Stable, gamma and neutron beams working group 2

N. de Séréville
Institut de Physique Nucléaire d'Orsay

On behalf

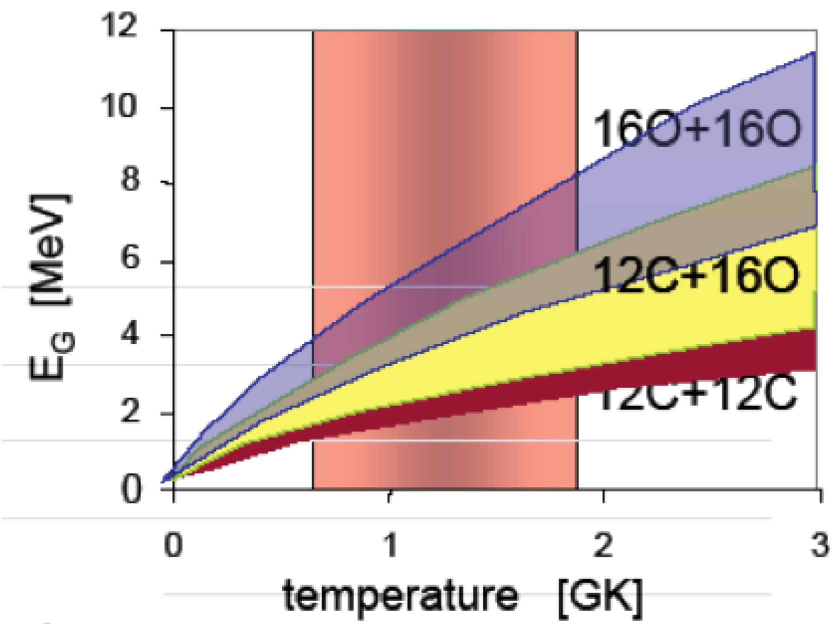
Laboratori Nazionali
del Sud

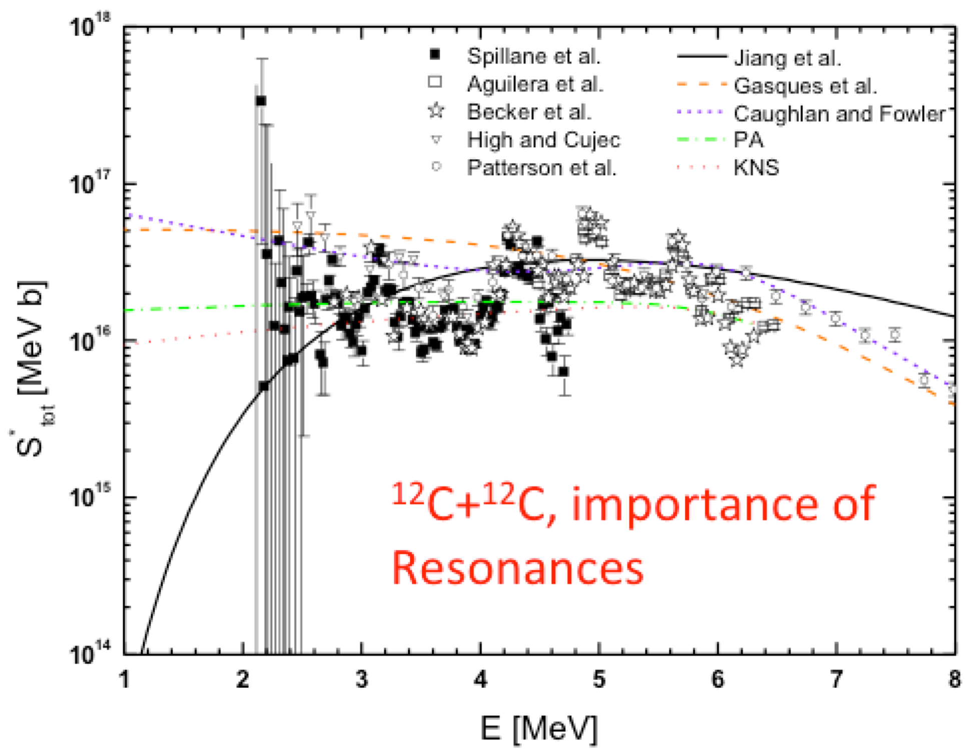
NuPECC LRP, nuclear astrophysics town meeting, GSI, February 16th - 17th

Fusion reactions of astrophysics interest within the STELLA project

S. Courtin et al, IPHC, IPNO, CSNSM, Strasbourg Planetarium (France)
Univ. Of York (UK), Univ. Of Surrey, STFC Daresbury (UK)
Univ. Of Aarhus (Denmark)

- Systems of interest $^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$ / Stars of mass $M > 8M_{solar}$
- Search for signs of **cluster effects**
- Excitation functions / cross sections of the sub-nanobarn range
- Detection systems based on γ-particle coincidences. Reduced background.
- High intensity beams (I > 1 μA) : GANIL (Caen France), Andromede (Orsay, France), ...





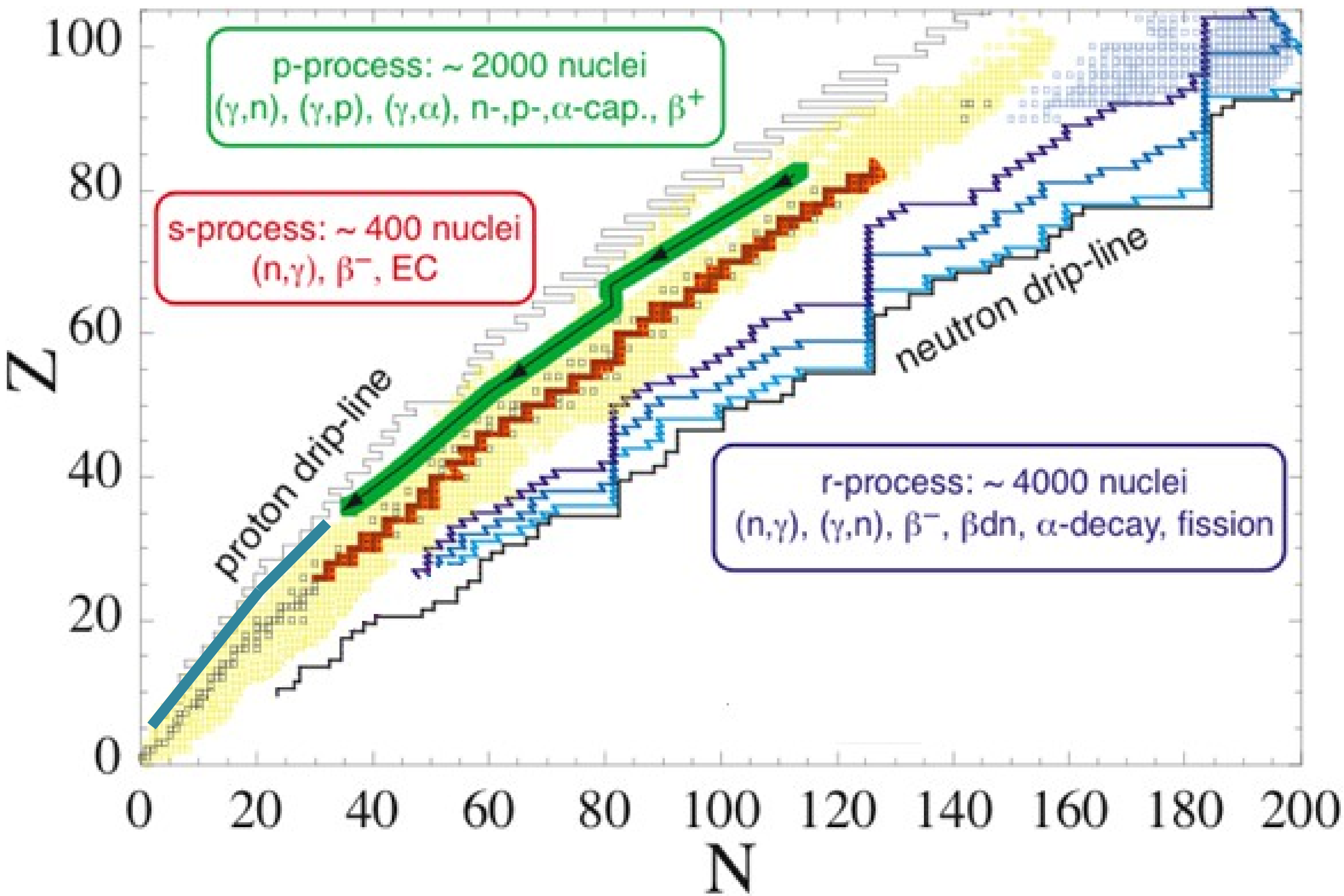
p-process: cross-section measurements with charged particules

Reviews:

Arnould-Goriely, Physics Report 384 (2003) 1

Rauscher *et al*, Rep. Prog. Phys. 76 (2013) 066201

Rapp *et al.* AJ 653 (2006) 474



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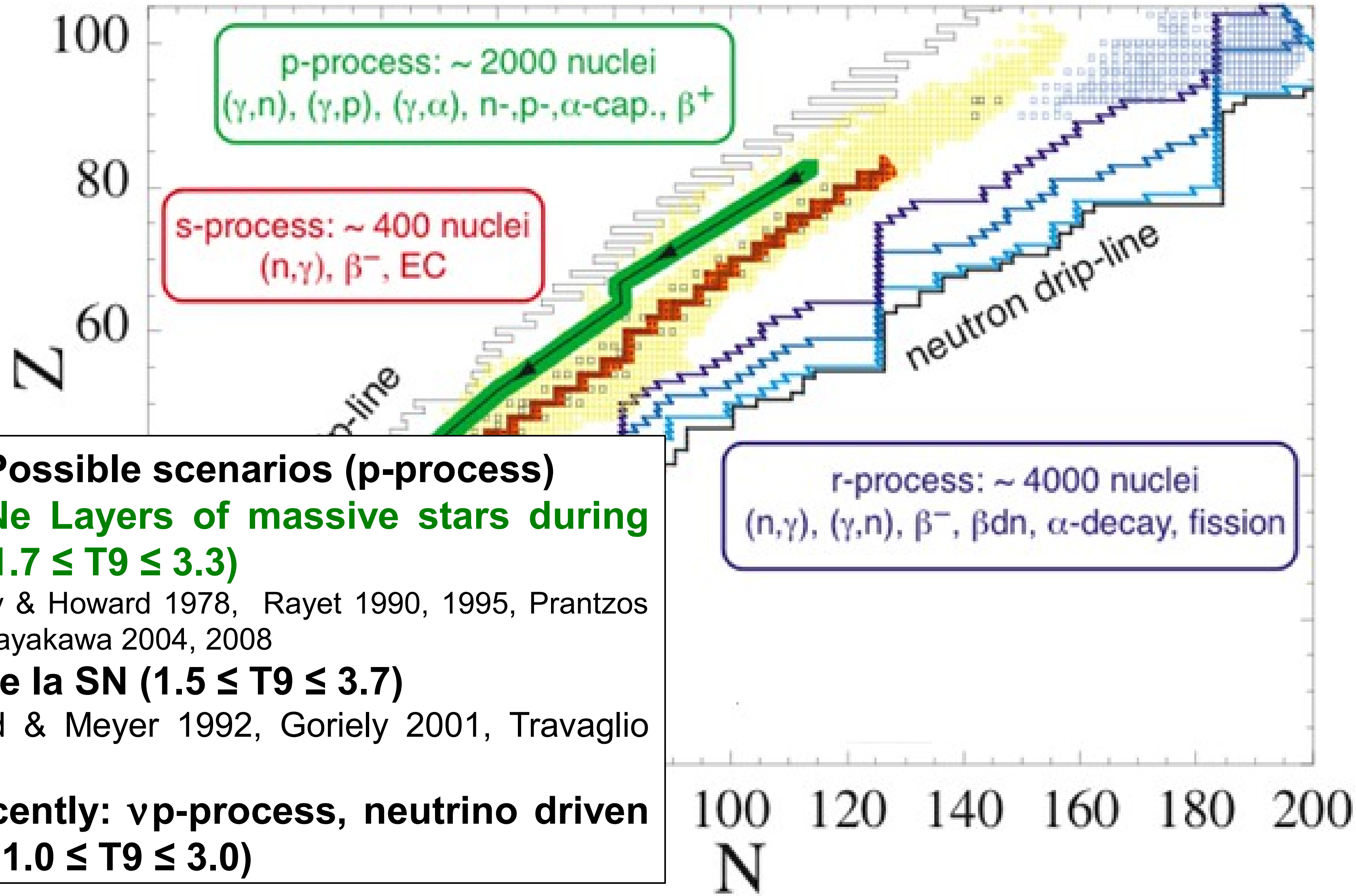

Possible scenarios (p-process)

1) O/Ne Layers of massive stars during SNII (1.7 ≤ T9 ≤ 3.3)
Woosley & Howard 1978, Rayet 1990, 1995, Prantzos 1990, Hayakawa 2004, 2008

2) Type Ia SN (1.5 ≤ T9 ≤ 3.7)
Howard & Meyer 1992, Goriely 2001, Travaglio 2011

3) Recently: νp-process, neutrino driven wind (1.0 ≤ T9 ≤ 3.0)

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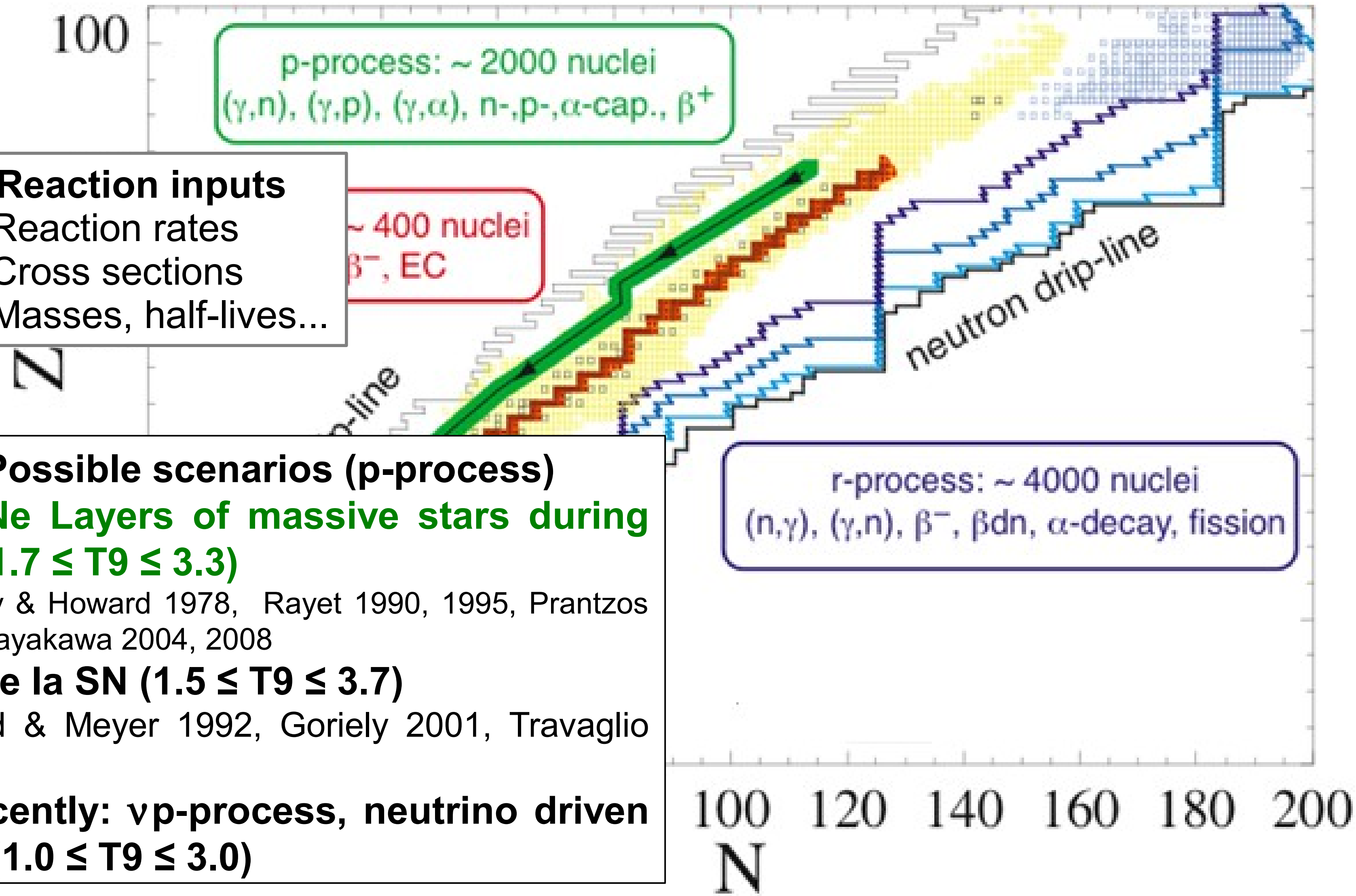

Reaction inputs
- Reaction rates
- Cross sections
- Masses, half-lives...

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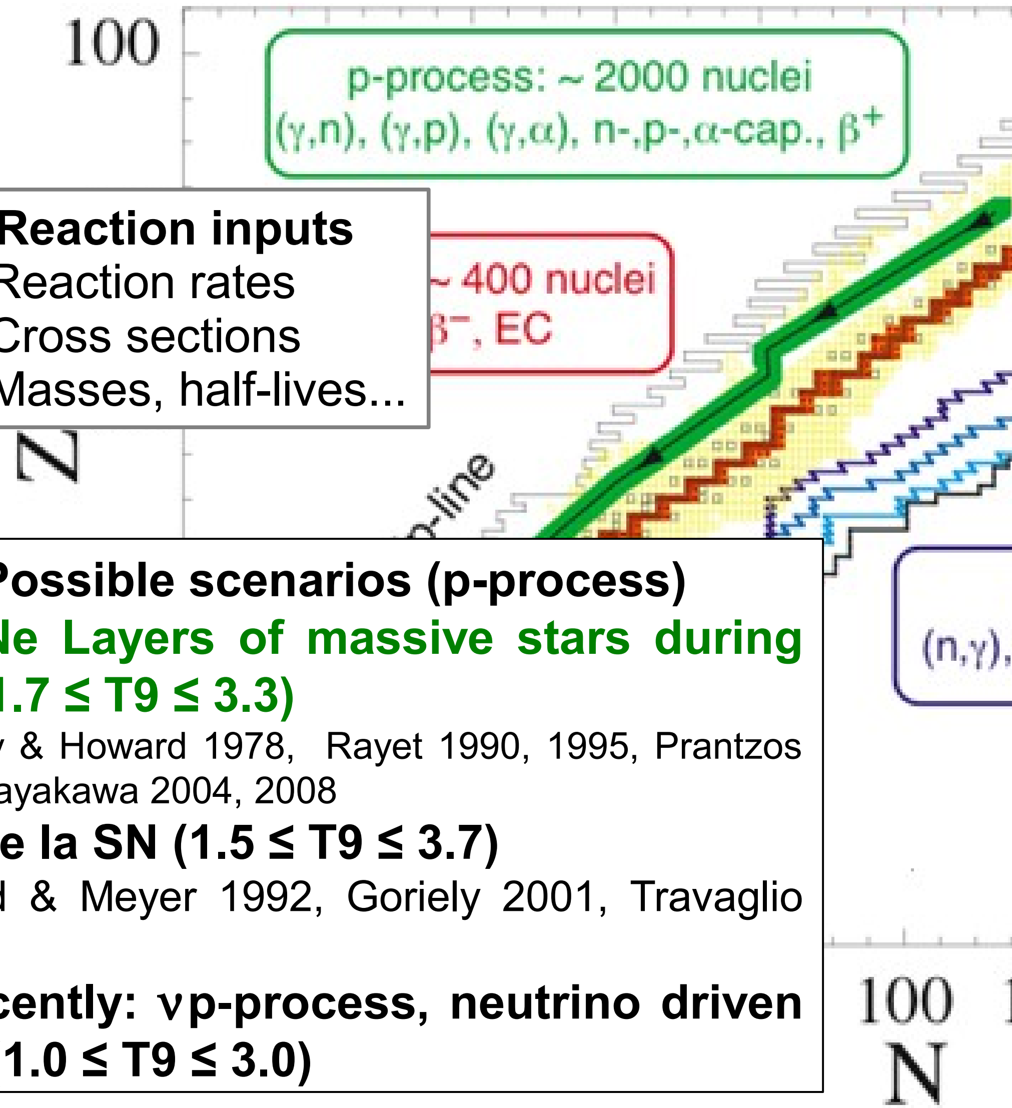

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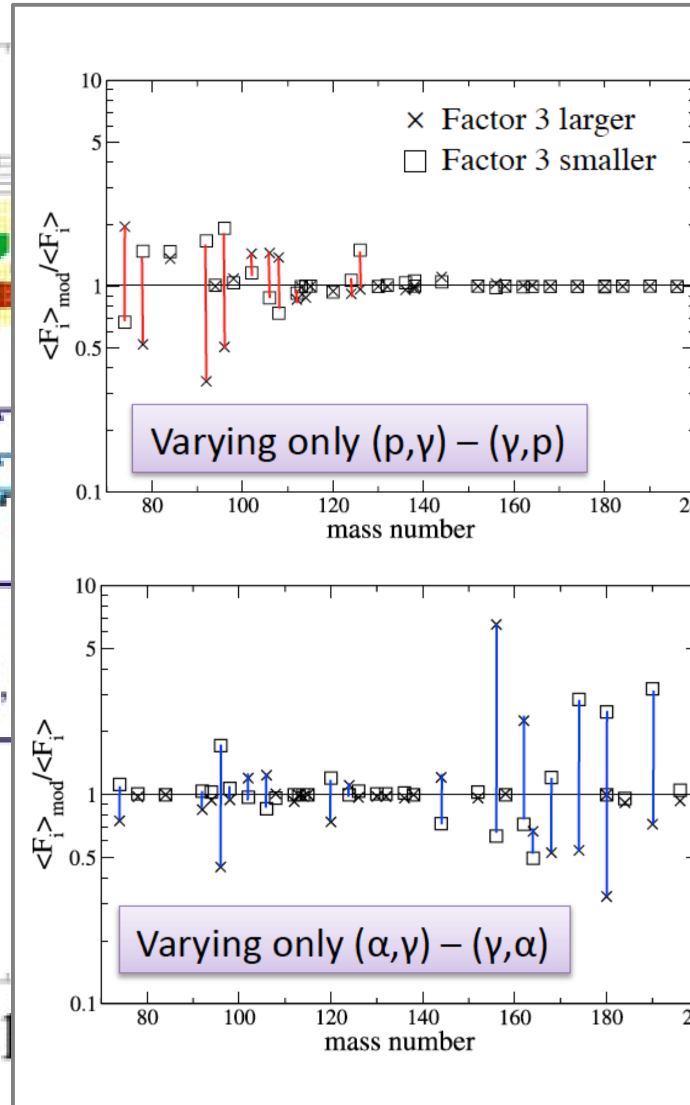
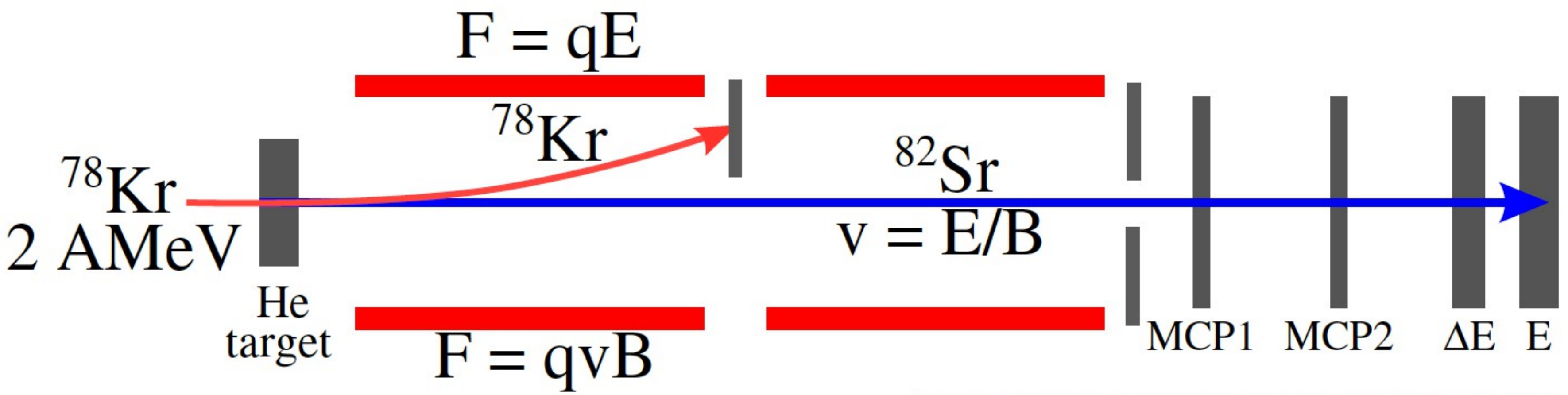


Rapp *et al.* AJ 653 (2006) 474

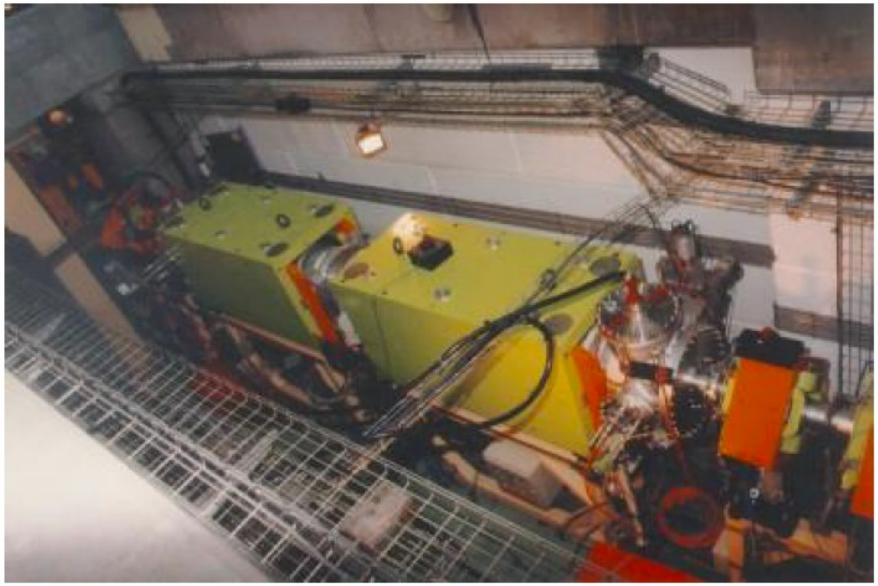
Inverse kinematics measurements @ GANIL

X(α,γ) and X(α,n) using LISE Wien Filter (FULIS)

Lol S. Harissopulos, F. de Oliveira, PhD of P. Ujic



- velocity selection $\Rightarrow$ beam rejection ($\sim 10^9$)
- Ideally collecting all the charge states
- $\Delta v \sim 5$ % between primary beam and CN
- July 2014 : test of a "windowless" gas target
  $\Rightarrow$ new design to obtain $N_0 \geqslant 10^{16} cm^{-2}$
- ToF vs ΔE ID is possible with ChIO (up to 10^5 pps)
- Test on July 2015 : ^{58}Ni+p/α @ 4.7 AMeV

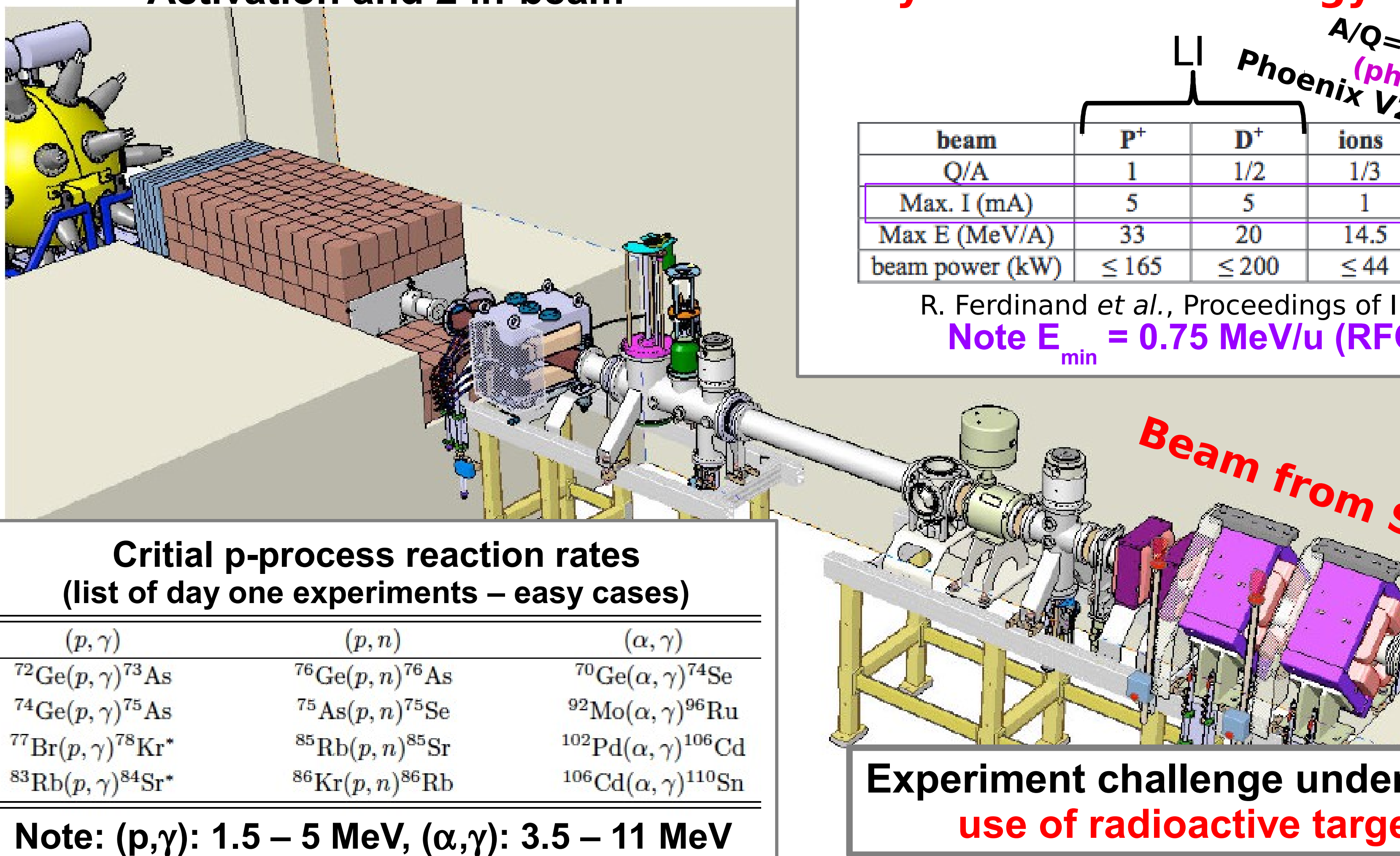


Contact person: F. de Oliveira

Direct kinematics measurements @ SPIRAL2

LoIs : B. Bastin, G. Randisi, C. Ducoin, I. Companis, O. Stezowsky *et al.*

3 experimental campaigns foreseen: Activation and 2 in-beam



Very intense low energy beams

LI: P^+, D^+ — Phoenix V2: ions (1/3) — A/Q=6 & SC ECR (phase 1++): ions (1/6)

beam	P^+	D^+	ions	ions
Q/A	1	1/2	1/3	1/6
Max. I (mA)	5	5	1	1
Max E (MeV/A)	33	20	14.5	8
beam power (kW)	≤ 165	≤ 200	≤ 44	≤ 48

R. Ferdinand *et al.*, Proceedings of IPAC2013

Note E_{min} = 0.75 MeV/u (RFQ)

Critial p-process reaction rates
(list of day one experiments – easy cases)

(p,γ)	(p,n)	(α,γ)
^{72}Ge$(p,\gamma)^{73}$As	^{76}Ge$(p,n)^{76}$As	^{70}Ge$(\alpha,\gamma)^{74}$Se
^{74}Ge$(p,\gamma)^{75}$As	^{75}As$(p,n)^{75}$Se	^{92}Mo$(\alpha,\gamma)^{96}$Ru
^{77}Br$(p,\gamma)^{78}$Kr*	^{85}Rb$(p,n)^{85}$Sr	^{102}Pd$(\alpha,\gamma)^{106}$Cd
^{83}Rb$(p,\gamma)^{84}$Sr*	^{86}Kr$(p,n)^{86}$Rb	^{106}Cd$(\alpha,\gamma)^{110}$Sn

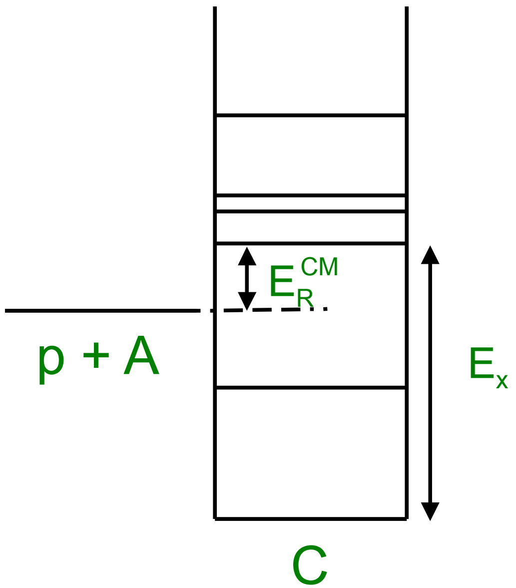
Note: (p,γ): 1.5 – 5 MeV, (α,γ): 3.5 – 11 MeV

Experiment challenge under study: use of radioactive targets!

Contact person: B. Bastin

Indirect measurements

Two-body reaction
p + A → C → x + B



Case of narrow resonance:

$$< \sigma v >= \left(\frac{2\pi}{\mu k T}\right)^{3/2} \hbar^2 \sum_i (\omega\gamma)_i \exp\left(-\frac{E_{R,i}^{CM}}{kT}\right)$$

$$\omega\gamma = \frac{2J+1}{(2J_p+1)(2J_A+1)} \frac{\Gamma_p \Gamma_x}{\Gamma_{tot}}$$

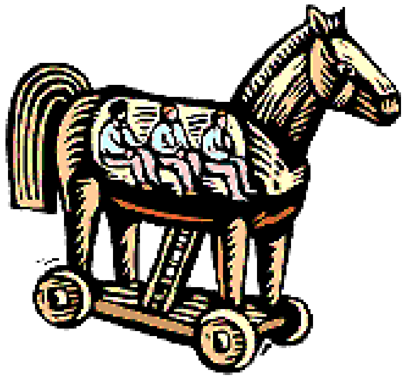
$$\Gamma_p = 2\gamma_{s.p.}^2 P_l C^2 S_p$$

- Resonance energy: $E_R = E_X - S_p$
- Resonance strength: $\omega\gamma$
  - Direct measurement when possible
  - Indirect measurement → J^π, Γ_x/Γ_{tot}, C^2S_p

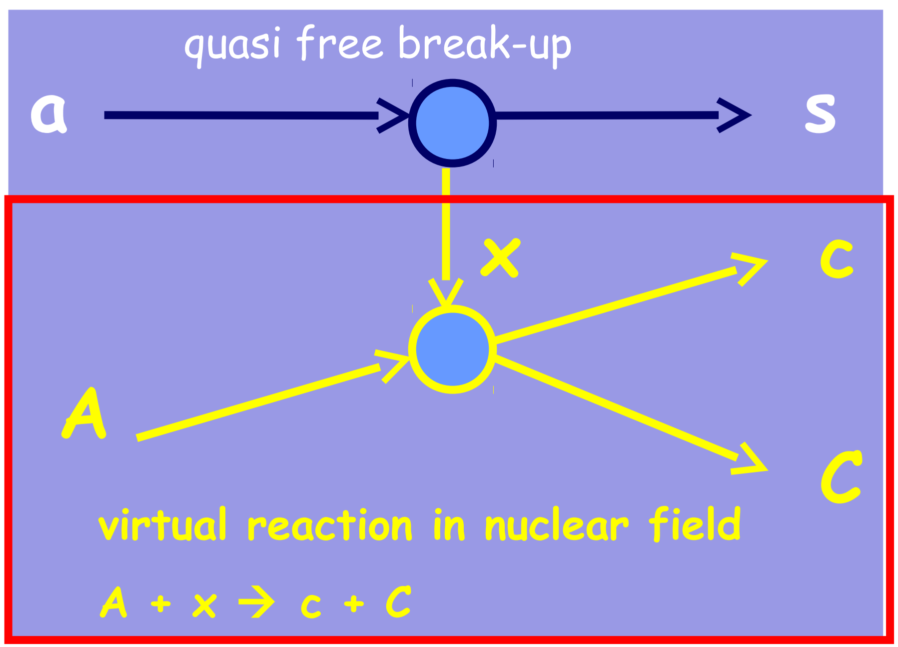
Indirect methods: transfer reaction, ANC method, Trojan Horse Method, Coulomb dissociation...

Nuclear astrophysics with the Trojan Horse Method

Laboratori Nazionali del Sud



The Trojan Horse Method (THM) is particularly suited to study the reaction of astrophysical interest x(A,C)c at Gamow energies, through selection of an appropriate three body reaction a(A,Cs)c, induced at energies higher than the Coulomb barrier.



The bare nucleus two body cross section is extracted by measuring the three body one

- No Coulomb-suppression
- No Screening effects

- No absolute value of the cross section is obtained (normalization to direct data at high energies is required)

- Access to sub-threshold resonances (e.g. $^{13}C(\alpha,n)^{16}O$)
- Neutron induced reactions (deuteron as virtual n source)
- Modified R-matrix approach for resonant 2-body reactions

Astrophysical scenarios and key nuclear reactions

Big Bang Nucleosynthesis and Light Element Depletion:
$^{2}H(d,p)^{3}H$, $^{2}H(d,n)^{3}He$, $^{6,7}Li(p,\alpha)$, $^{10,11}B(p,\alpha)$, $^{9}Be(p,\alpha/d)$, $^{7}Be(n,\alpha)$

AGB stars: $^{15}N(p,\alpha)$, $^{18}O(p,\alpha)$, $^{19}F(p,\alpha)$, $^{19}F(\alpha,p)$, $^{14}N(n,p)$

Classical novae: $^{17}O(p,\alpha)$, $^{18}F(p,\alpha)$

Massive stars: $^{12}C(^{12}C,\alpha)$, $^{12}C(^{12}C,p)$, $^{16}O(^{16}O,)$, $^{23}Na(p,\alpha)$

Red color
=
under analysis or to be performed soon

TH nuclei: d, ^{3}He, ^{6}Li, ^{14}N, ^{16}O, ^{20}Ne

Exp: LNS-Catania, IRB Zagreb

Applications: Electron screening, energy production in fusion reactors

Recent publications:

R. Tribble, et al., Rep. Prog. Phys. 77 (2014), 106901 (Review Article)
C. Spitaleri et al., Phys. Rev. C 90 (2014) 035801
Tumino et al., ApJ 785 (2014) 96
R.G. Pizzone et al., ApJ 786 (2014) 112
M.L. Sergi et al., Phys. Rev. C 91 (2015) 065803
S. Cherubini et al., Phys. Rev. C 92 (2015) 015805
M. La Cognata et al. ApJ 805 (2015) 128
L. Lamia et al., ApJ 811 (2015) 99

Classical novae (1)

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$^{30}P(p,\gamma)^{31}S$

- bottle–neck for nucleosynthesis towards heaviest isotopes
- influence S abundances that can be used as nova thermometer
- determines Si abundances to be used for metering the mixing process and establish paternity of presolar grains

$^{34}Cl(p,\gamma)^{35}Ar$

- constrains nova ^{34}S production, important observable in presolar grains
- impact on type I X–ray bursts

Poor spectroscopic information (especially in terms of widths) available for ^{31}S and ^{35}Ar

C. Michelagnoli (GANIL)

Classical novae (2)

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^{22}Na(p,γ)^{23}Mg

- main destruction mechanism for ^{22}Na, ONe nova tracer
- knowledge of the rate needed for observational predictions at space γ–ray telescopes
- cross section at nova energies dominated by the resonance corresponding to the 7.786 MeV state in ^{23}Mg
- discrepancy among values of the strength in literature

A precise determination of Γ(7.786 MeV) in ^{23}Mg is needed
($\Gamma = \hbar/\tau$, $\tau \approx$10 fs)

High sensitivity γ-ray studies of interest for novae

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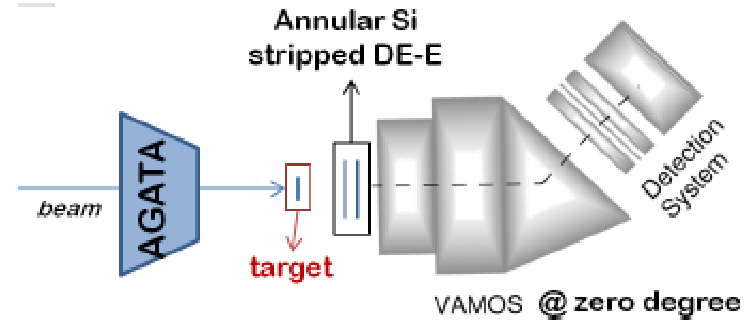
Objective

constrain radiative p-capture reactions of interest for explosive H–burning by the measurement of resonance properties:

✓ Measurement of the lifetime of the 7.786 MeV state in ^{23}Mg
accepted experiment
(CM, F. de Oliveira et al., July 2016)

- Lifetime measurements and spectroscopy of ^{31}S and ^{35}Ar
possible proposals
(CM, C. Langer et al.)

Experimental method @ GANIL



- inverse kinematics reactions ((^{3}He,α),(d,t)) on Au implanted target

⋆ VAMOS magnetic spectrometer for kinematics reconstruction from detected α/t[a]

⋆ Advanced–GAmma–Tracking–Array AGATA for γ–ray detection ⇒ (femtosecond) lifetime sensitivity via DSAM over continuous distribution of angles[b]

⋆ Si detector for p branching ratio measurement

[a] F. Boulay, PhD Thesis, GANIL, 2015

[b] CM, PhD Thesis, Univesity of Padova, 2013

C. Michelagnoli (GANIL)

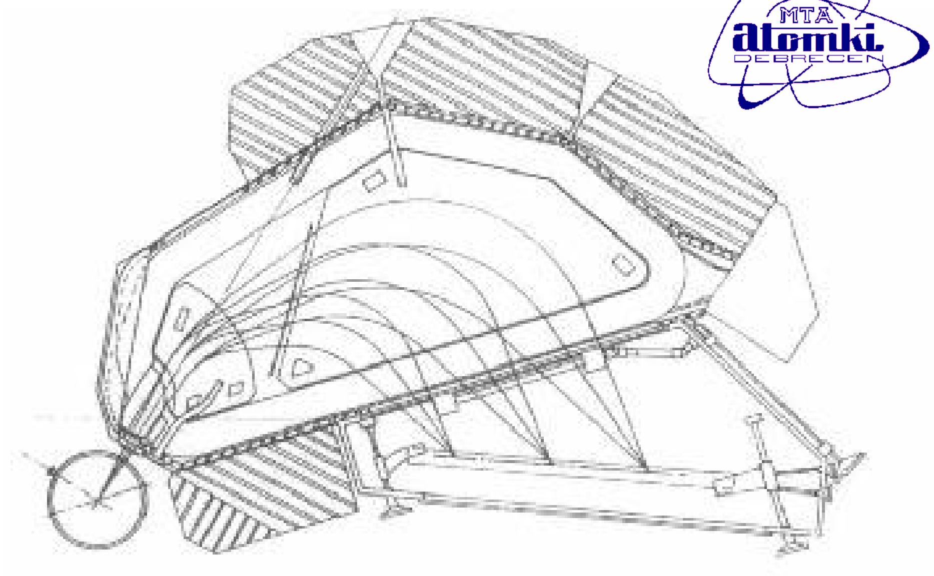
High-resolution magnetic spectrometers

IPN ORSAY

MTA atomki DEBRECEN

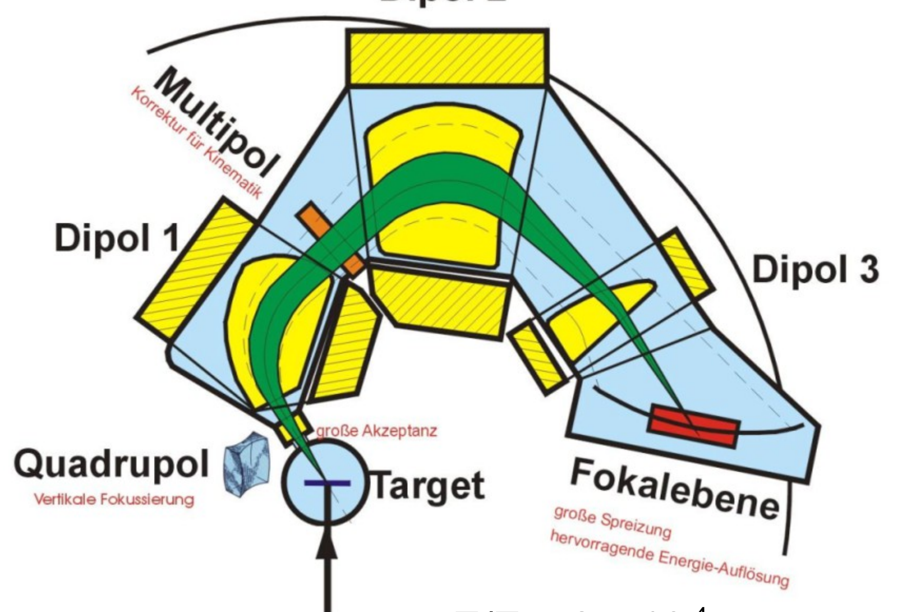
MLL

Split-Pole



- $\Delta E/E = 5 \times 10^{-4}$
- $\Delta\Omega = 1.7$ msr

Q3D



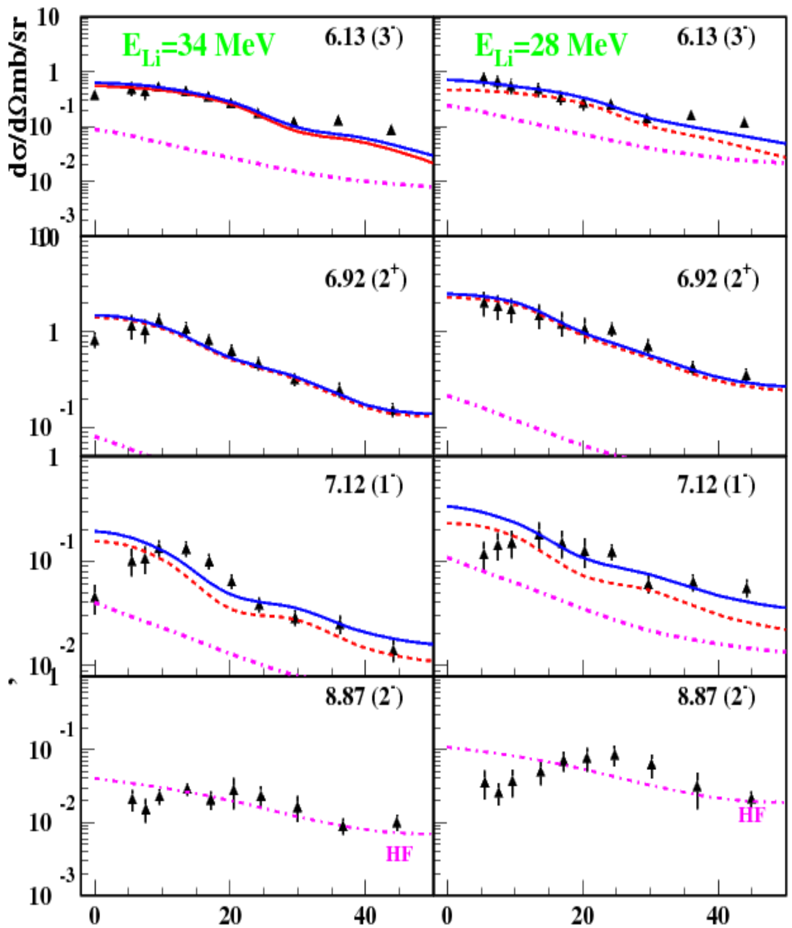
- $\Delta E/E = 2 \times 10^{-4}$
- $\Delta\Omega = 14$ msr

→ determination of level energies with high precision ~ 2 – 4 keV

(+ MAGNEX – LNS, VAMOS – GANIL, ...)

Transfer reaction, branching ratios...

Transfer reactions $^{12}C(^{7}Li,t)^{16}O$

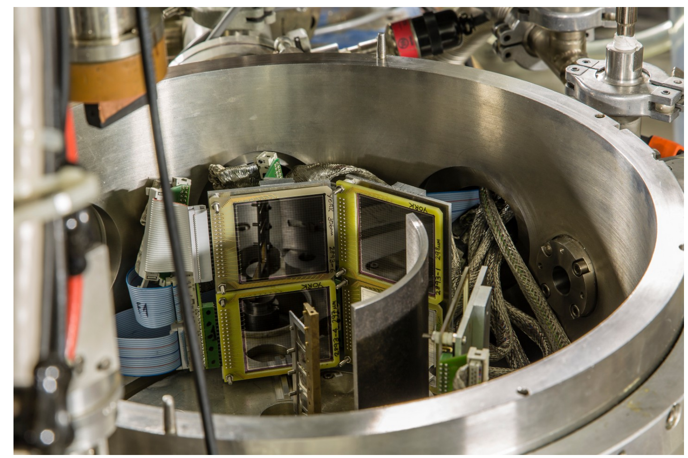


$S_\alpha(2^+) = 0.15\ (5)$ $S_\alpha(1^-) = 0.08\ (3)$

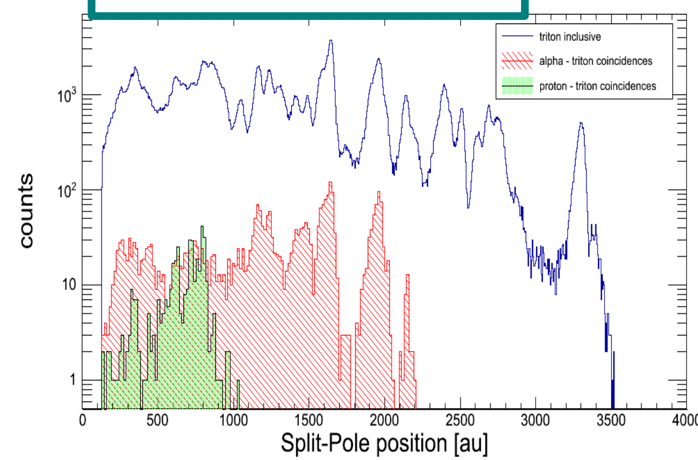
N. Oulebsir et al. PRC 85, 035804 (2012)

Coincidence setups $\varepsilon \sim 15\%$

York + IPNO



$^{19}F(^{3}He,t)^{19}Ne(\alpha|p)$



J. Riley, A. M. Laird, N. de Séréville, under analysis

Study of α-capture: e.g. $^{22}Ne(\alpha,n)$

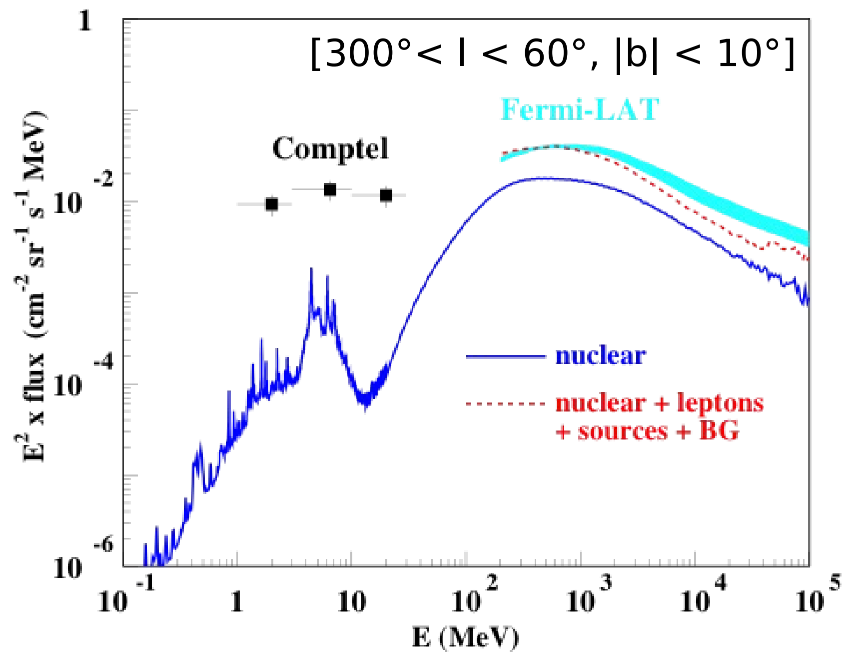
Other reactions: (p,p'), (^{3}He,t), (d,p), (d,t), (d,^{3}He), ...

Accelerated-particle induced γ-ray emission

❑ Is there a distinct hadronic low-energy cosmic-ray component in the Galaxy?

⇒ Observations of high ionization rates in diffuse clouds in the inner Galaxy from low-energy cosmic rays

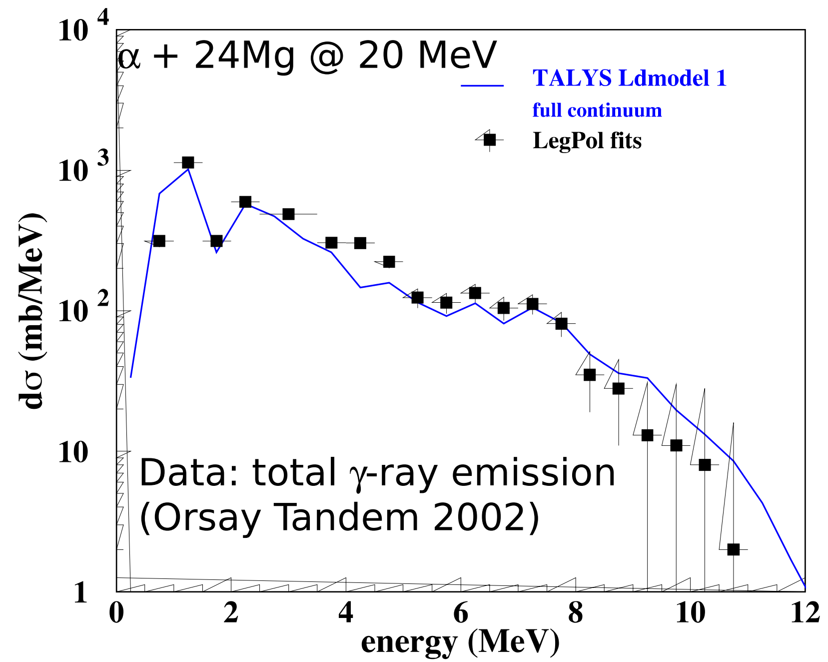
⇒ detection of nuclear γ-ray line emission with the next-generation telescope in the MeV range? (Benhabiles-Mezhoud et al. 2013) (coll. MPE Garching)



❑ What are the properties of accelerated particles in solar flares?

⇒ Observations of γ-ray lines from solar flares with INTEGRAL/SPI (Ge detectors) and other satellites: line intensity and shape → energetic particle composition, energy and directional distributions; importance of weak-line quasi-continuum; connections to solar-energetic particles (Europ. projects SEPServer & Hesperia: CSNSM, LESIA Meudon, Helsinki, Athens, ...)

- Nuclear γ-ray line emissions from p + α <−> He, C, O, Ne, Mg, Si, Fe; cross section measurements and line shape studies at Orsay Tandem, iThemba LABS cyclotron and HZ Berlin + data compilation



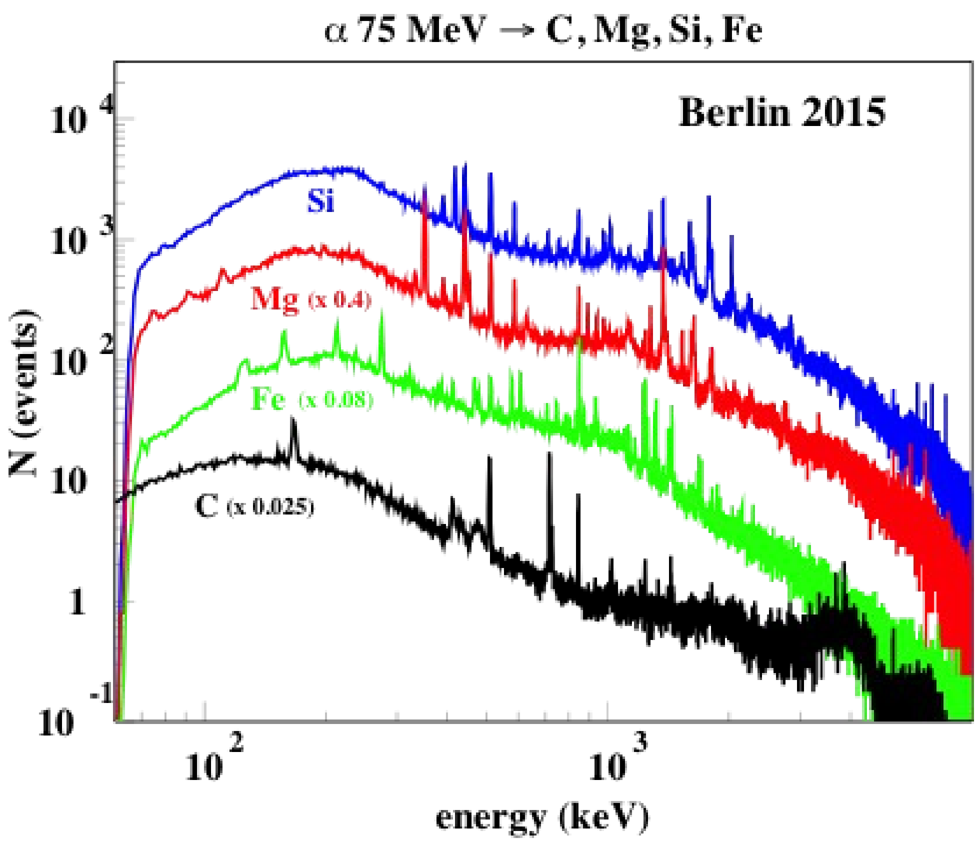
Project GRAPE: Gamma Ray emission in Accelerated Particle Environments

Aim: Construct a database for γ–ray emissions in the interaction of accelerated particles in various astrophysical sites (cosmic rays, solar flares, SN remnants) and for applications (e.g. proton therapy).

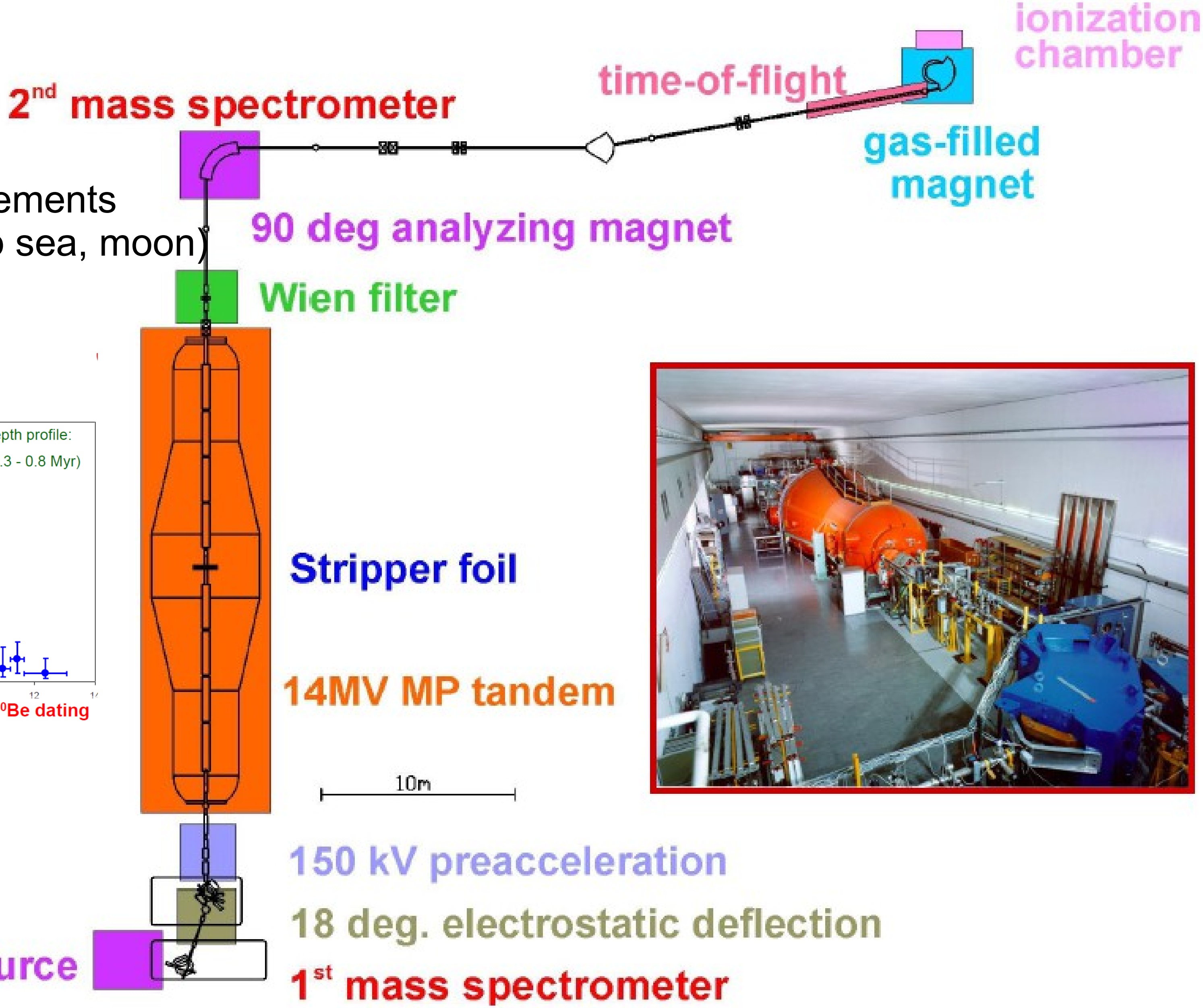
GRAPE since 2013: extend the measurements at tandem/ALTO to higher beam energies
→ cyclotrons of Helmholtz-Zentrum Berlin and iThemba Labs at Cape Town

iThemba LABS: protons 30-200 MeV -> C, O, Mg, Al, Si, Ca, Fe, Ni
(iThemba, USTHB Alger, CSNSM, IPNO)
Exps. in Sept./Oct. 2013 – Jan. 2015
E(p) = 33 – 110 MeV
(results: Yahia-Chérif et al., York 2015)
→ most recent exp. Jan./Feb. 2016
E(p) = 125 – 200 MeV

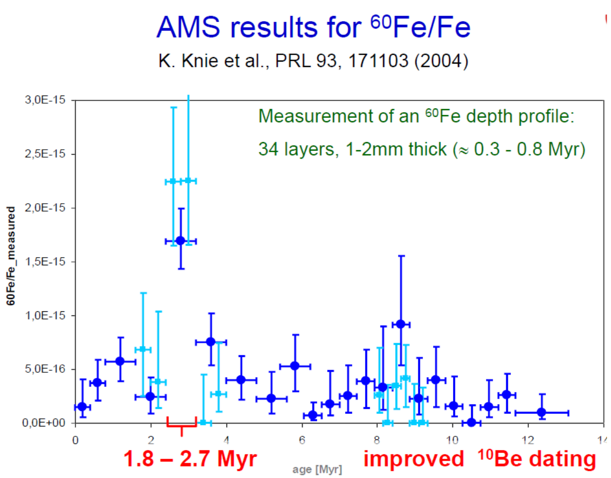
Berlin: α particles 50-150 MeV -> C, Mg, Si, Fe
(CSNSM, HZ Berlin, IPNO, U. Boumerdes)
1st exp. May 2015 E(α) = 50 et 75 MeV
(analysis ongoing, see spectra)
→ new exp. probably mid-2016



AMS measurements



- Cross-section measurements
- Sample analysis (deep sea, moon)
- ...



- Case of ^{244}Pu

Summary and recommendations

- Many reactions can still be studied (in)directly with stable beams and a variety of instruments (magnetic and γ-ray spectrometers, charge particle array, gas detectors, ...) and methods (transfer reaction, THM, DSAM, …)

- Several stable beam facilities (e.g. electrostatic machines) in Europe, but less "supported" than next generation RIBs
  - risk that these facilities could be closed (e.g. Munich)
  - equipment is sometimes old (Split-Pole & Q3D)

- Need to sustain and maintain existing facilities & equipment (e.g. spectrometer)