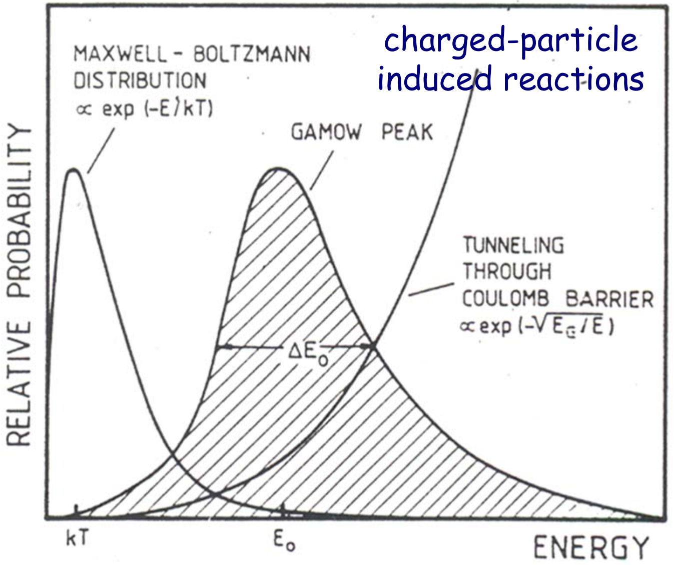


$$T(E) = \exp(-2\pi\eta)$$

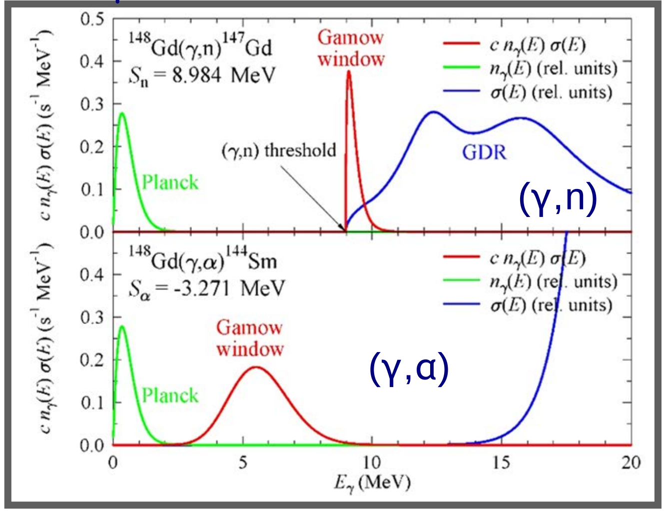
$$2\pi\eta = \sqrt{\frac{E_G}{E}}$$

$$E_G = 2\mu\frac{Z_p^2 Z_t^2 \pi^2 e^2}{\hbar^2}$$

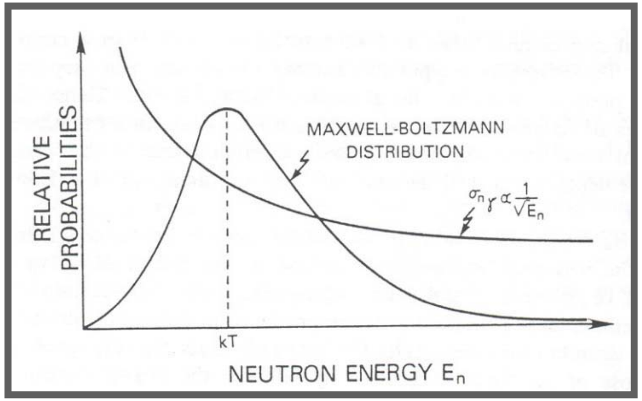
charged-particle induced reactions



photon-induced reactions



neutron-induced reactions



$E_o \approx kT$ ΔE_n = 20 ÷ 500 keV

$$E_0 = (bkT/2)^{2/3}$$

$$b^2 = E_G = 2\mu\pi^2\frac{e^4 Z_t^2 Z_p^2}{\hbar^2}$$

$$\Delta E = (16E_0kT/3)^{1/2}\exp(-3E_0/kT)$$

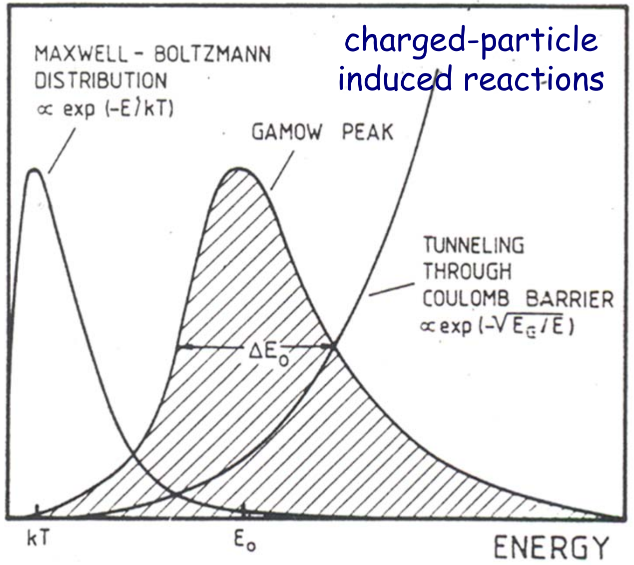
Gamow peaks and windows: the astrophysical relevant energy regimes

REACTION	$Z_{TARG.}$	E_{COUL} (MeV)	T=1.8 T_9: E_0 (MeV)	T=1.8 T_9: ΔE (MeV)	T=3.3 T_9: E_0 (MeV)	T=3.3 T_9: ΔE (MeV)
^{74}Se + p	34	7.9	1.89	1.27 – 2.52	2.83	1.80 – 3.87
^{90}Zr + p	40	8.8	2.11	1.45 – 2.77	3.16	2.07 – 4.26
^{103}Rh + p	45	9.5	2.28	1.60 – 2.97	3.42	2.28 – 4.56
^{124}Sn + p	50	10	2.45	1.74 – 3.16	3.67	2.49 – 4.85

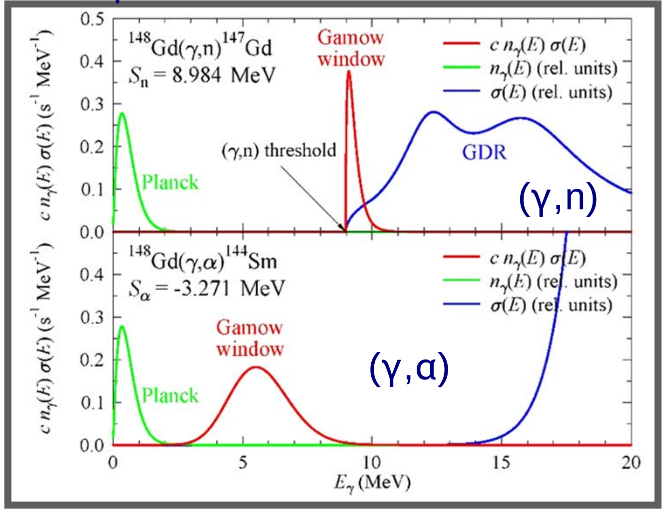
(p,γ) reactions:
$E_{CM} = 1 - 5$ MeV,
$\sigma = 1\ \mu b \div 1\ mb$

(α,γ) reactions:
$E_{CM} = 6 - 12$ MeV,
$\sigma = 0.1 \div 100\ \mu b$

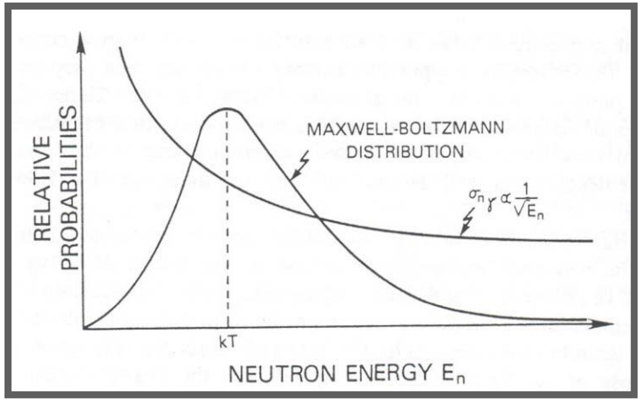
charged-particle induced reactions



photon-induced reactions



neutron-induced reactions



$E_0 \approx kT$ $\Delta E_n = 20 \div 500$ keV

$$E_0 = (bkT/2)^{2/3}$$

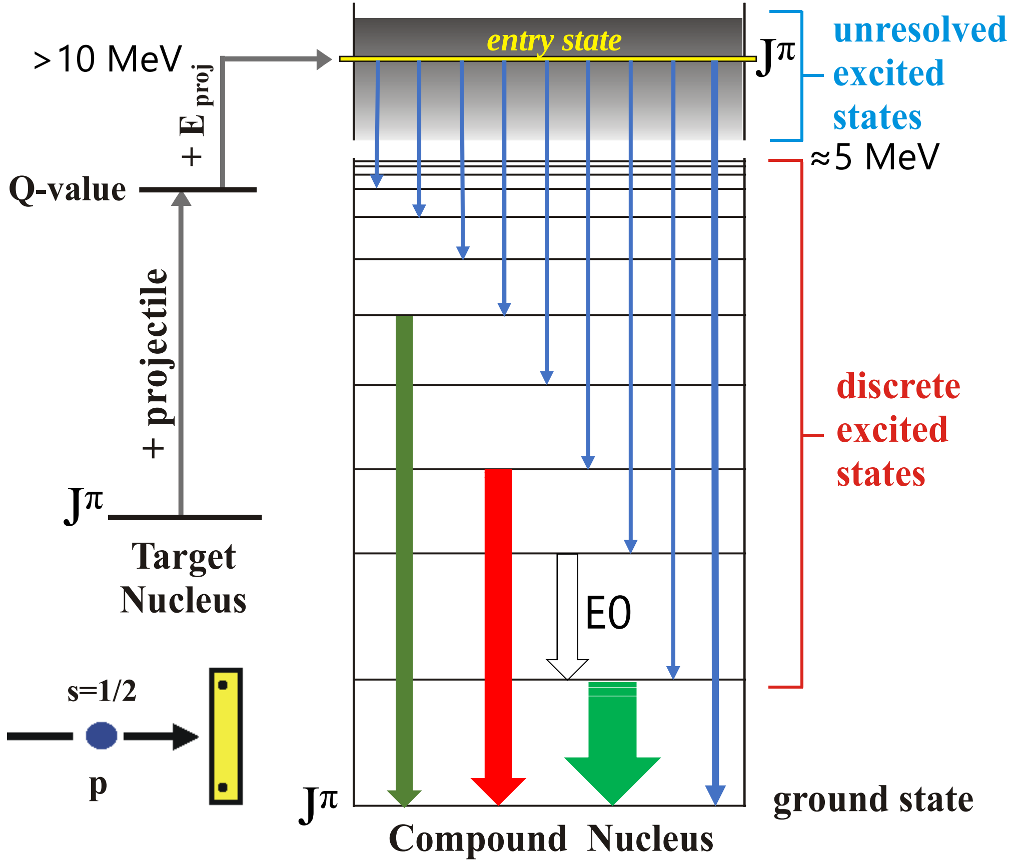
$$b^2 = E_G = 2\mu\pi^2 \frac{e^4 Z_t^2 Z_p^2}{\hbar^2}$$

$$\Delta E = (16 E_0 kT/3)^{1/2}\ exp(-3E_0/kT)$$

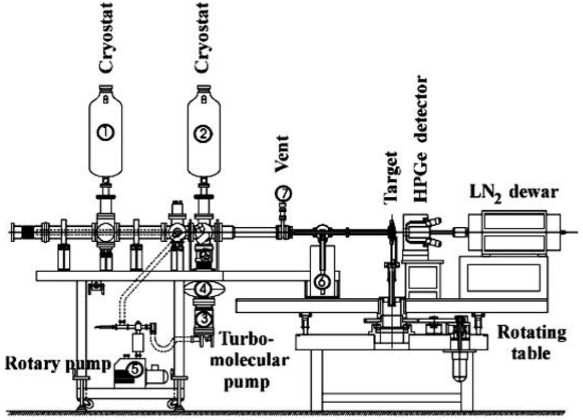
Direct methods for cross-section measurements of capture reactions

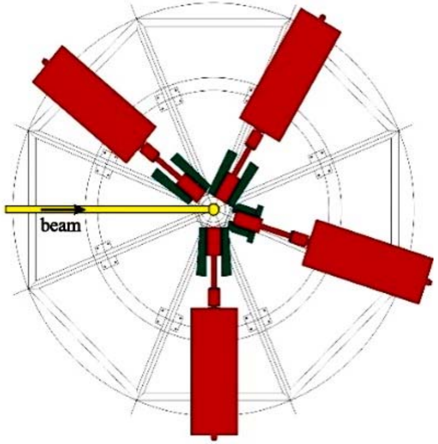
	OFF–BEAM activation measurements	IN–BEAM γ-angular distribution measurements	IN–BEAM angle-integrated measurements
reaction to study	final nucleus must be unstable	any	any
target	enriched or natural	enriched	enriched
backing	If, then low-Z (C, Al, Si ...)	If, then high-Z (Ta, Au, ...)	If, then mostly high-Z (Ta, Au, ...)
detectors	normal size HPGe (ε≈30%)	large-volume HPGe (arrays) (ε≥70%)	4π calorimeters [large NaI(Tl)] (ε≈100%)
γ rays to detect	in most cases $E_\gamma \leq 2$ MeV	up to $E_\gamma \approx 15$ MeV	up to $E_\gamma \approx 15$ MeV

cross sections from γ-angular distribution measurements (1/4)

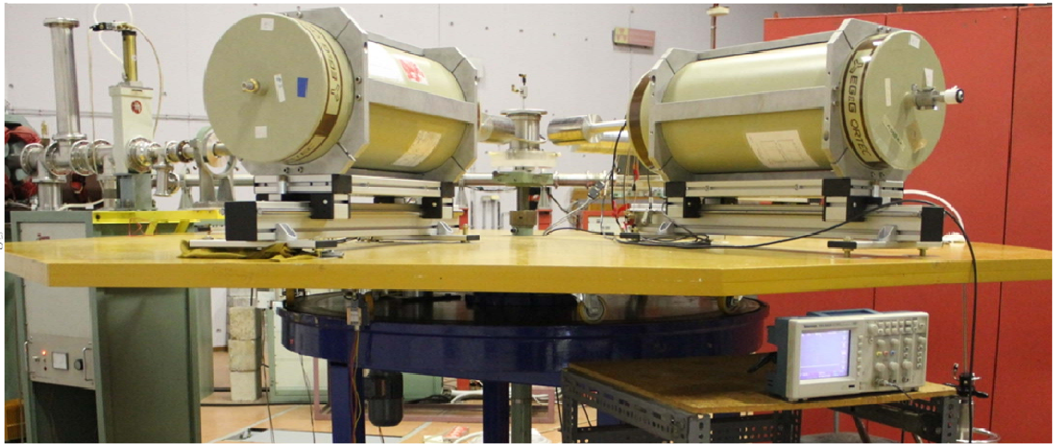


The Stuttgart HPGe-detector array

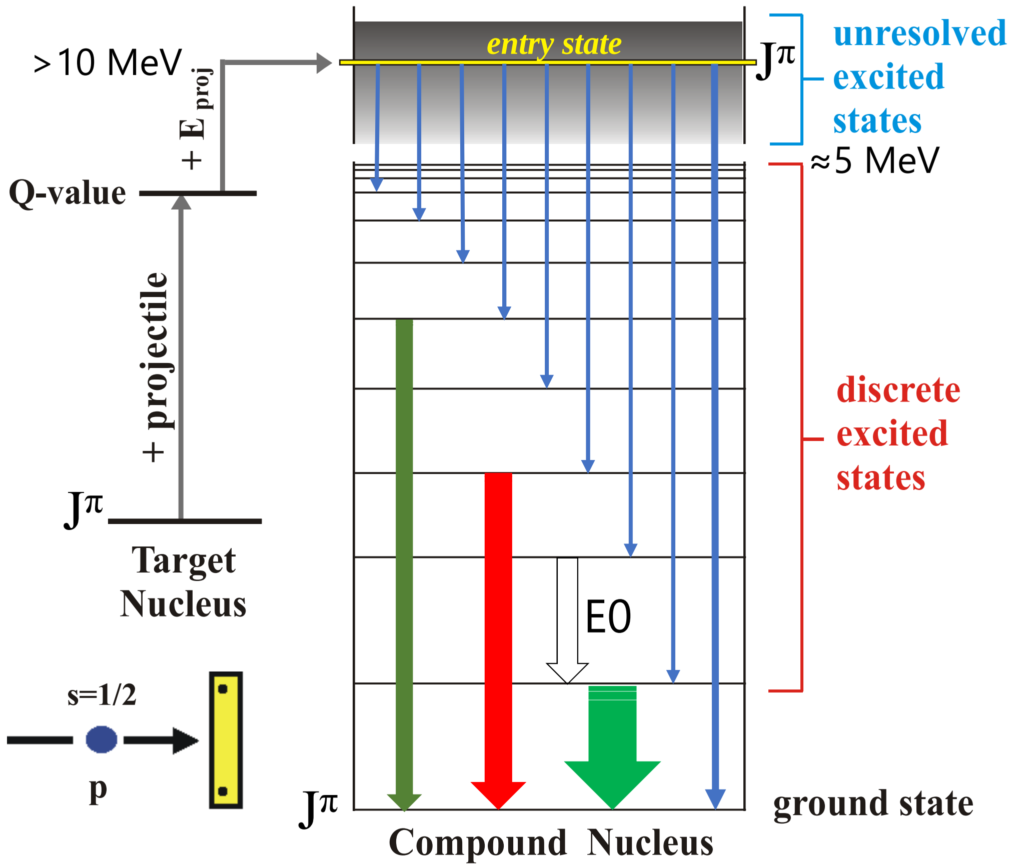




… now at “Demokritos” (no BGOs)



cross sections from γ-angular distribution measurements (2/4)



entry-state parity:

$\pi(gs)_{TARGET} * (-1)^{Lp} = \pi(exc.\ state)_{CN}$

entry-state spin:

$|J_T - J_p| \leq J_{ENTRY} \leq |J_T + J_p|$

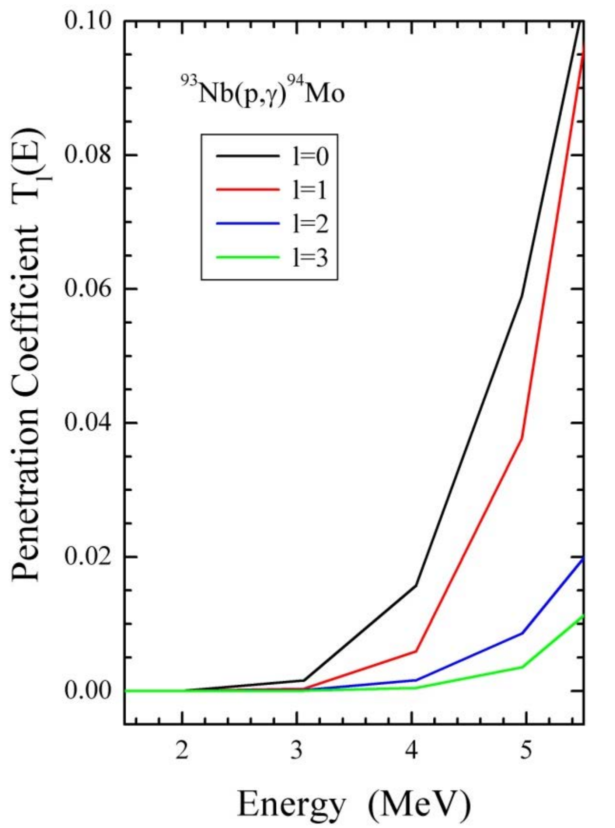
TARGET : even-odd nucleus

	$L_p=0$	$L_p=1$
J_{TARG}	J_{ENTRY}	J_{ENTRY}
1/2	0 , 1	0 , 1 , 2
3/2	1 , 2	0 , 1 , 2 , 3
5/2	2 , 3	1 , 2 , 3 , 4
7/2	3 , 4	2 , 3 , 4 , 5
9/2	4 , 5	3 , 4 , 5 , 6

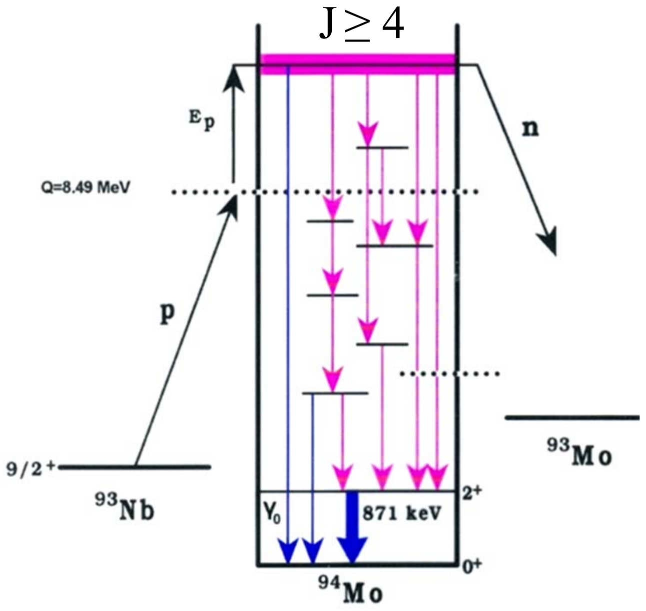
TARGET : even-even nucleus

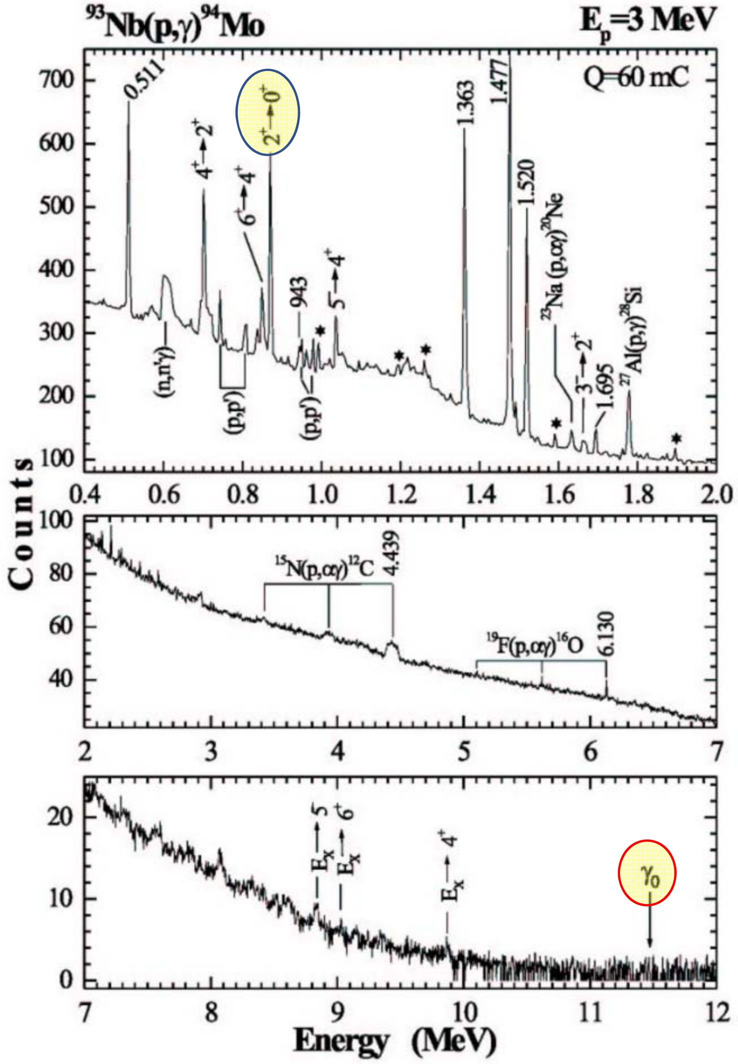
	$L_p=0$	$L_p=1$
J_{TARG}	J_{ENTRY}	J_{ENTRY}
0	1/2	1/2 , 3/2

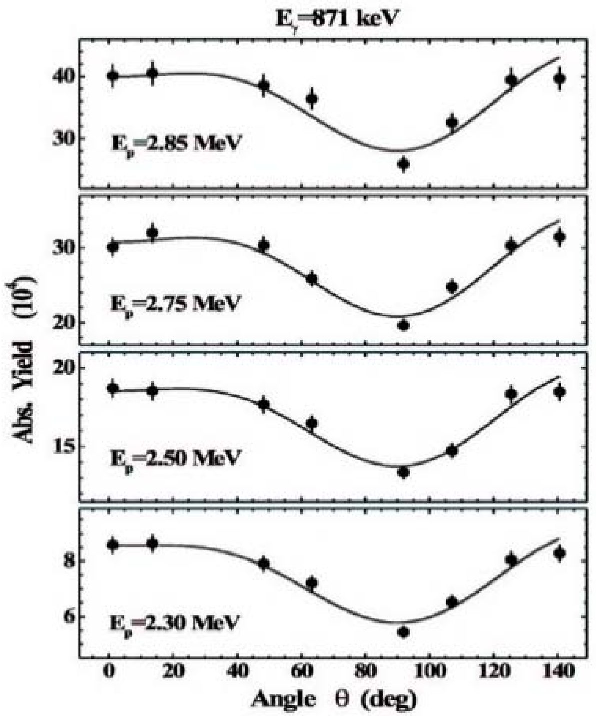
OMP used: Jeukenne et al., Phys. Rev. C 16, 80 (1977)



$^{93}Nb(p,\gamma)^{94}Mo$



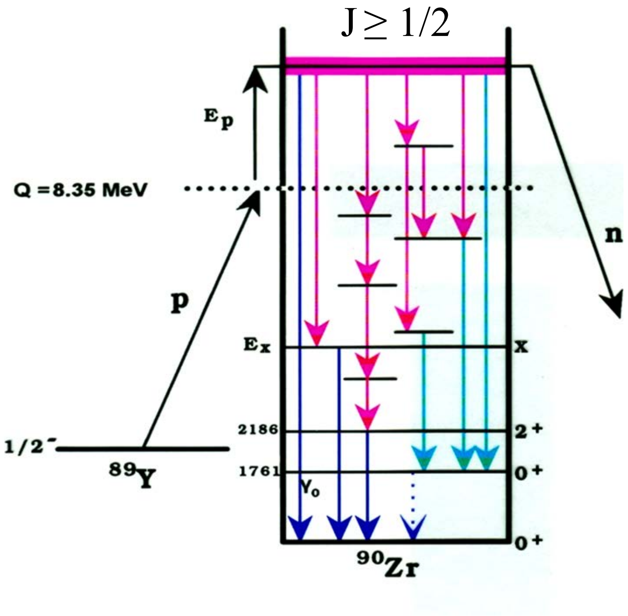


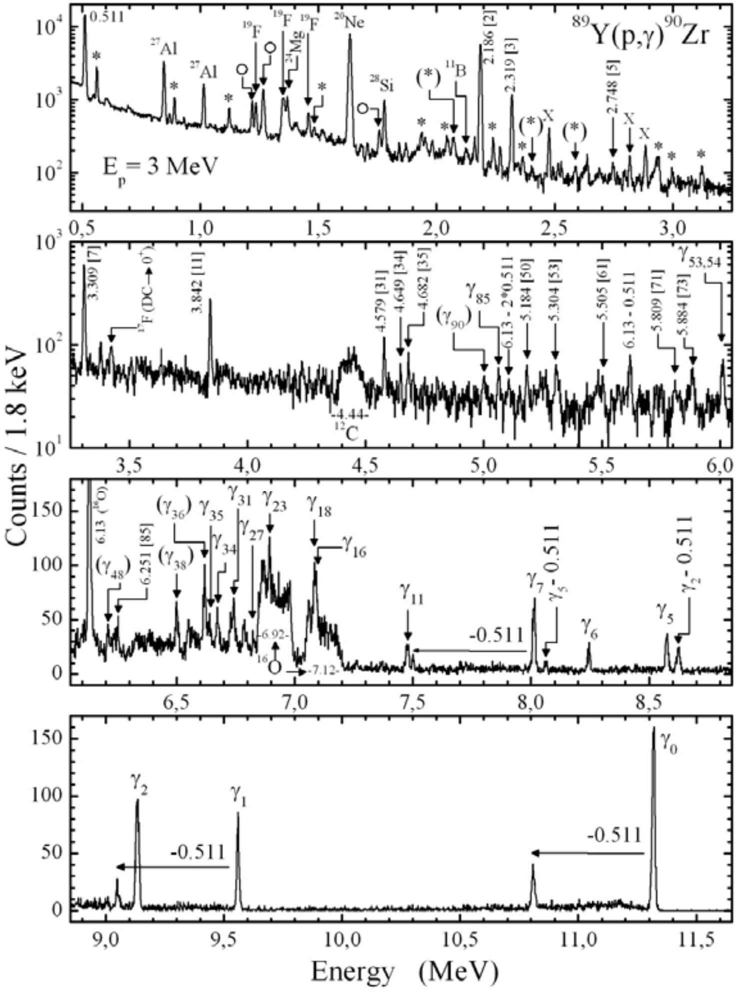


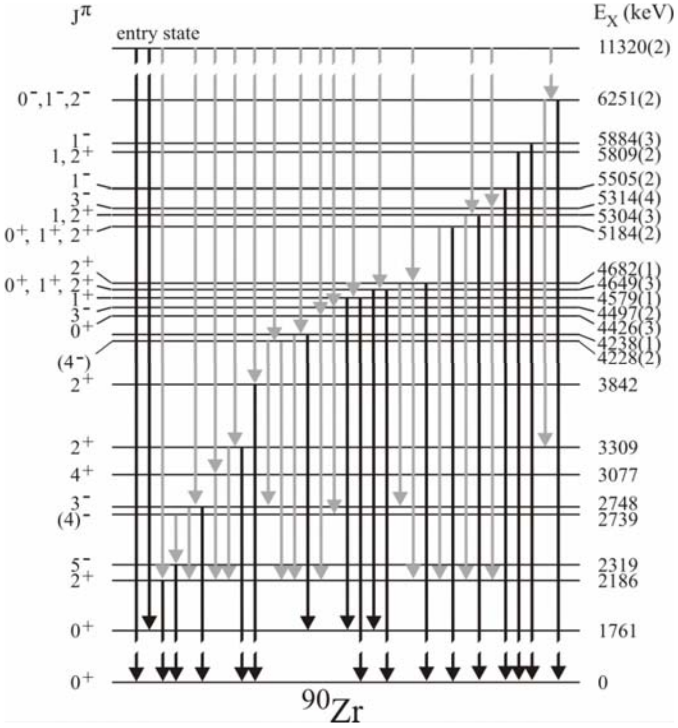
$$W(\vartheta) = A_0\left(1 + a_2P_2(\cos\vartheta) + a_4P_4(\cos\vartheta)\right)$$

$$\sigma = \frac{A}{N_A N_p \xi}\sum_j (A_0)_j$$

$^{89}Y(p,\gamma)^{90}Zr$



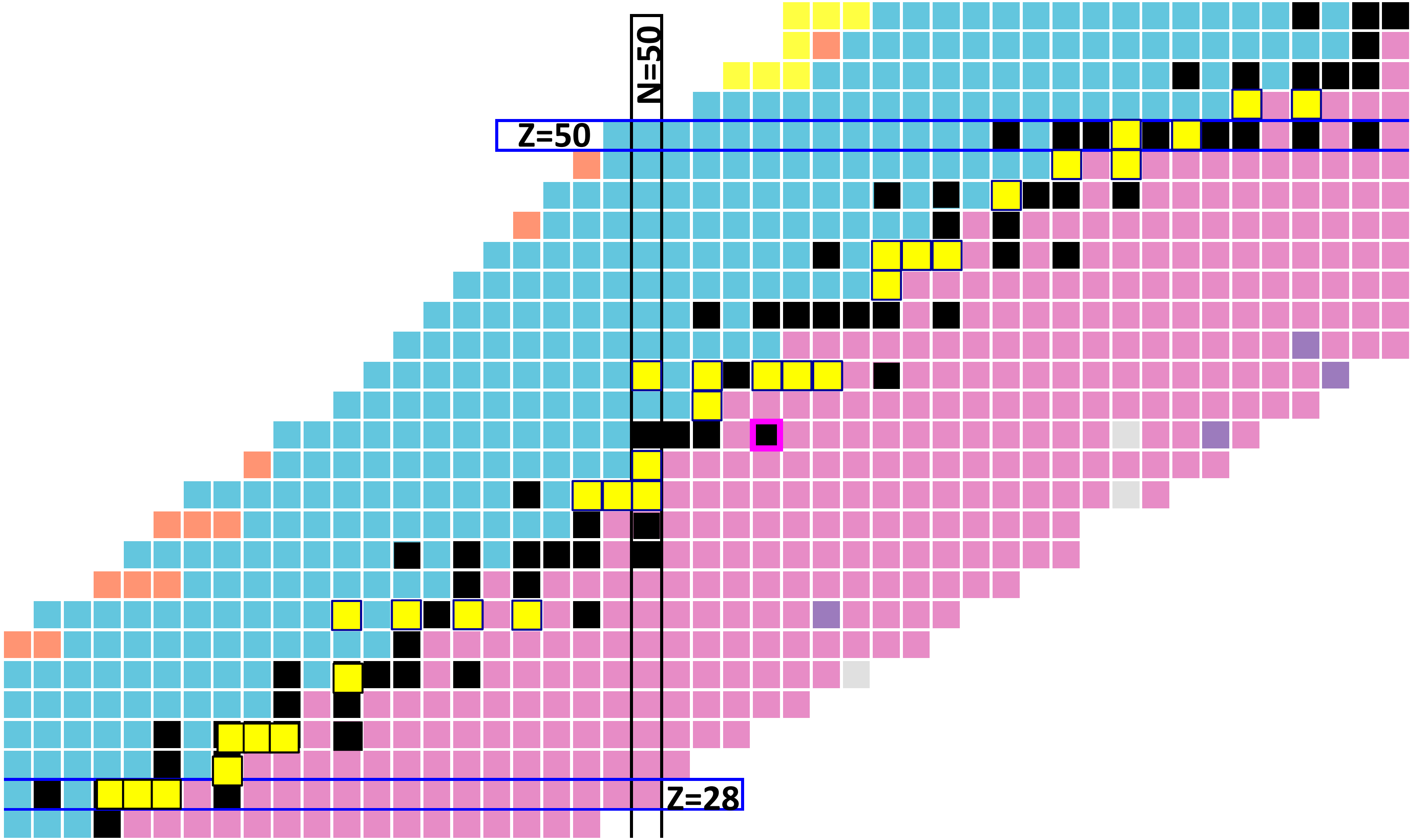




$$W(\vartheta) = A_0\left(1 + a_2 P_2(\cos\vartheta) + a_4 P_4(\cos\vartheta)\right)$$

$$\sigma = \frac{A}{N_A N_p \xi} \sum_j (A_0)_j$$

capture reactions investigated by "Demokritos"



Conclusions based on (p,γ) measurements

In most cases, uncertainties affecting nuclear input (OMP, NLD) give rise to at most 30-40% uncertainties in the reaction rates.

HF predictions are more sensitive to OMP rather than to NLD.

At this stage no global predictions possible using a given OMP-NLD combination. OMPs and NLDs need further improvement to be taken as “global”

Conclusions based on (α,γ) measurements

The α-potential is (still) poorly known; Consequently, the astrophysical (α,γ) reaction rates obtained from HF calculations can be highly uncertain and abundance calculations may strongly be affected!

So far, the α-potential of Demetriou et al., reproduces new experimental data. However, more data are needed in the mass range A≈100 and higher to further constrain potential parameters.

to Claus Rolfs …