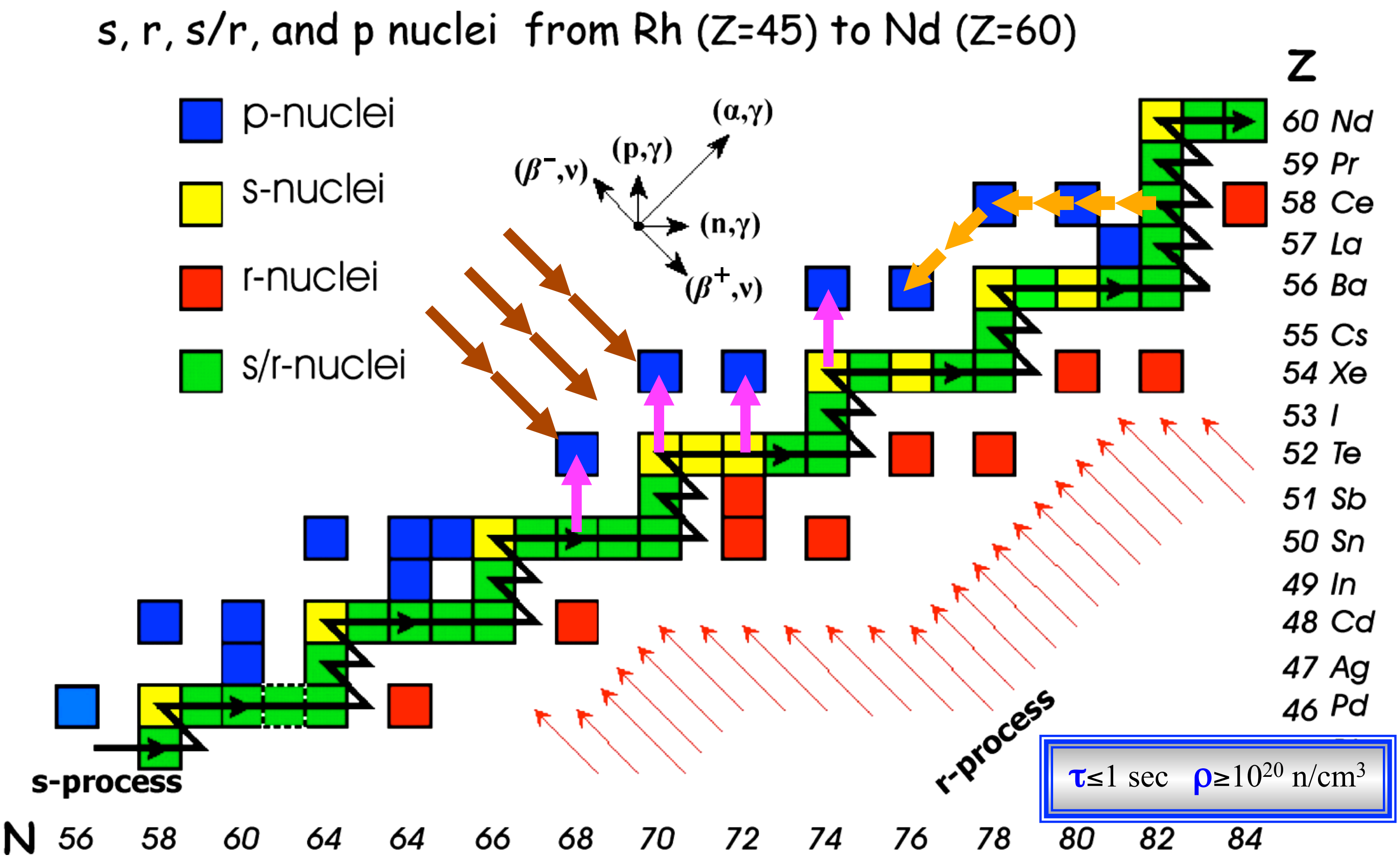
Cross section measurements of capture reactions relevant to Nuclear Astrophysics

A. Lagoyannis
Institute of Nuclear and Particle Physics,
N.C.S.R. “Demokritos”

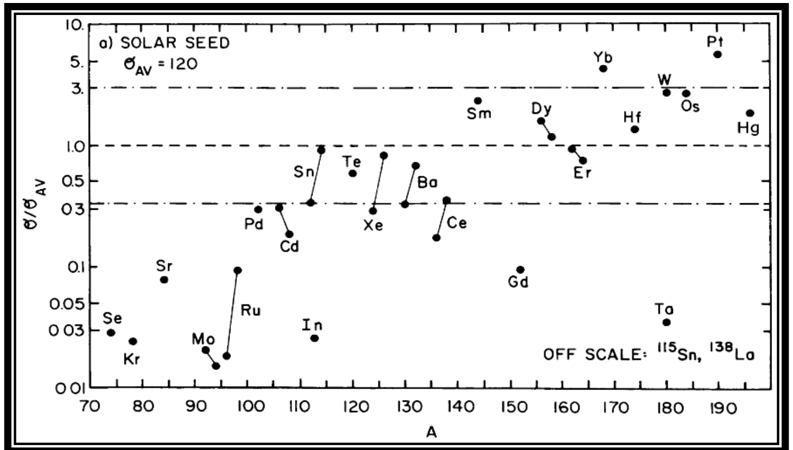
Pathways for heavy-element nucleosynthesis



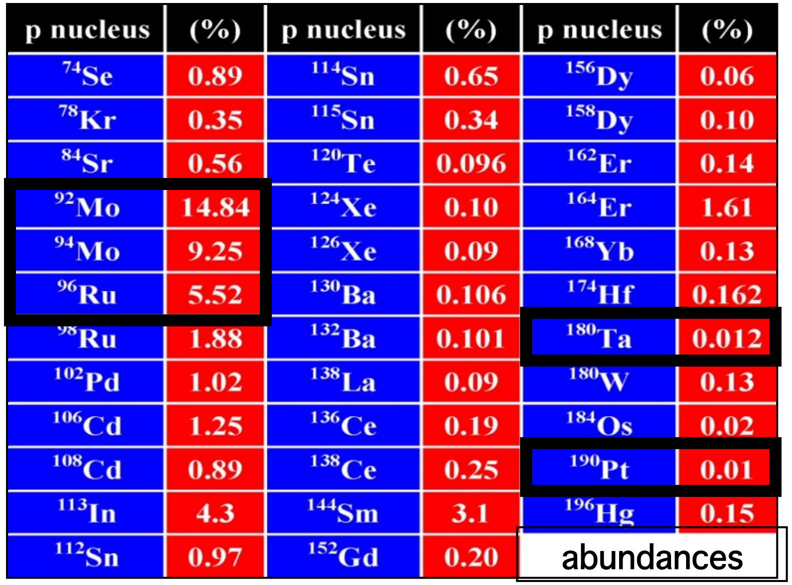
$\tau \leq 1$ sec $\rho \geq 10^{20}$ n/cm^3

$\tau \geq 100$ yr $\rho \approx 10^8$ n/cm^3

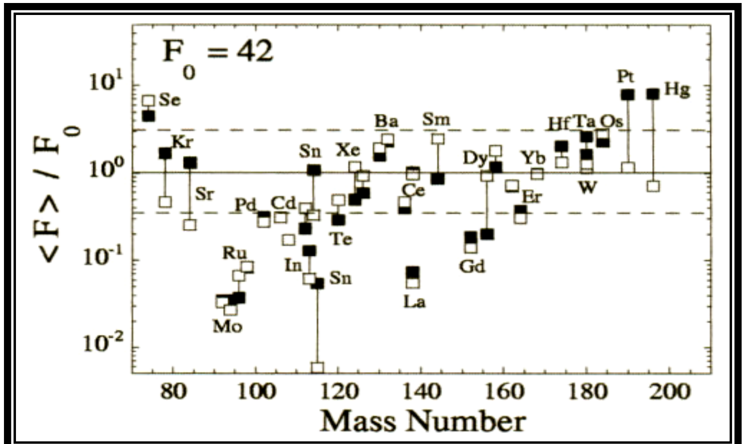
p nuclei and p-nuclei abundances



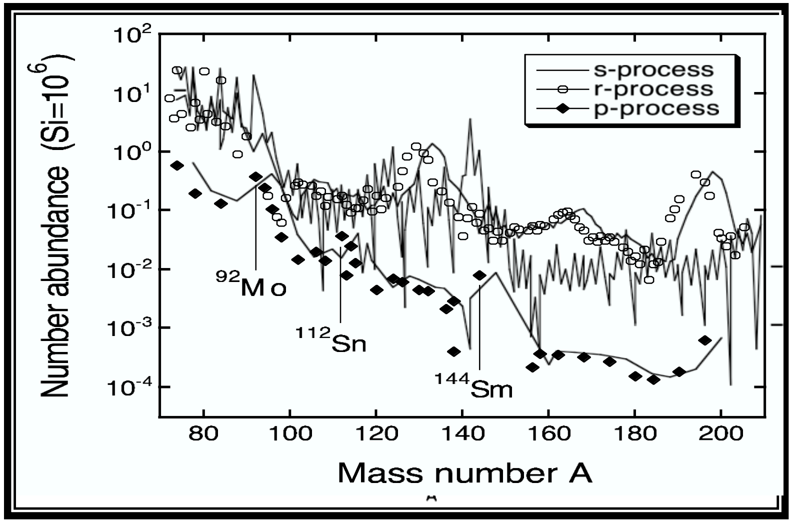
Woosley and Howard, Ap. J. Suppl. 36, 285 (1978)



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}Cd	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	abundances	

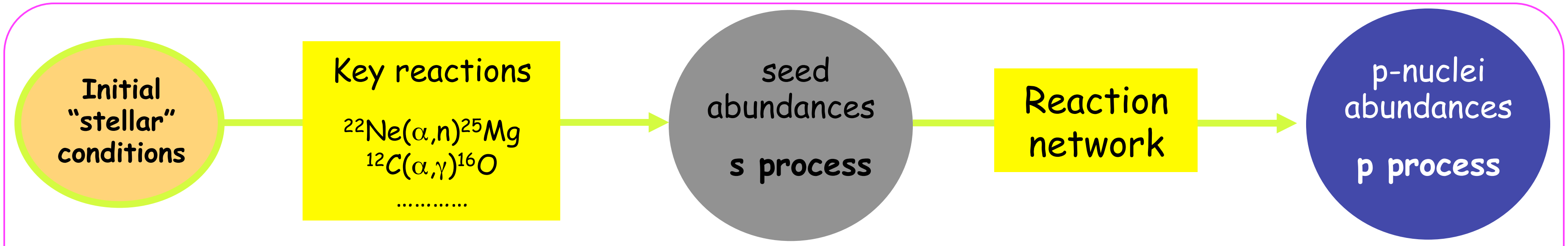


S. Goriely et al., A&A 375, 35 (2001)



C. Iliadis, Nuclear Physics of Stars (2008)

Reaction network



Initial “stellar” conditions

Key reactions

$^{22}Ne(\alpha,n)^{25}Mg$

$^{12}C(\alpha,\gamma)^{16}O$

…………

seed abundances

s process

Reaction network

p-nuclei abundances

p process

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

HAUSER-FESHBACH THEORY is required !

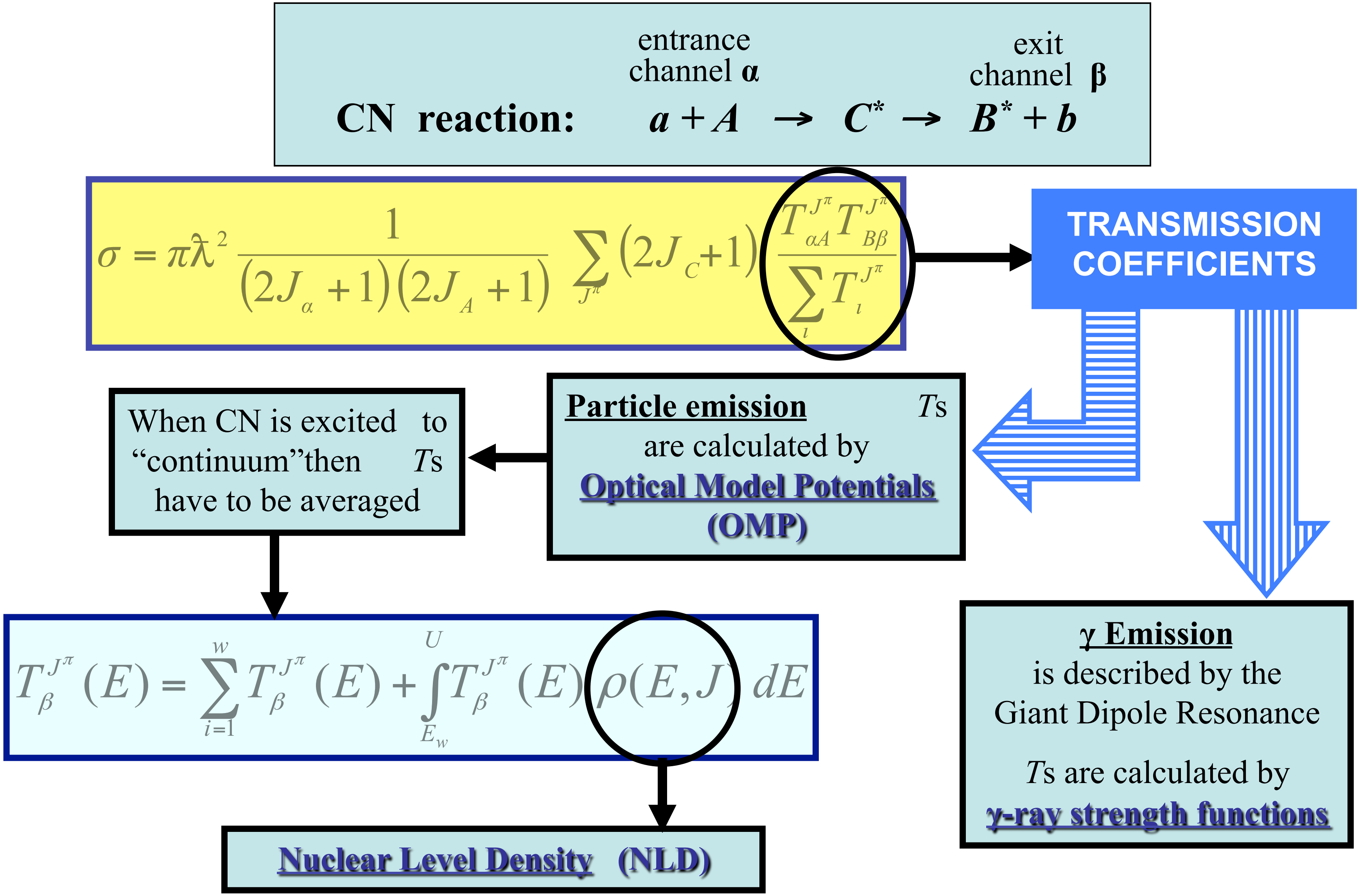
HAUSER-FESHBACH THEORY

Optical Model Potentials - Nuclear Level Densities
γ-ray strength functions - Masses

(32≤Z≤83 , 36≤N≤131)

NEED FOR GLOBAL MODELS OF OMP, NLD, …

Cross section calculations using the HF theory



entrance channel **α** exit channel **β**

CN reaction: $\boldsymbol{a + A \rightarrow C^* \rightarrow B^* + b}$

$$\sigma = \pi \lambda\!\!\!^{-2} \frac{1}{(2J_\alpha + 1)(2J_A + 1)} \sum_{J^\pi} (2J_C + 1) \frac{T^{J^\pi}_{\alpha A} T^{J^\pi}_{B\beta}}{\sum_\iota T^{J^\pi}_\iota}$$

TRANSMISSION COEFFICIENTS

Particle emission *T*s are calculated by **Optical Model Potentials (OMP)**

When CN is excited to "continuum" then *T*s have to be averaged

$$T^{J^\pi}_\beta(E) = \sum_{i=1}^{w} T^{J^\pi}_\beta(E) + \int_{E_w}^{U} T^{J^\pi}_\beta(E)\, \rho(E,J)\, dE$$

Nuclear Level Density (NLD)

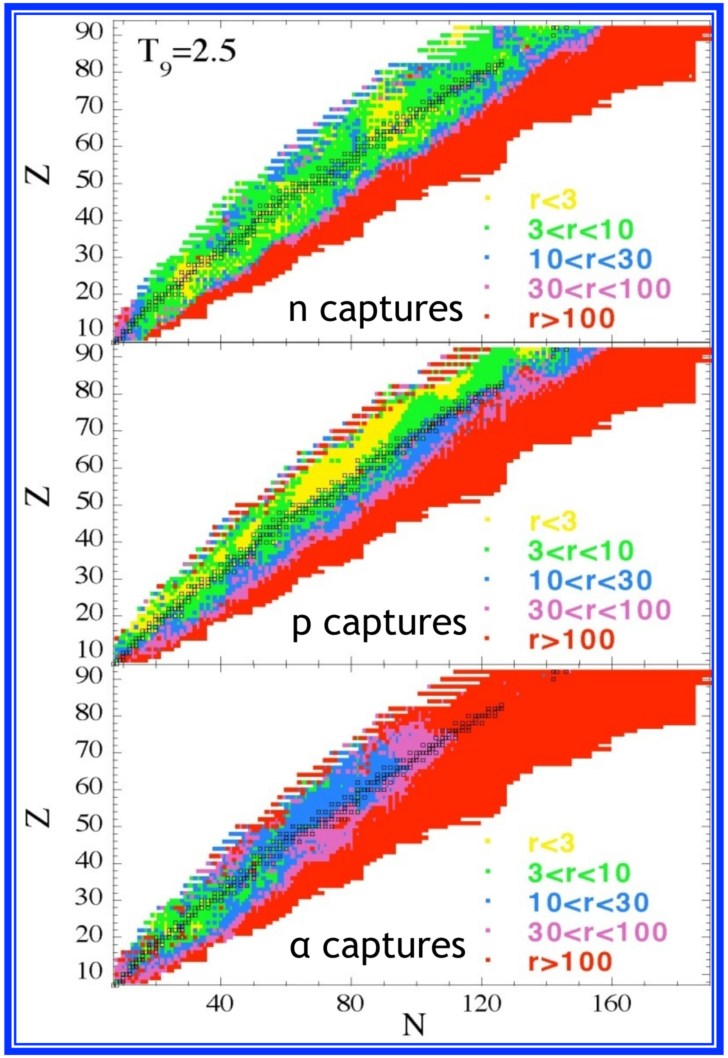
γ Emission is described by the Giant Dipole Resonance

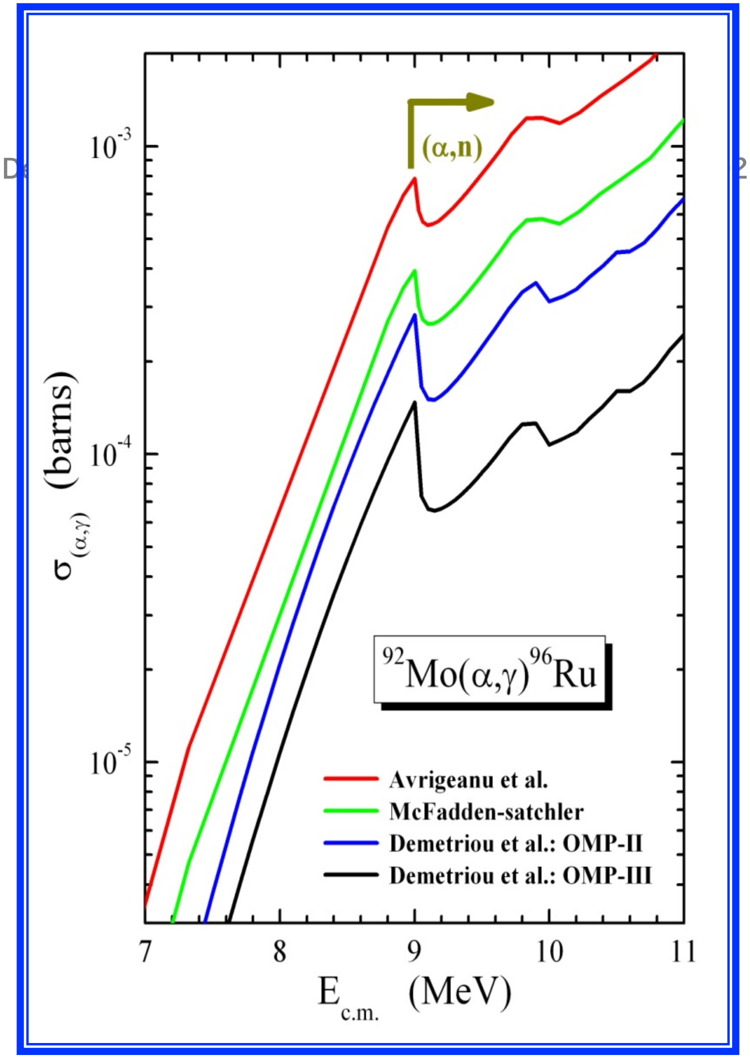
*T*s are calculated by **γ-ray strength functions**

Impact of nuclear physics uncertainties on p-nuclei abundances

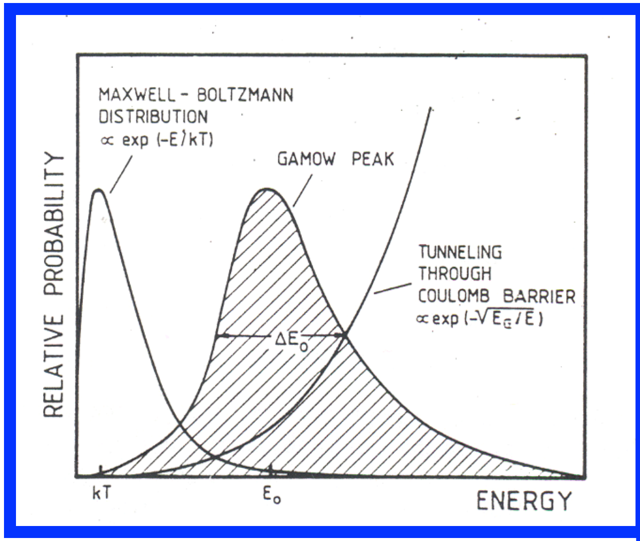
$r := \langle \sigma \upsilon \rangle_{\text{max.}} / \langle \sigma \upsilon \rangle_{\text{min.}}$ obtained with 14 different sets of nuclear ingredients (OMP, NLD, ...) in HF calculations.

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





Gamow peaks and windows: the astrophysically relevant energies



charged-particle induced reactions

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

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

$$\Delta E = \sqrt{\frac{16 E_0 kT}{3}} \exp(-3E_0/kT)$$

reaction	barrier (MeV)	E_0 (keV)	T (K)
p + p (sun)	0.55	5.9	1.5×10^7
α + ^{12}C (red giants)	300	56	1.5×10^8
^{12}C + ^{12}C (massive stars)	10.44	1500	≈ 1×10^9
p + ^{74}Se (p process)	7.9	2800	≈ 3×10^9

(p,γ) reactions: E_{CM} = 1 - 5 MeV

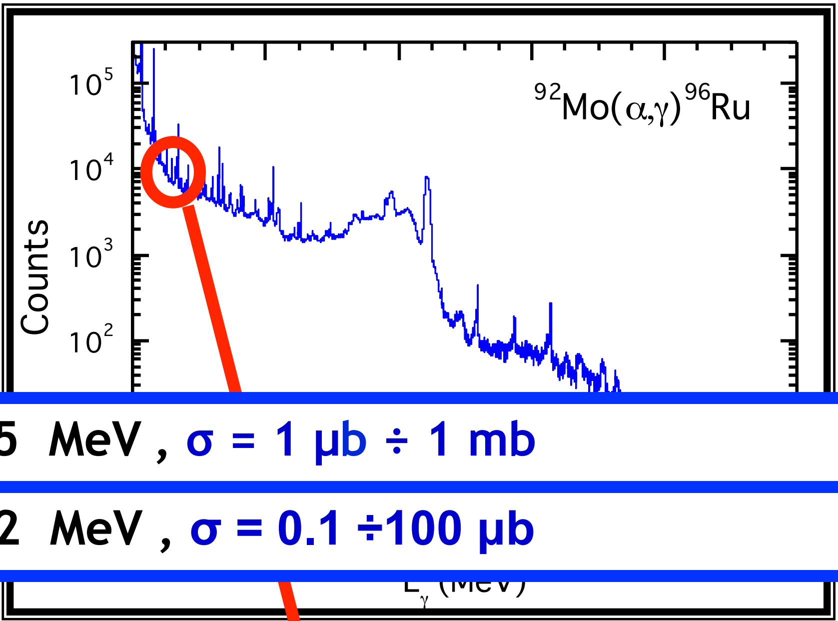
(α,γ) reactions: E_{CM} = 6-12 MeV

OUR GOAL

To measure the cross section
σ
at these energy regions

γ angular distribution measurements: the (α,γ) problem

MINIBALL @ IKP/Cologne

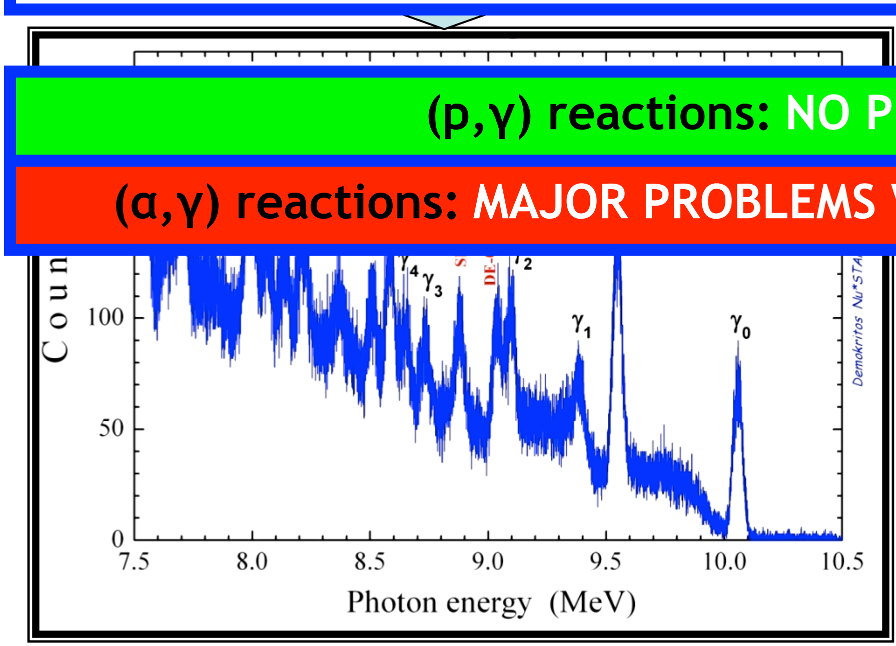


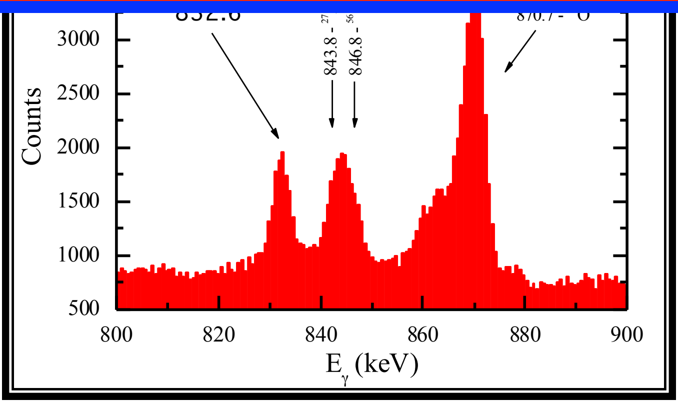
(p,γ) reactions: E_{CM} = 1 - 5 MeV , σ = 1 μb ÷ 1 mb

(α,γ) reactions: E_{CM} = 6-12 MeV , σ = 0.1 ÷100 μb

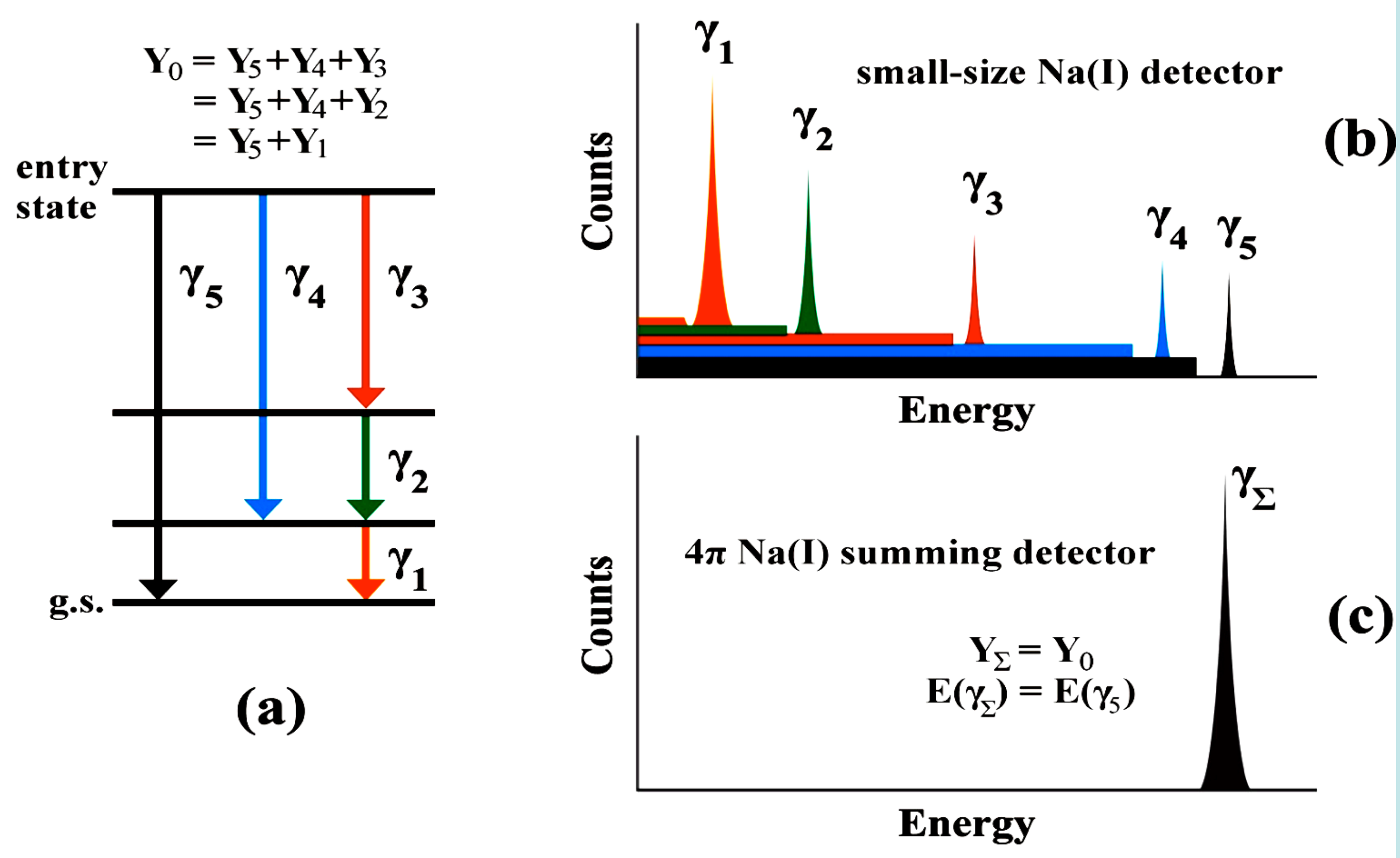
(p,γ) reactions: NO PROBLEM TO MEASURE

(α,γ) reactions: MAJOR PROBLEMS WITH BEAM-INDUCED BACKGROUND

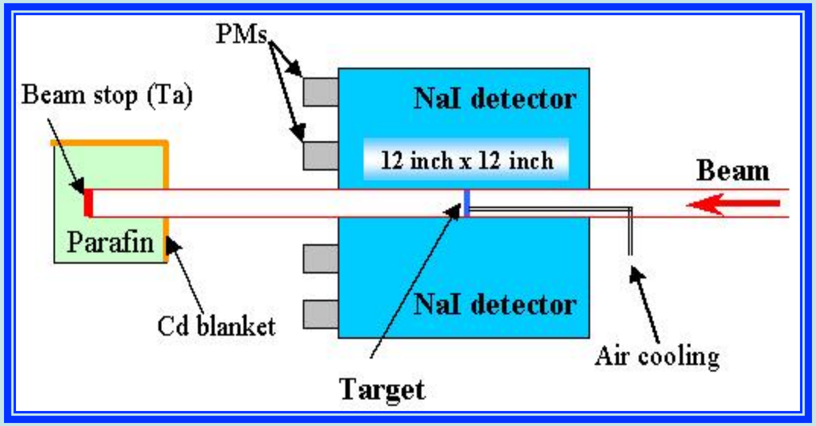




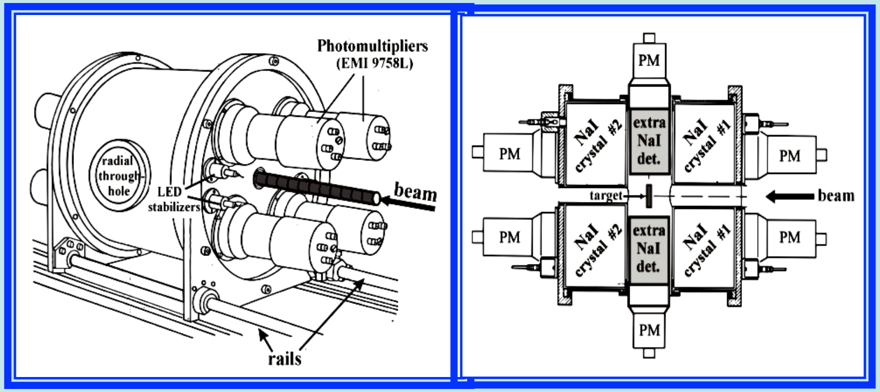
The 4π γ-summing method: The principle



The 4π γ-summing method: The setup



@ DTL-Bochum



@ INP-Demokritos

The 4π γ-summing method: The ^{92}Mo(α,γ)^{96}Ru example

^{92}Mo(α,γ) ^{96}Ru

$E_\alpha = 6 – 12$ MeV

$\xi = 398$ μgr/cm^2

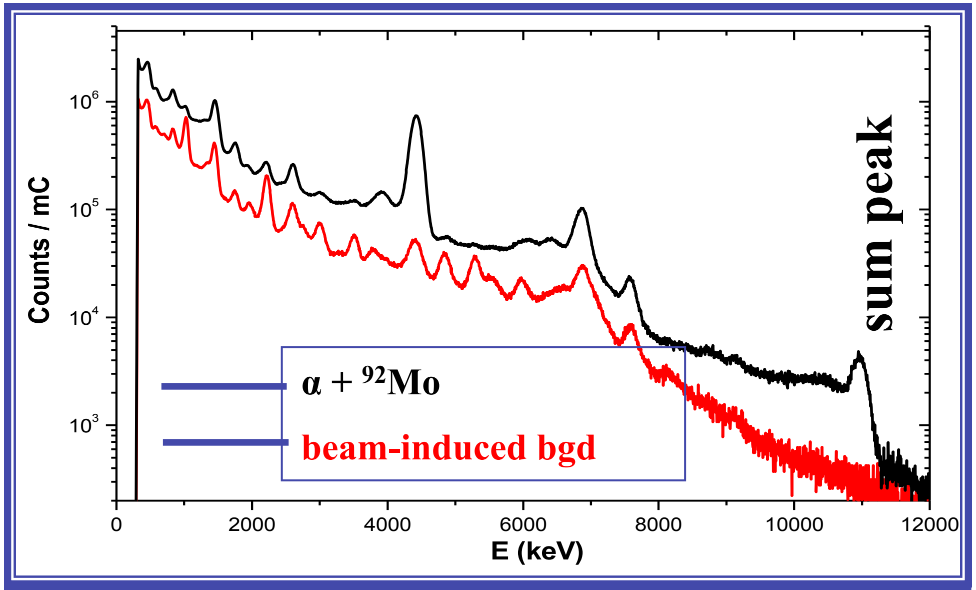
$\sigma = (Y/\varepsilon) * (1/\xi) * (A/N_A)$

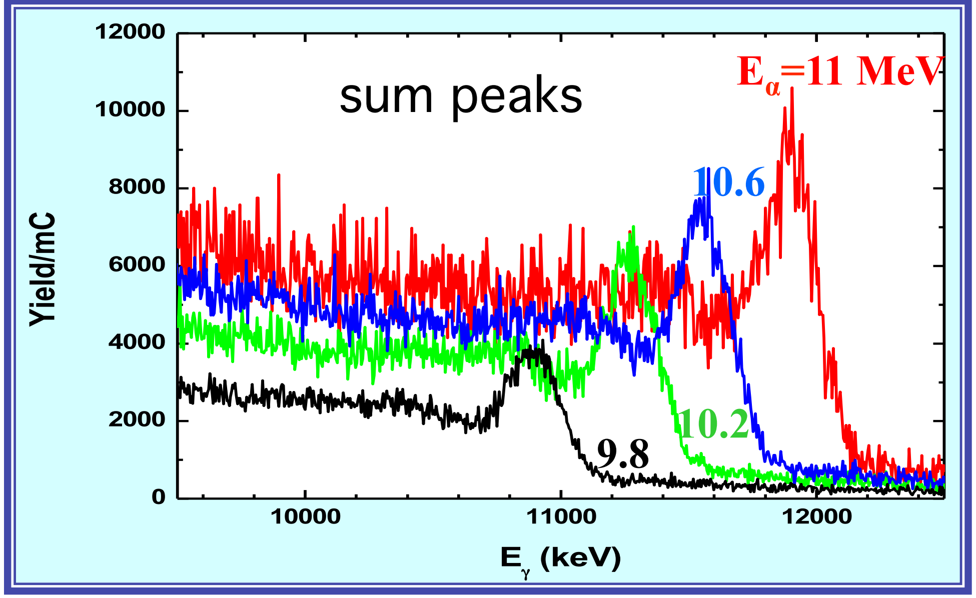
BUT $\varepsilon = f(E,M)$

Solutions (up to now):

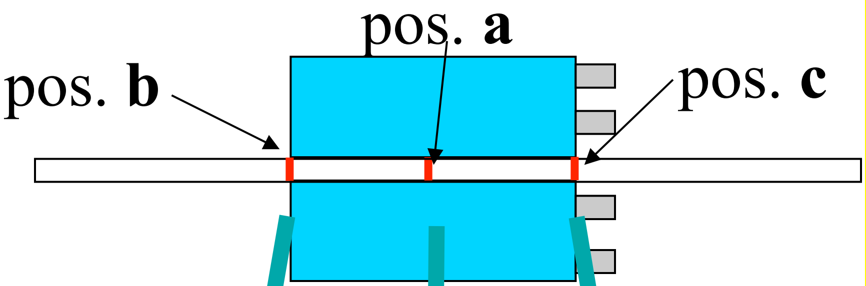
- Theoretical calculations
- Simulation

No “real” experimental solution





The 4π γ-summing method: Efficiency calculation



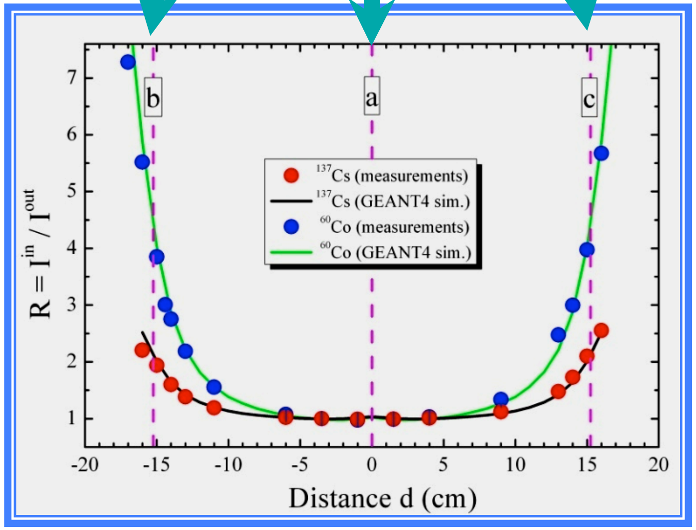
<u>in/out ratios</u>:

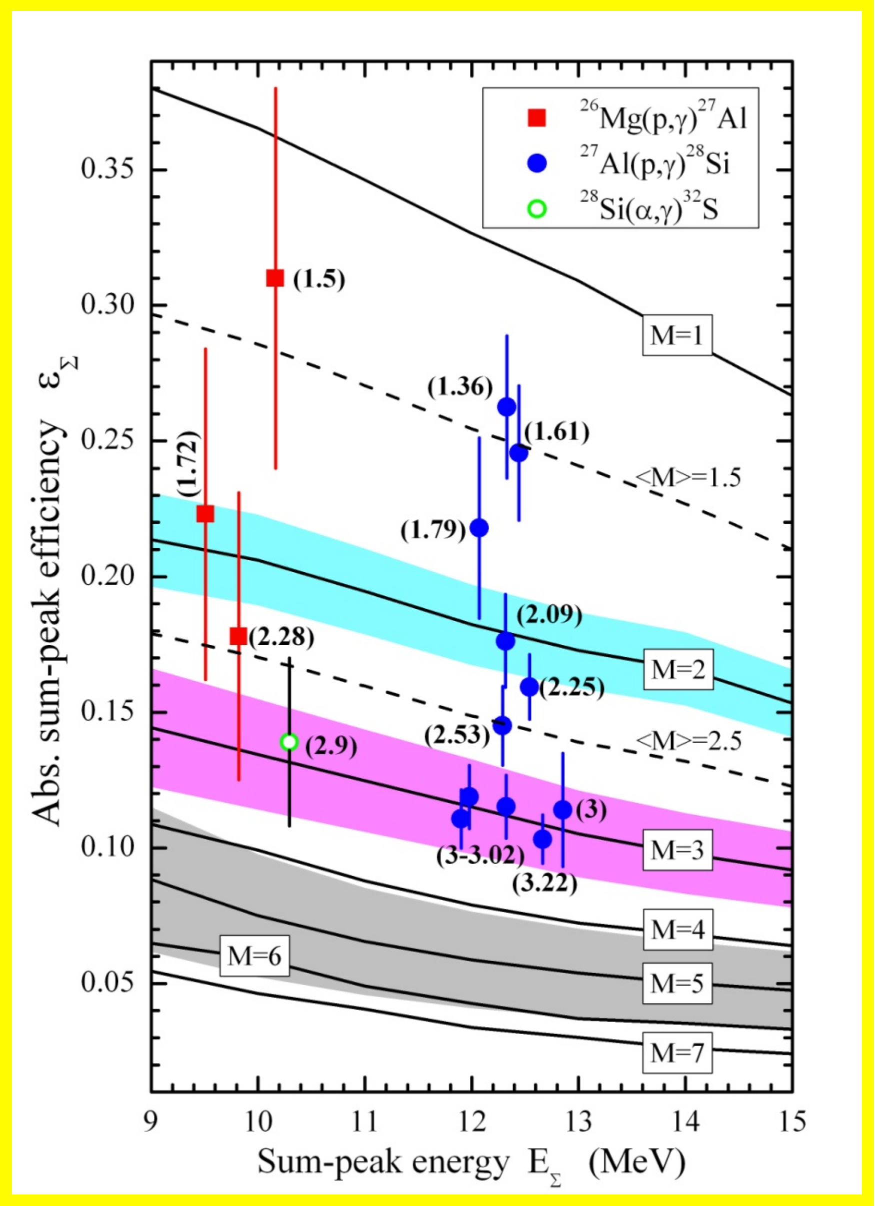
M=1 → R = 2

M=2 → R = 2 × 2 = 4

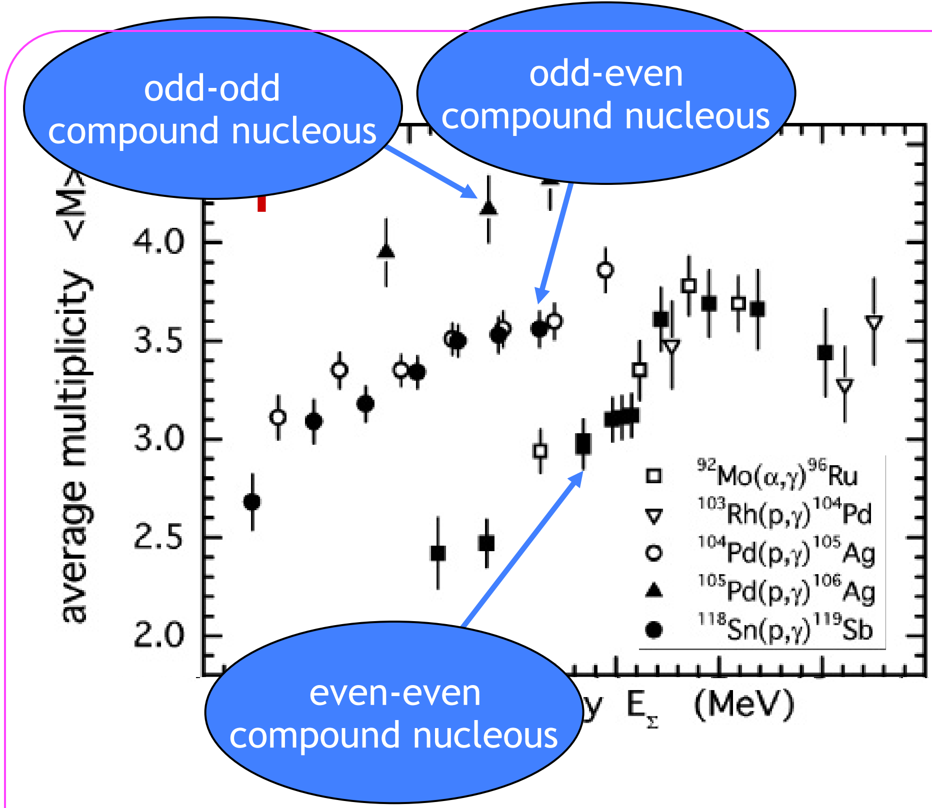
M=3 → R = 2 × 2 × 2 = 8

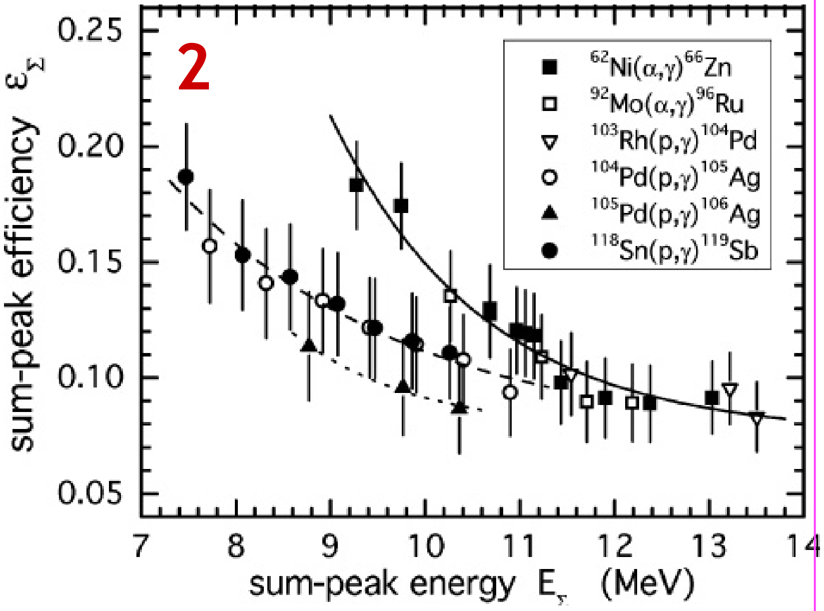
M=4 → R = 2 × 2 × 2 × 2 = 16





The 4π γ-summing method: Efficiency calculation II



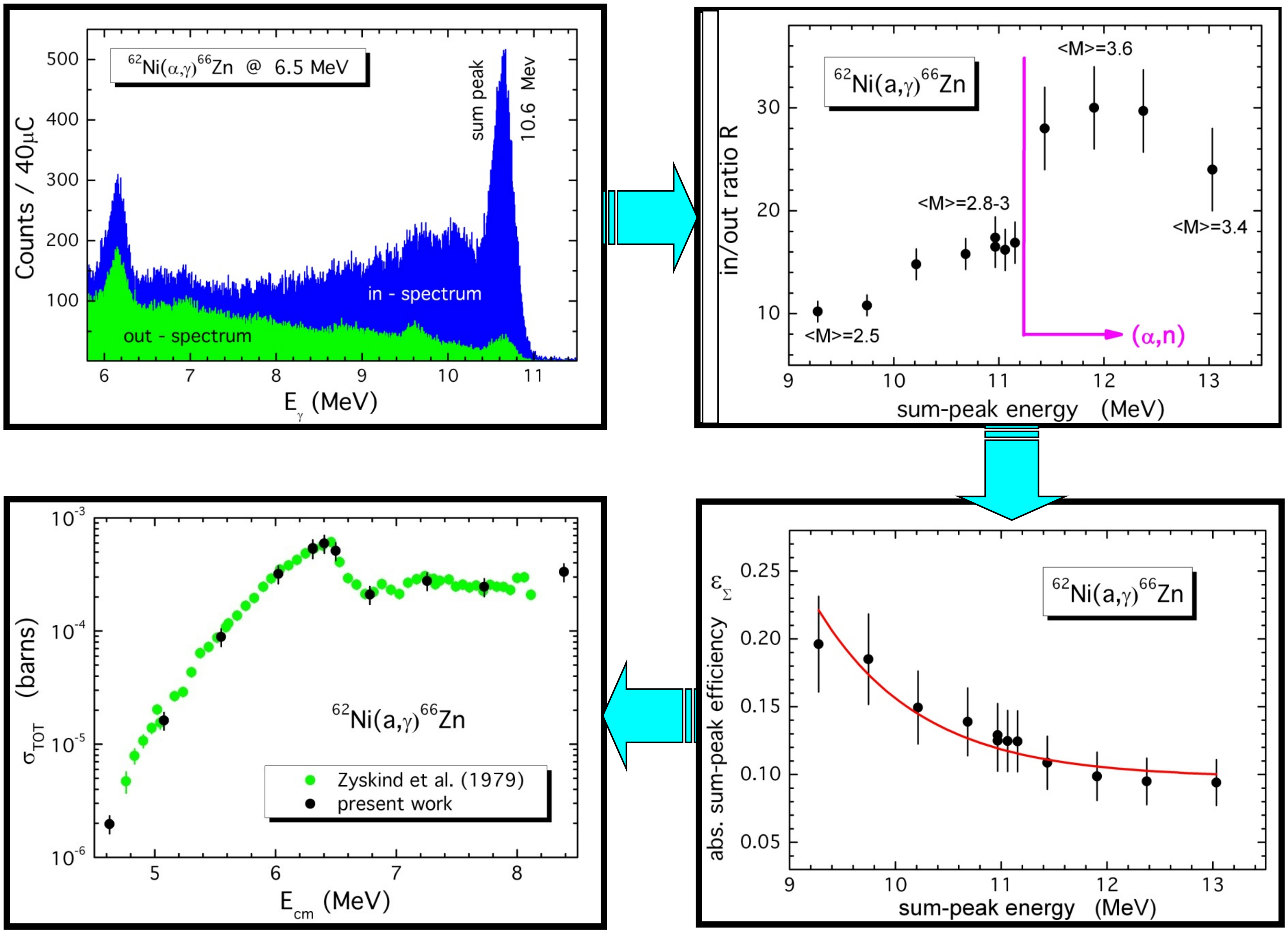


$$\boxed{\boldsymbol{\varepsilon}_\Sigma = \boldsymbol{\varepsilon}_0 + \boldsymbol{\alpha} \cdot \exp(-E_\Sigma / b)}$$

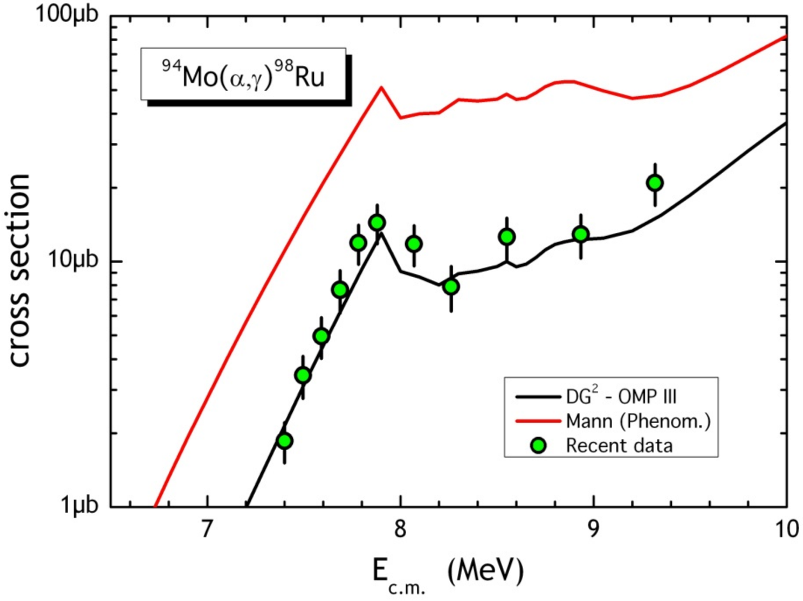
ε_0, α and b vary for even-even, odd-even and odd-odd compound nucleus

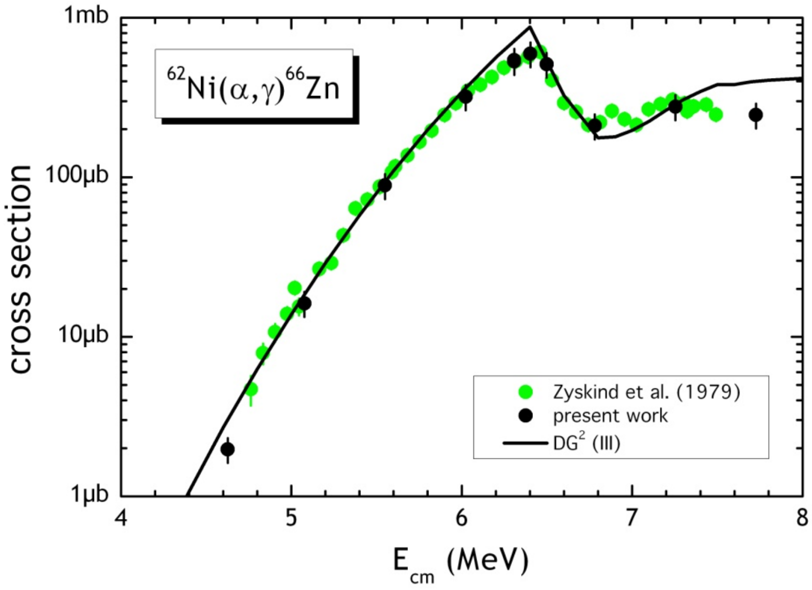
Spyrou et al. Phys. Rev. C 76,015802 (2007)

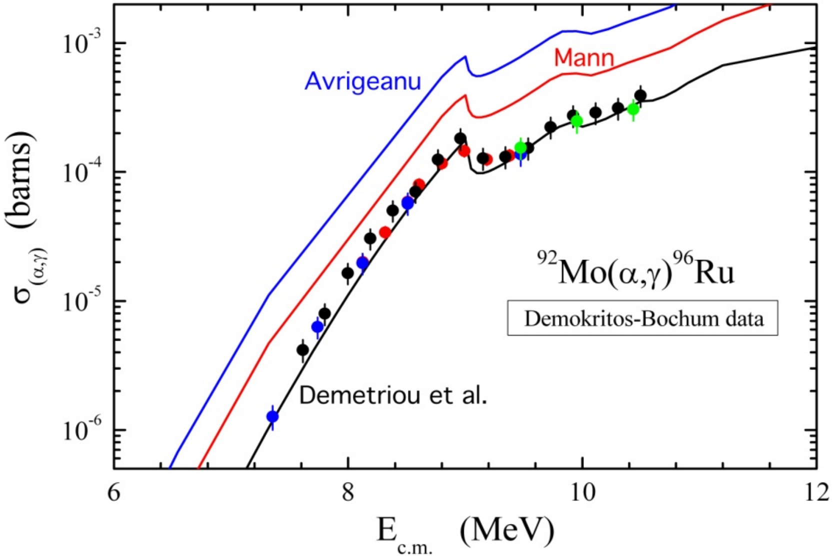
The 4π γ-summing method: Efficiency check with known reactions



(α,γ) results: Comparison with theory

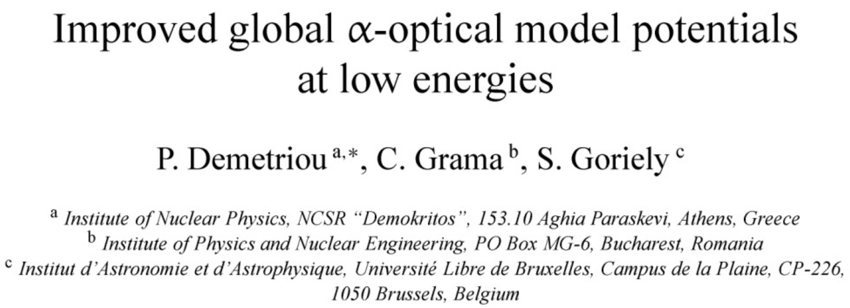






DG^2: a global α – optical model potential

Nucl. Phys. A. 707, 253 (2002)


Improved global α-optical model potentials
at low energies

P. Demetriou[a,*], C. Grama[b], S. Goriely[c]

[a] *Institute of Nuclear Physics, NCSR "Demokritos", 153.10 Aghia Paraskevi, Athens, Greece*
[b] *Institute of Physics and Nuclear Engineering, PO Box MG-6, Bucharest, Romania*
[c] *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine, CP-226, 1050 Brussels, Belgium*

$$U = V_c + V + iW + \Delta V$$

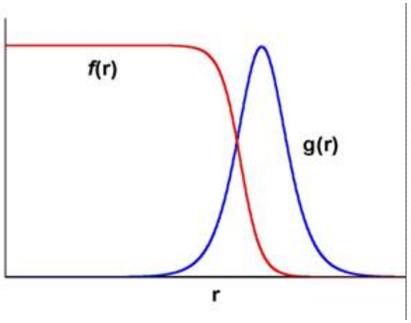
Real part V : double-folding method

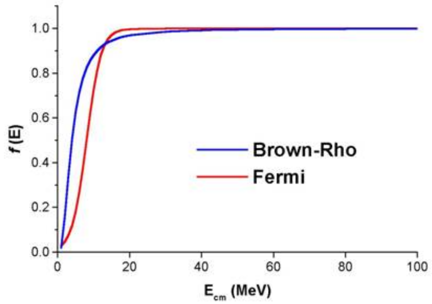
effective NN interaction:
M3Y -density dependent (Kobos et al, 1984)
projectile density:
n/p densities from elastic scattering data
target density: Hartree-Fock theory

Imag. part W : Woods-Saxon type

Volume + Surface (ratio, damping C)
geometry: r_W, a_W
Fermi-type energy dependence
of imaginary potential depth fitted
to el. scattering + reaction data at E< 20 MeV

Correction ΔV : dispersive relations

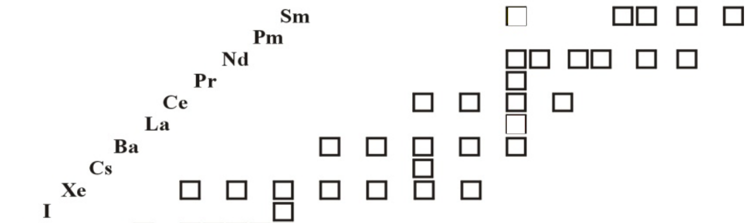




Alpha-particle capture reaction cross-section systematics

Measurements of low-energy (α,γ) reactions

(α,γ) cross section data: 10 isotopes



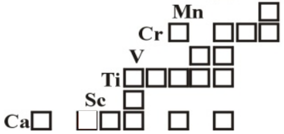
Summary

Few data exist in higher mass regions

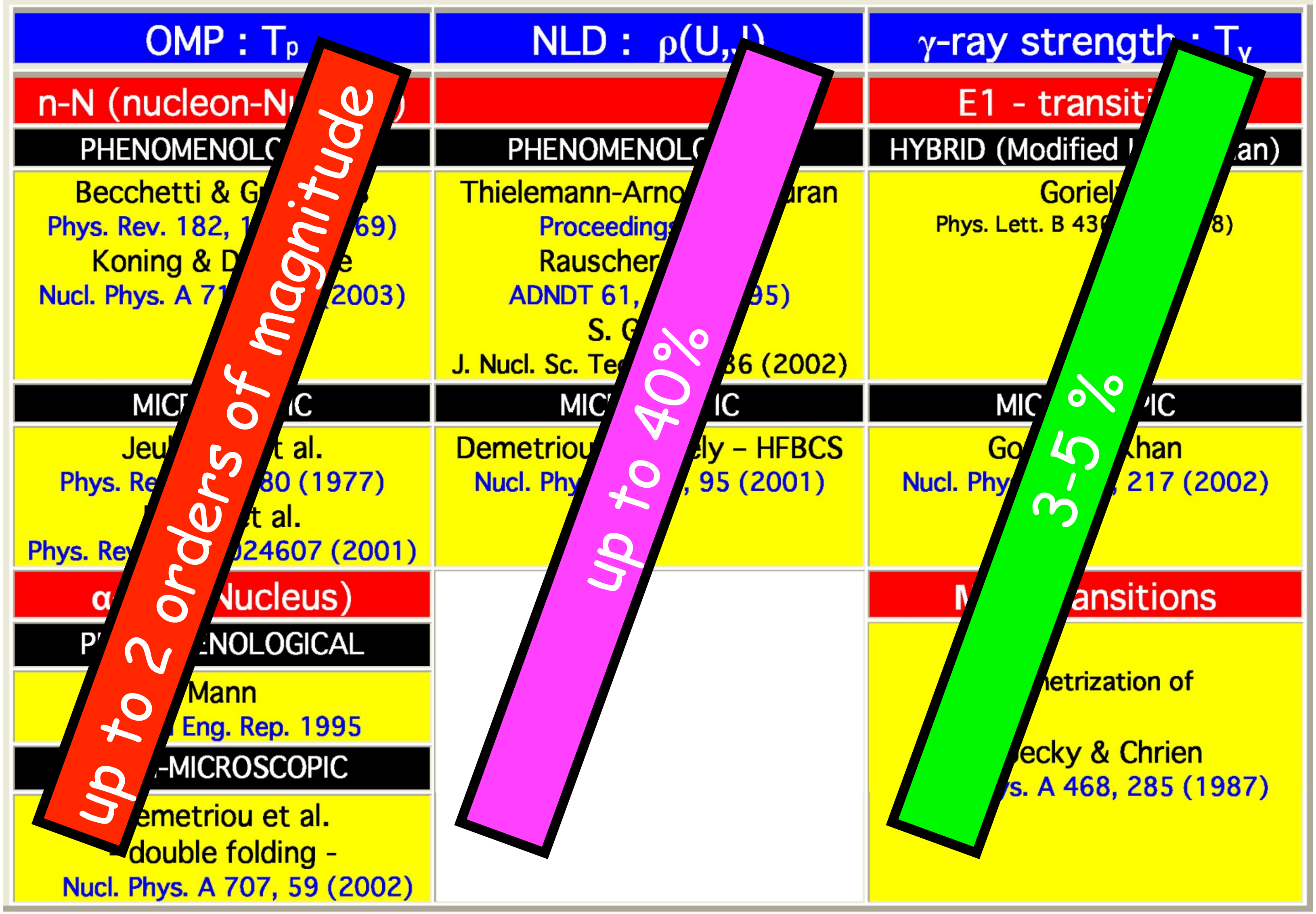
where uncertainties are large.

But from experimental point of view such measurements are very challenging: need high current α beams + target development + efficient γ - arrays.

Perspectives: Explore the unstable mass regions using RIB’s



Input parameters in HF calculations



OMP : T_p	NLD : ρ(U,)	γ-ray strength : T_γ
n-N (nucleon-Nu)		E1 - transiti
PHENOMENOLO	PHENOMENOLO	HYBRID (Modified L an)
Becchetti & G s Phys. Rev. 182, 1 69) Koning & D e Nucl. Phys. A 71 (2003)	Thielemann-Arno uran Proceeding Rauscher ADNDT 61, 95) S. G J. Nucl. Sc. Te 36 (2002)	Goriel Phys. Lett. B 43 8)
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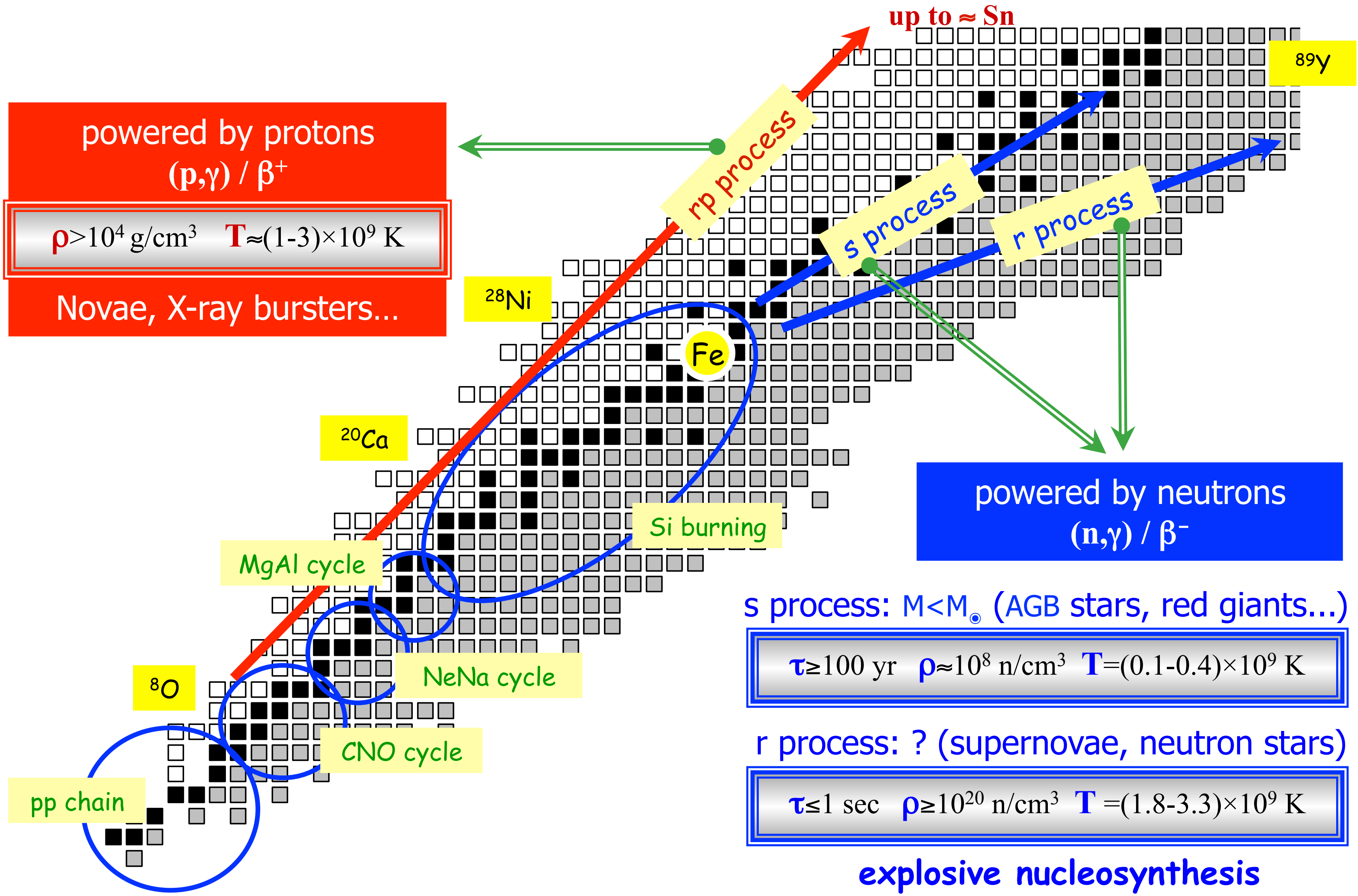
Mann Eng. Rep. 1995		
-MICROSCOPIC		
emetriou et al. double folding - Nucl. Phys. A 707, 59 (2002)		

up to 2 orders of magnitude

up to 40%

3-5 %

Nucleosynthesis along the table of isotopes



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…

powered by neutrons
(n,γ) / β^-

s process: $M<M_\odot$ (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