Nuclear astrophysics with stable beams:
Present status and perspectives in nuclear astrophysics studies of the $^{12}C(\alpha,\gamma)^{16}O$ reaction

Problematics

Present status

Perspectives

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CSNSM Orsay

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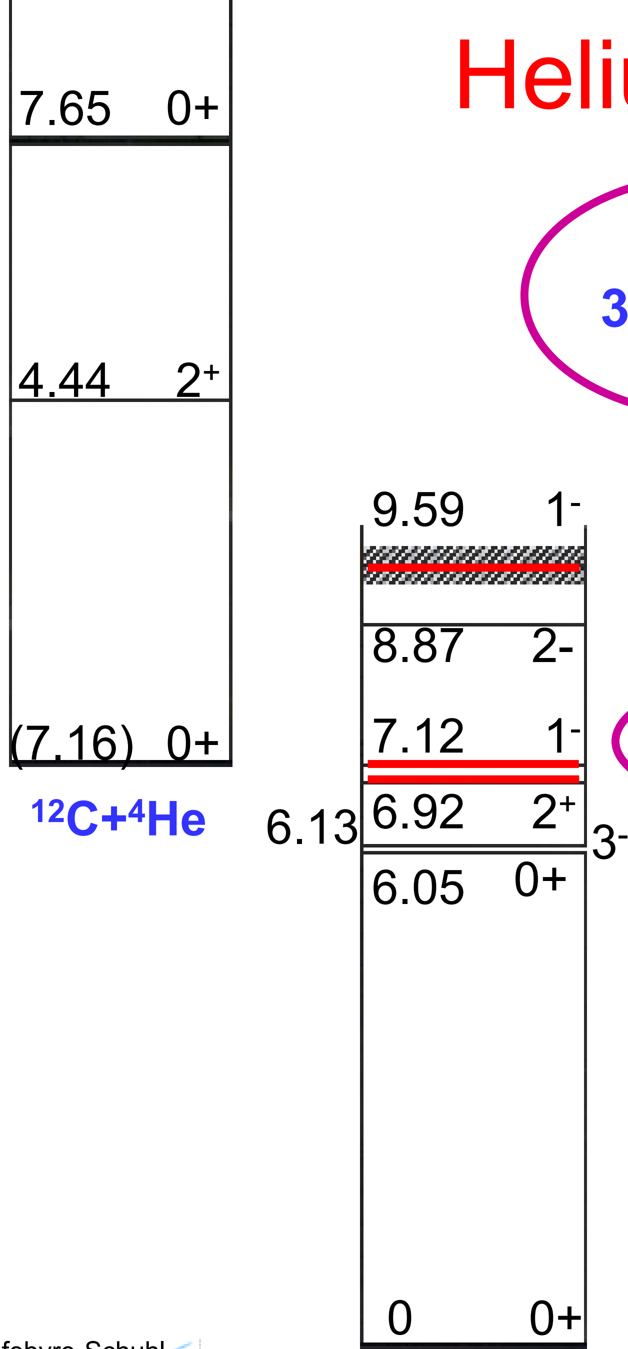
Gammapool, Strasbourg

Helium burning



$3\,\alpha \rightleftharpoons {}^{12}C$

$^{12}C+^{4}He \rightleftharpoons {}^{16}O$

Influence on:

- [C]/[O]
- Further hydrostatic burning stages
- Final states of stars

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

T ~ 0.2 x 10^9 K

→ E(Gamow peak) ~ 300 keV

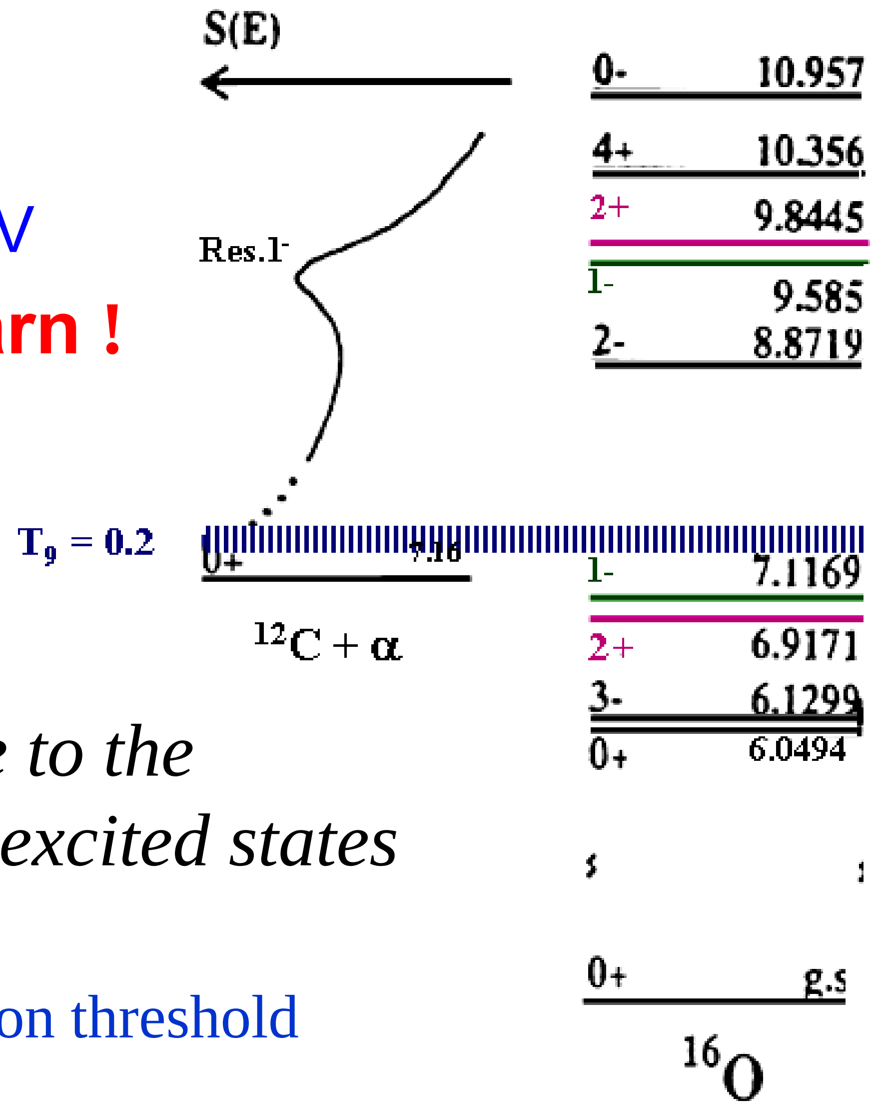
σ(300 keV) ≈ 10^{-17} barn !

Reaction rates

→ Extrapolation :

R- or K-matrix formalism

Microscopic cluster models



For each contribution: capture to the ground state and to excited states

E1 : large 1^- subthreshold resonance
+ 1^- level below the reaction threshold

E2 : Direct capture
+ 2^+ level below the reaction threshold

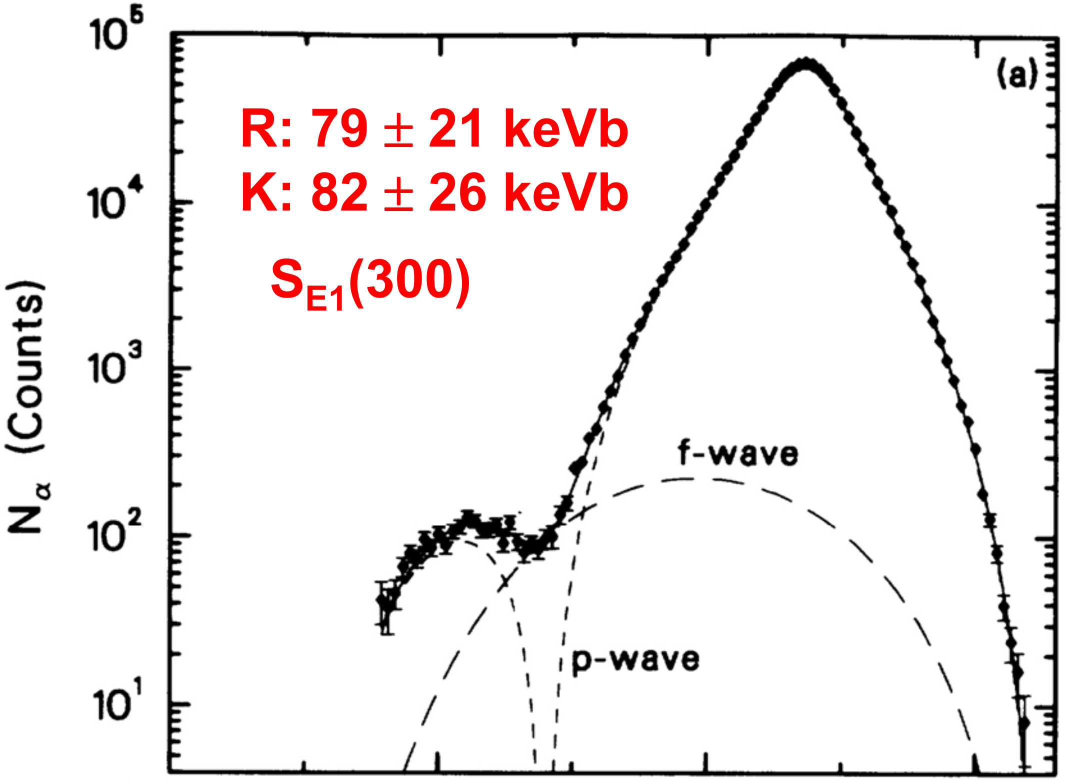
Need of E1, E2 for E* → ground state

(γ-ray angular distributions)

and for E* → excited state

Indirect methods :

- ✓ β-delayed α-decay of ^{16}N
- ✓ ^{16}O Coulomb breakup
- ✓ Transfer reaction, ANC method
- ✓ Trojan-horse method
- ✓ β-delayed p-decay of ^{17}Ne



$^{16}N \rightarrow \beta^- + {}^{16}O \rightarrow \alpha + {}^{12}C$

Azuma et al.
Phys. Rev. C **50**, (1994) 1194

Direct methods in direct kinematics:

α-beam, ^{12}C target, γ-ray detection

☆ Intense α-beam : up to 700 pμA *(Stuttgart dynamitron)*
pulsed α-beams *(Tokyo, Karlsruhe)*

☆ ^{12}C targets: isotopically pure and resistant to α-beams :
^{12}C implantation
efficient water cooling

☆ sophisticated γ-ray arrays:
angular distribution:
in a few steps (turn table)
simultaneously (4π-array)
background suppression: shieldings
or coincidences with pulsed beams

γ-ray angular distributions :

in a few steps: turn table *(as Kunz et al, Fey et al...)*

simultaneously: 4π-array *(as Assunçao et al)*

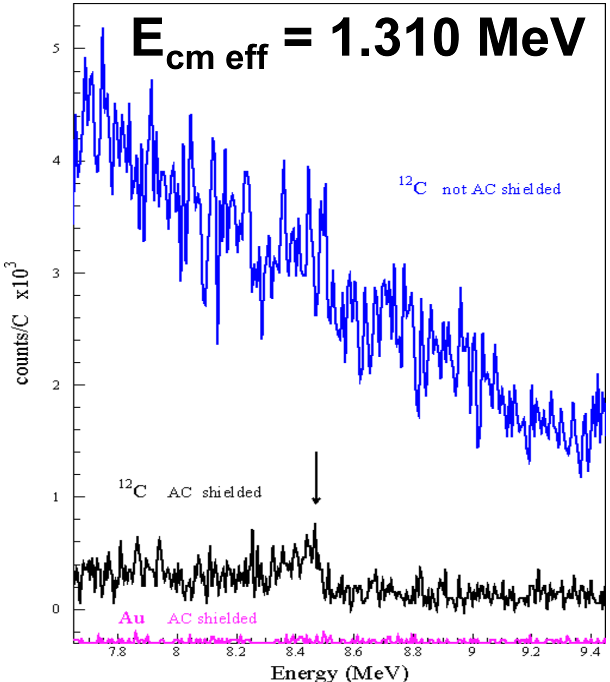
Ex : Assunçao et al. PRC 73 (2006) 055801 :

« Eurogam » setup

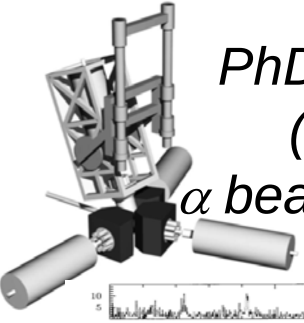
γ-ray angular distribution at 9 different angles simultaneously with 9 HP-Ge detectors

$\rightarrow$ very good energy resolution

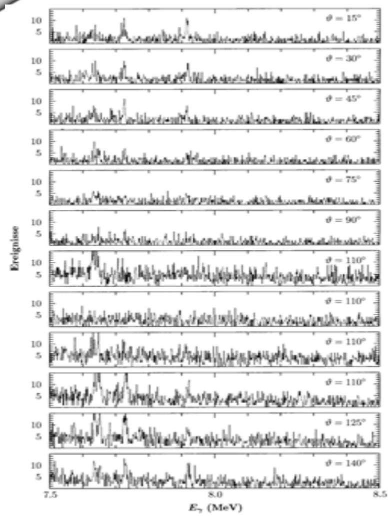
Compton suppression (active BGO shields)

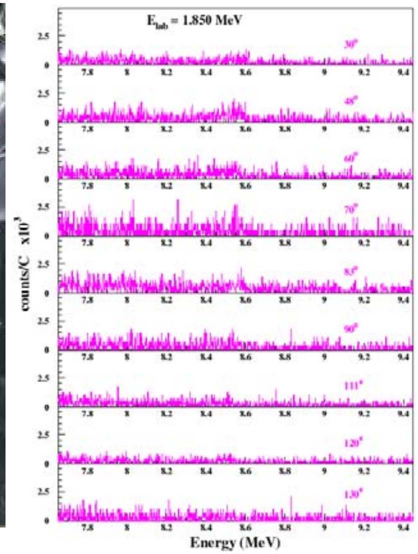


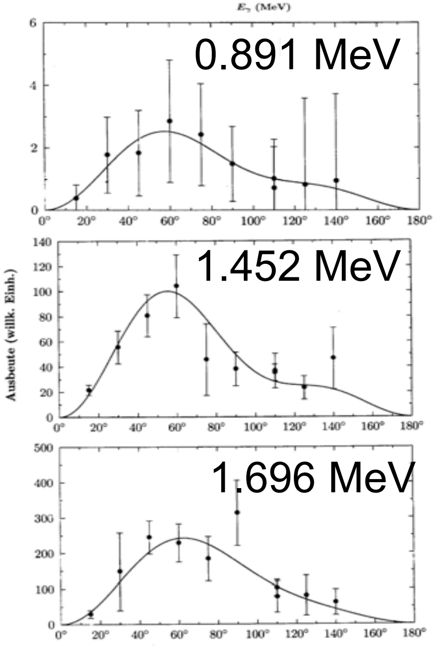
Total γ efficiency at 10 MeV :
$1.2x10^{-3}$ in experimental conditions
($7\ 10^{-3}$ at 1.33MeV)



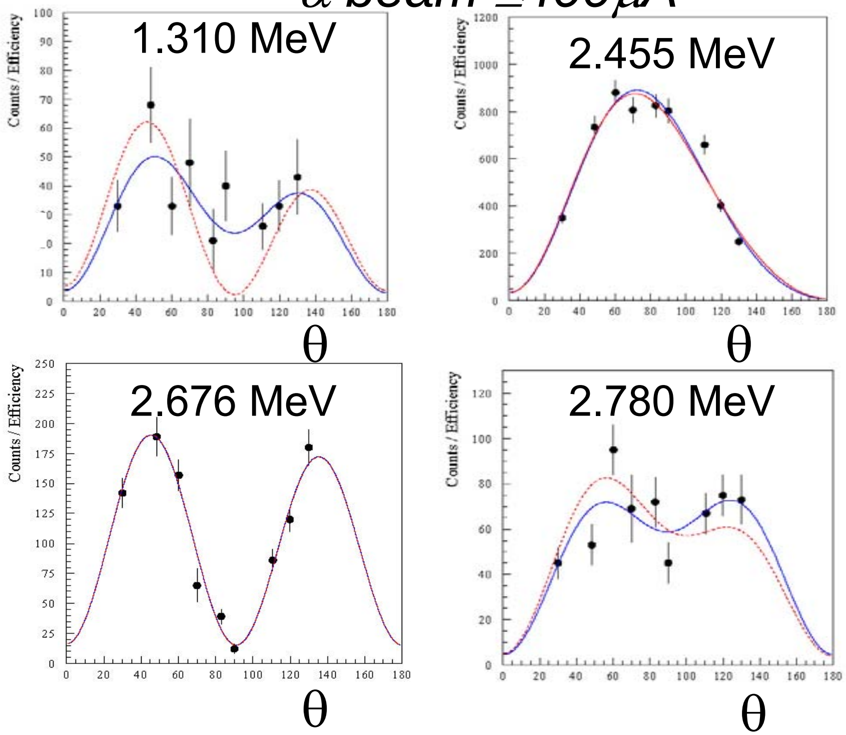
PhD M. Fey (2003)
α beam $\leq 700 \mu A$

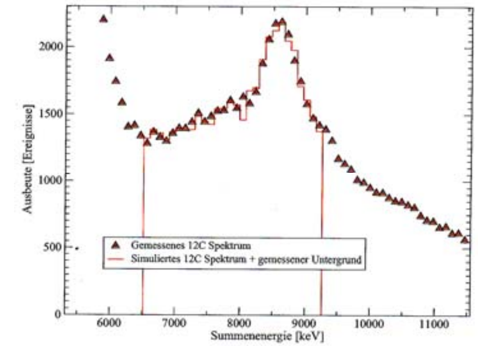


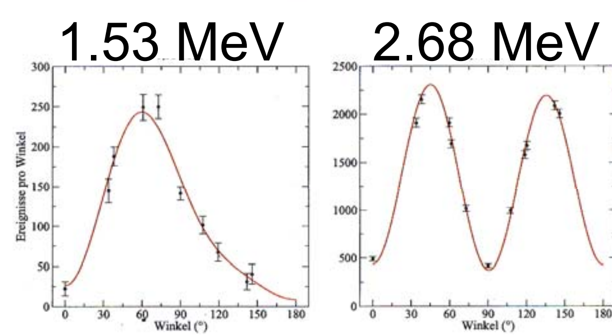




Assunçao et al. PRC 73 (2006) 055801
α beam $\leq 400 \mu A$







PhD R. Plag (2005)
pulsed beam ; $6 \mu A$

Present S_{E1} results to the ground state

$$\sigma(E) = \frac{S(E)}{E} \exp\left(-2\pi Z_1 Z_2 e^2/\hbar v\right)$$

R-matrix fits of

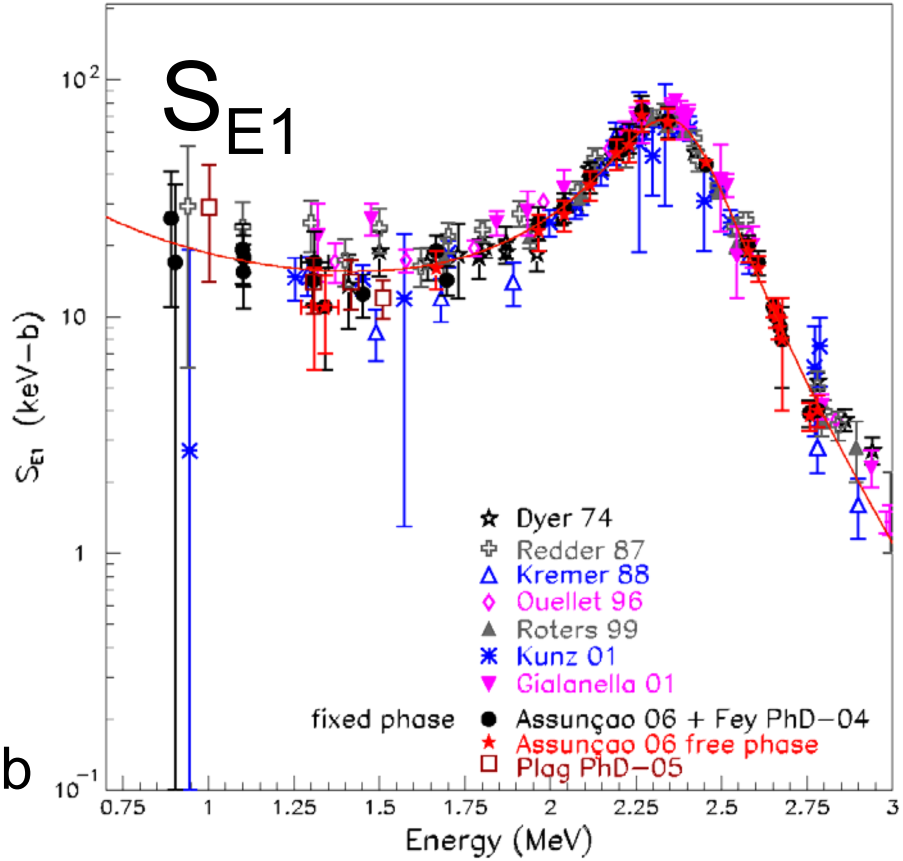
✓ α-scattering data

✓ β-delayed α-decay of ^{16}N

✓ the radiative capture data

taking into account 3 levels

→ 4 interference combinations



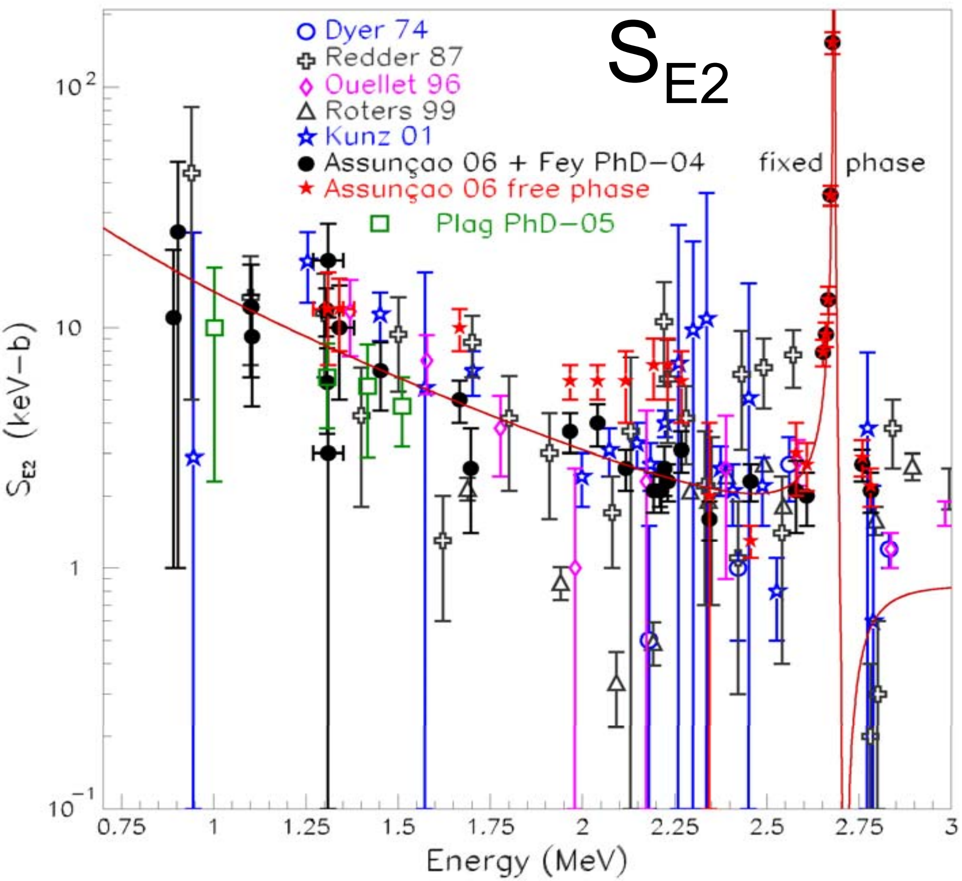
Best χ^2 -> $S_{E1}(300) = 77\pm17$ keVb

Hammer et al.

Nucl. Phys. A758 (2005) 363c

Present S_{E2} results to the ground state

$$\sigma(E) = \frac{S(E)}{E} \exp\left(-2\pi Z_1 Z_2 e^2/\hbar v\right)$$



R-matrix fits of
✓α-scattering data
✓the radiative capture data

taking into account 5 levels
→ 16 interference combinations

Best χ^2-> $S_{E2}(300) = 81 \pm 22$ keVb

Hammer et al.*Nucl. Phys. A758 (2005) 363c*

→ S_{E1}, S_{E2} to ground state

Cascades and S_{tot}

→ radiative capture to ^{16}O excited states:

$J^{\pi} = 1^{-}$, 7.12 MeV ; $J^{\pi} = 2^{+}$, 6.92 MeV and $J^{\pi} = 0^{+}$, 6.05 MeV

High γ-ray background:

Up to 2006, only based on intensities of the 6.92 MeV and 7.12 MeV or both together

γ-ray considered as giving the cascade amount:

⇒ only an upper limit

Results obtained either in direct or inverse kinematics

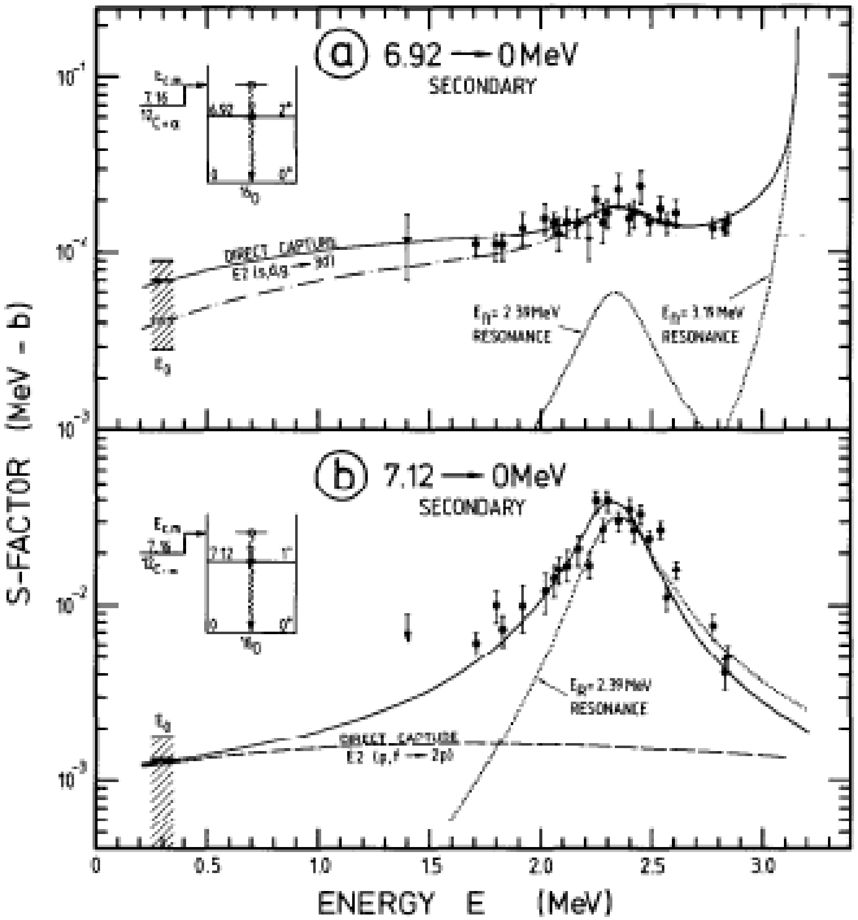
Kettner et al. Z. Phys. A **308** (1982) 73

Redder et al. Nucl.Phys. **A462**, 385 (1987)

Cascades to the 6.92 and 7.12 MeV levels

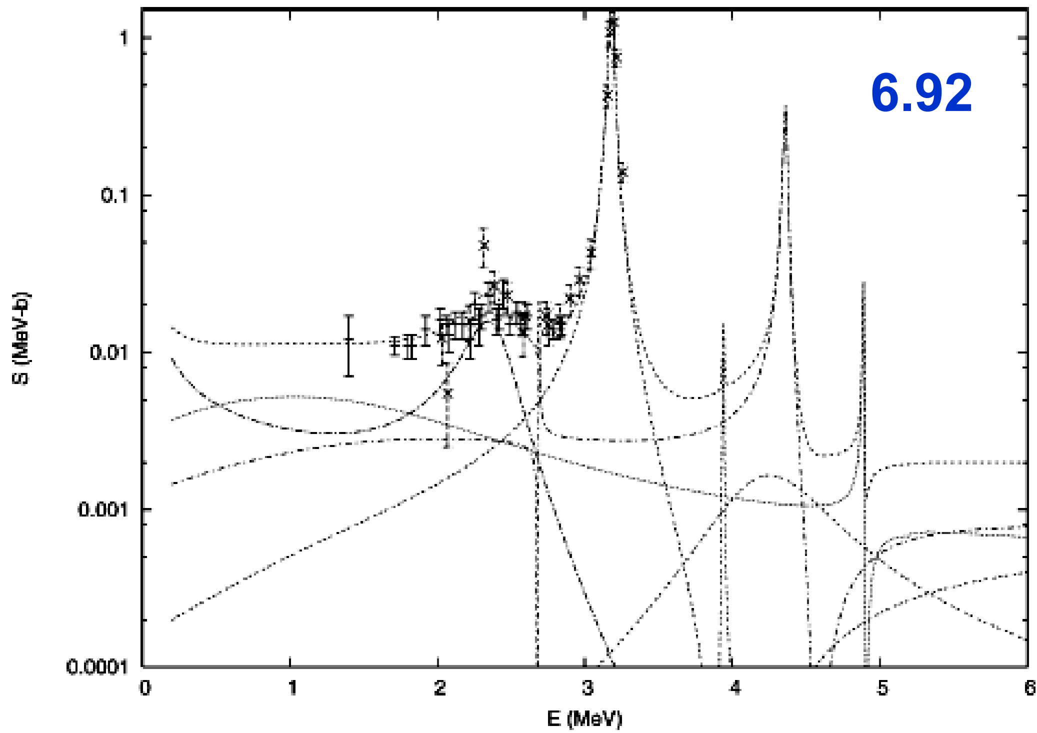
Redder et al. Nucl.Phys. **A462**, 385 (1987)

$S_{6.9}(300) = 6 \pm 3$ keVb



$S_{7.1}(300) = 1.3^{+0.5}_{-1.0}$ keVb

x : Kettner et al.
Z. Phys. A **308** (1982) 73
- : Redder et al.
Nucl.Phys. **A462**, 385 (1987)



$S_{6.9}(300) = 7^{+13}_{-4}$ keVb

Buchmann& Barnes
Nucl. Phys. A777 (2006) 254

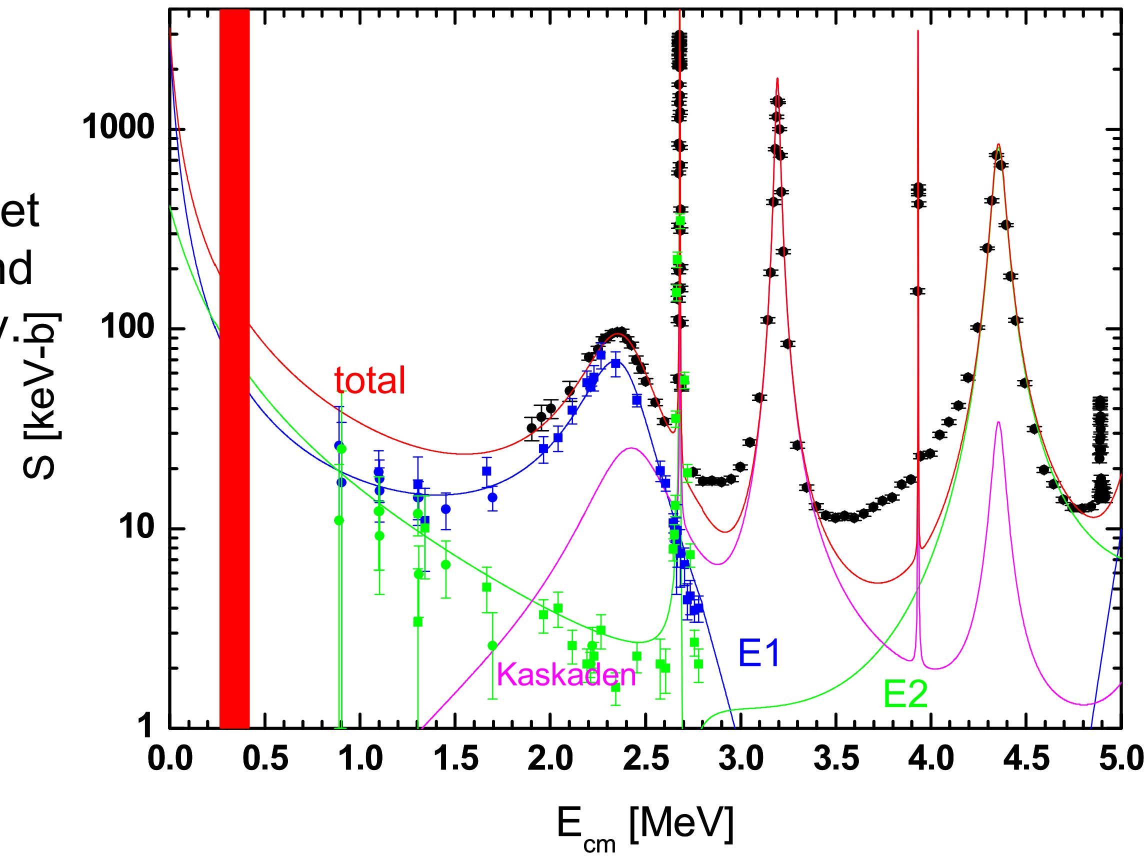
Direct methods in inverse kinematics:

^{12}C-beam, ^{4}He-gas target
γ-ray detection
^{16}O-recoil measurement

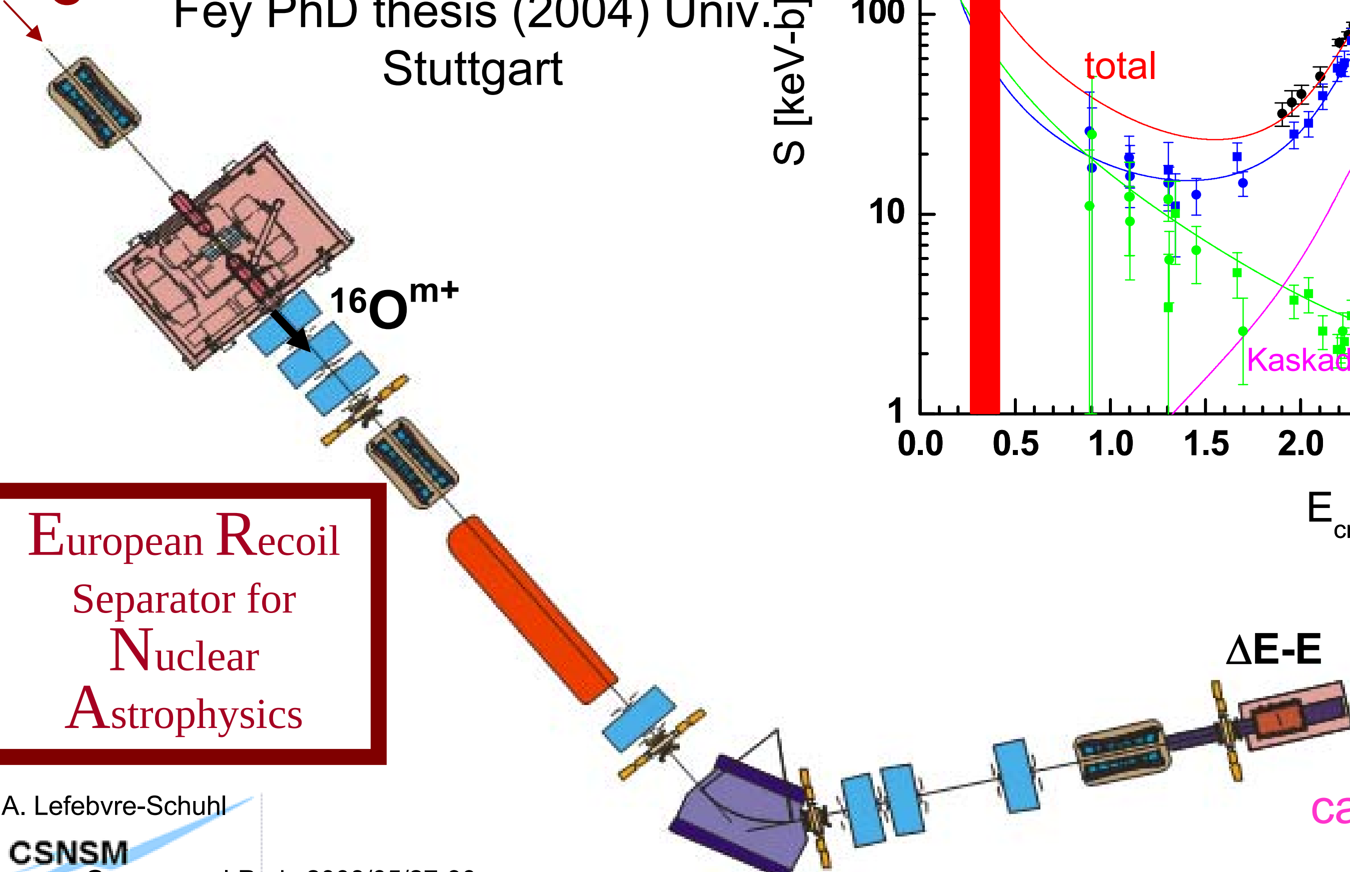
ERNA's data

Schürmann et al. EpJ A 26 (2005) 301

Thanks Schürmann, Kunz, Strieder et al.



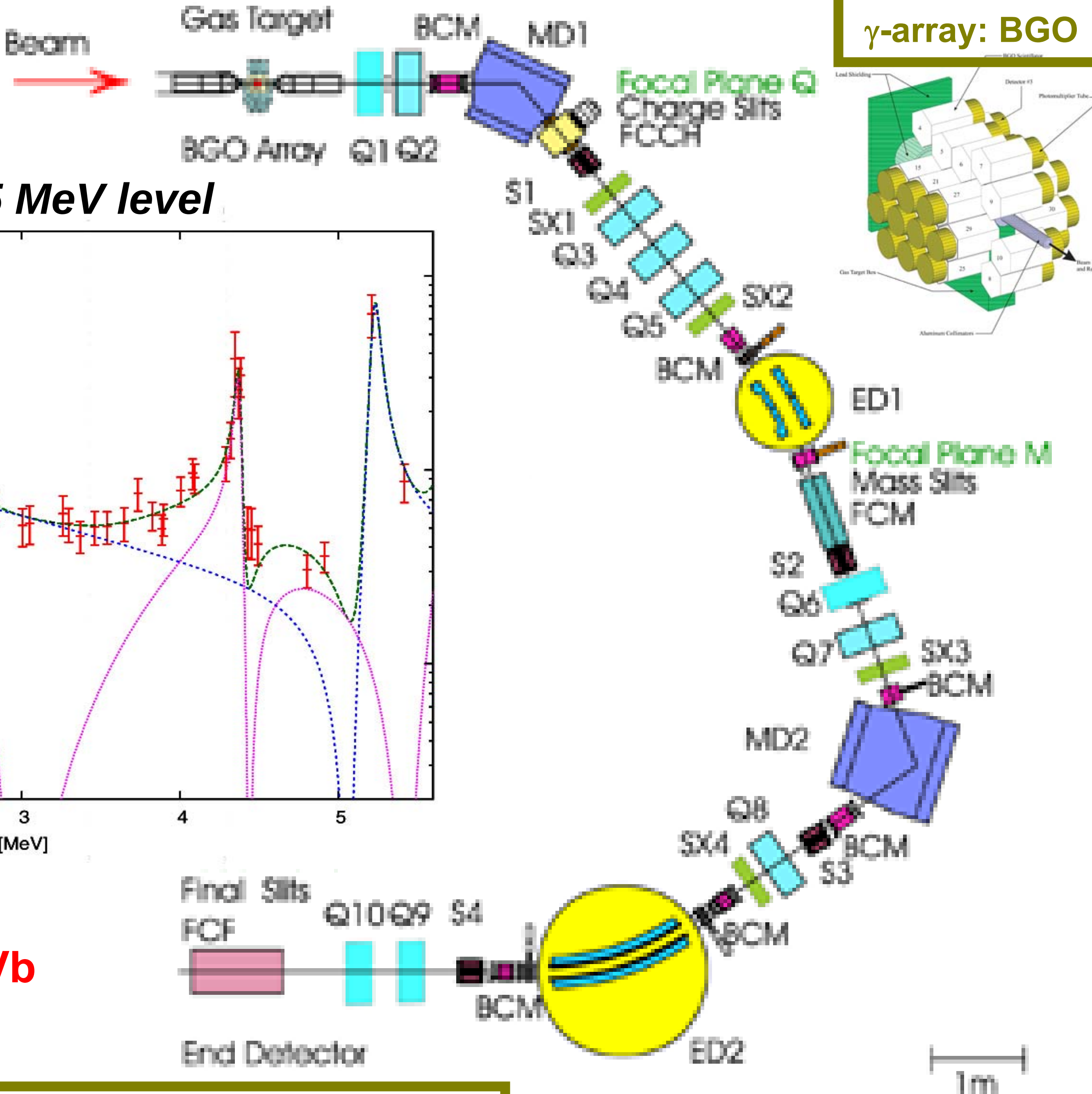
E1 and **E2** data : Assunçao et al. PRC 73(2006)055801 and Fey PhD thesis (2004) Univ. Stuttgart



European Recoil Separator for Nuclear Astrophysics

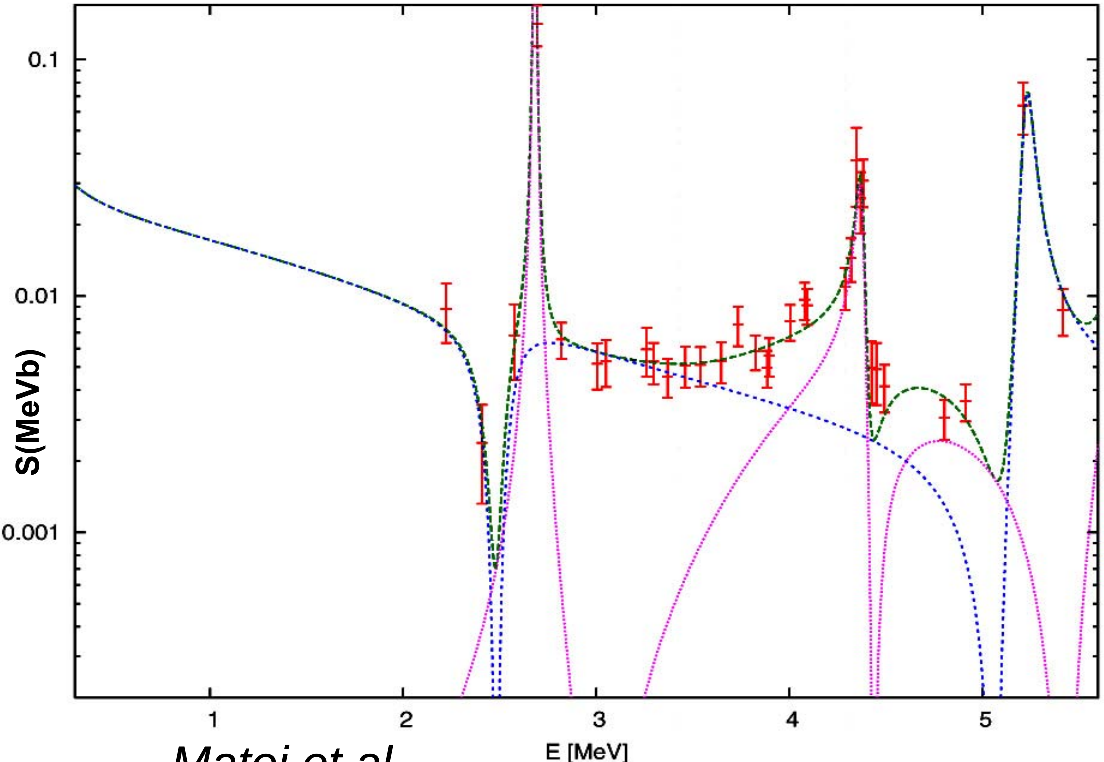
R-Matrix calculation
Kunz et al.
Ap.J. 567 (2002) 643
E1, E2,
cascades (6.92+7.12), total

CSNSM
A. Lefebvre-Schuhl



γ-array: BGO

Cascades to the 6.045 MeV level



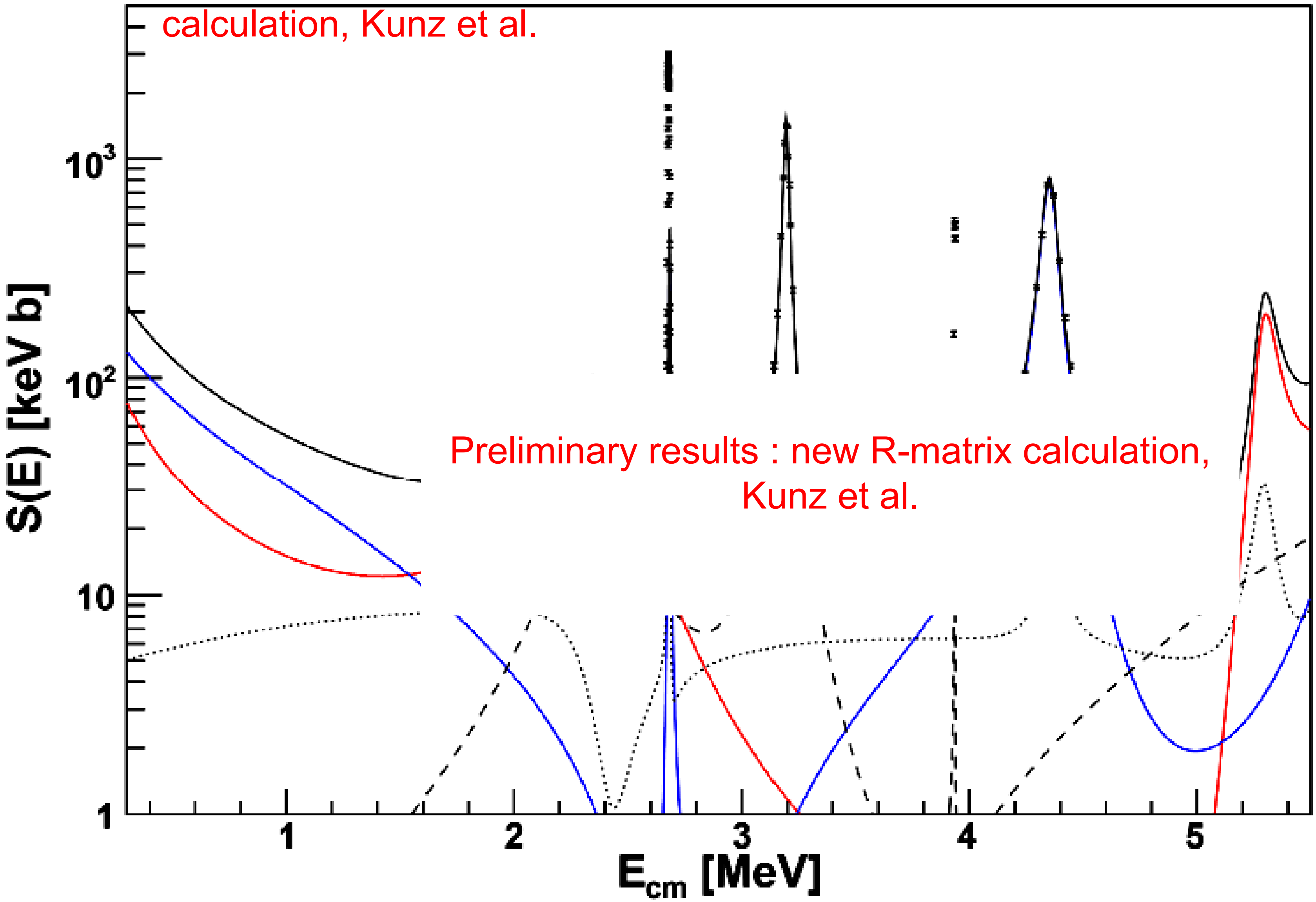
Matei et al.
PRL 97 (2006) 242503

$S_{6.0}(300) = 25^{+16}_{-15}$ keVb

Detector of Recoils and Gammas of Nuclear reactions

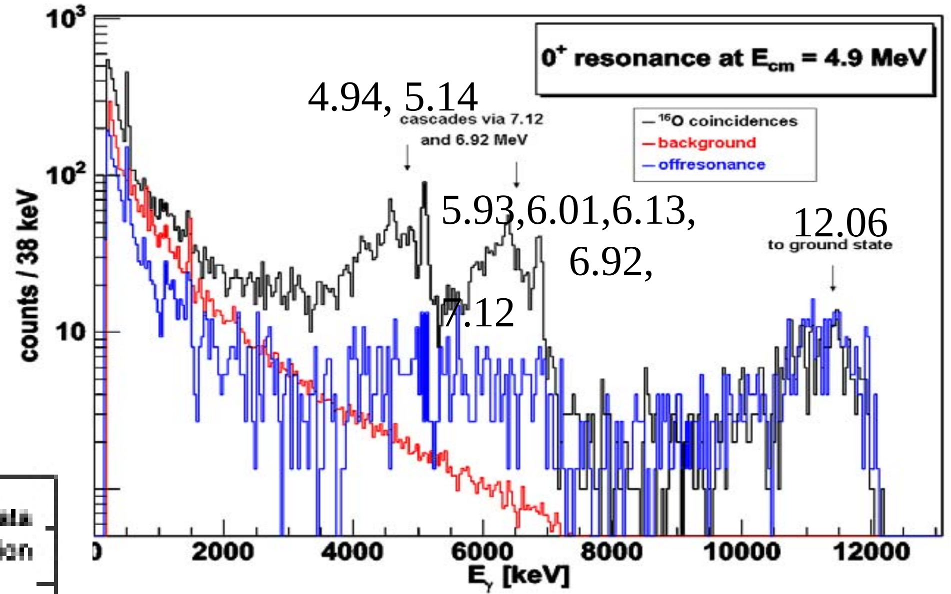
ERNA‘s data
Schürmann et al. EpJ A 26 (2005) 301
Thanks Kunz, Strieder et al.

Preliminary results : new R-matrix calculation, Kunz et al.

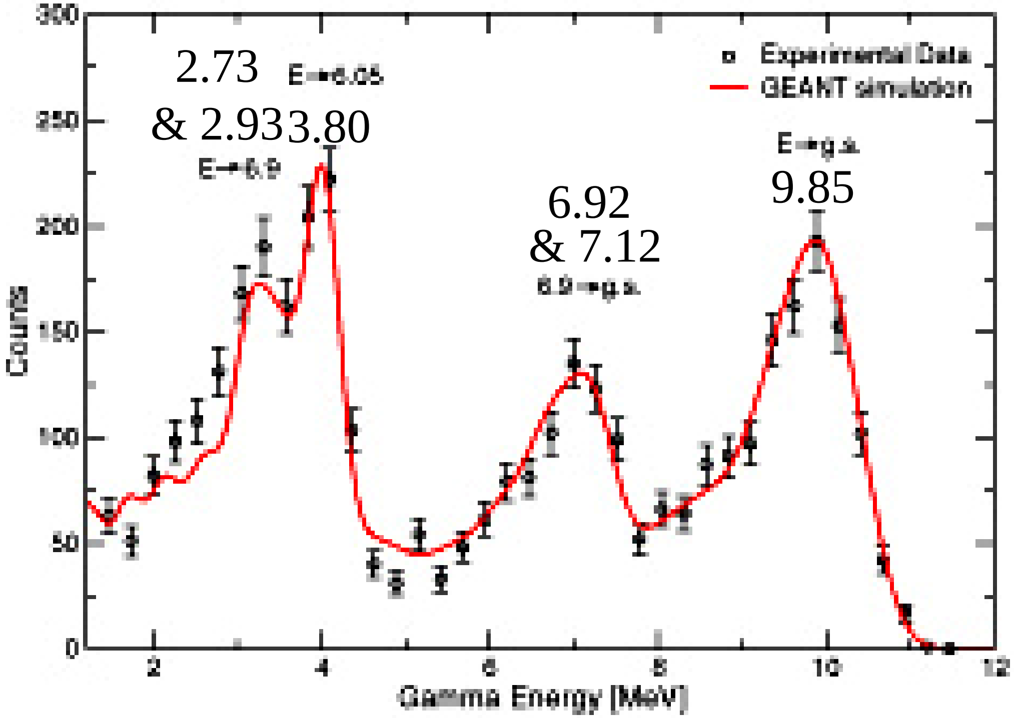


Ge detector at 90°
coïncidence with ^{16}O in ERNA :
at E_{cm} = 4.9 MeV on resonance,
off resonance
without target

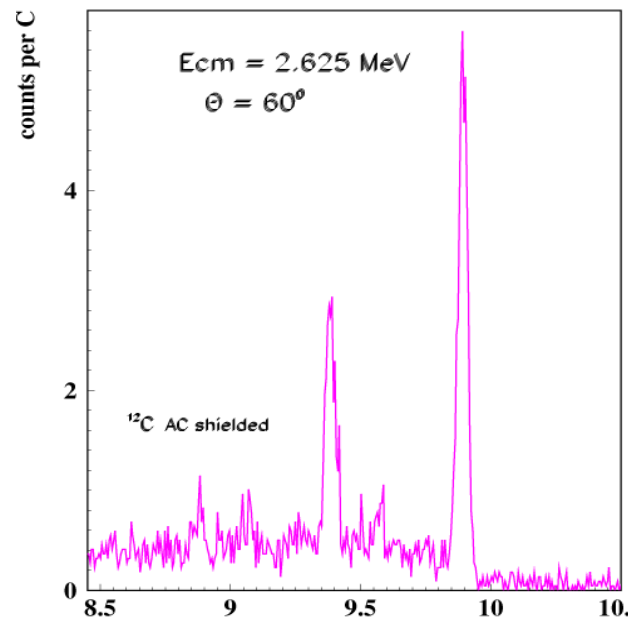
Matei et al. PRL 97 (2006) 242503



D. Schürmann PhD, Univ. Bochum 2007



E_{cm} = 2.694 MeV
Sum of the BGO spectra in coincidence with ^{16}O
recoil nuclei



Assunçao et al. PRC 73 (2006) 055801

Doppler shift amplified by target extension

3 R-matrix calculations S(300)

	Fey et al (2004) 2 experiments + previous $E_{cm\ eff}$: 0.89-2.8 MeV	Buchmann and Barnes (2006) All available data + ERNA +DRAGON	*NACRE (1999)*
$E1_0$	77 ± 17 keVb	80 ± 20 keVb	*79 ± 21 keVb*
$E2_0$	81 ± 22 keVb	53^{+13}_{-18} keVb	*120 ± 60 keVb*
Casc.	4 ± 4 keVb	7^{+13}_{-4} keVb *(6.92 MeV)*	
		25^{+16}_{-15} keVb *(6.05 MeV)*	
Total	162 ± 39 keVb	*(Σ=165 keVb)*	

Perspectives

$^{16}N \rightarrow \beta^- + {}^{16}O \rightarrow \alpha + {}^{12}C$

New measurements to improve the precision on the S_{E1}

Accelerator of intense ^{4}He beam

3 to 5 MV with ECR source

With pulsed beams?

Gas vs ^{12}C targets

(Coincidences with) a new γ-ray detector array

(angular distributions, cascades)

+ a recoil separator

(for inverse kinematics studies)

2 in use : DRAGON (TRIUMF) and ERNA (Bochum)

Detection efficiency : up to 100% of the more probable charge state at the charge equilibrium (50% of the ^{16}O with a poststripper)

- present limitations : intensity through WF, target extension
- only the total cross section

with dense jet gas target (smal extension)

Perspectives

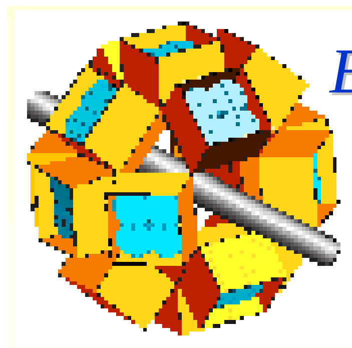
+ a new γ-ray detector array

energy resolution vs efficiency

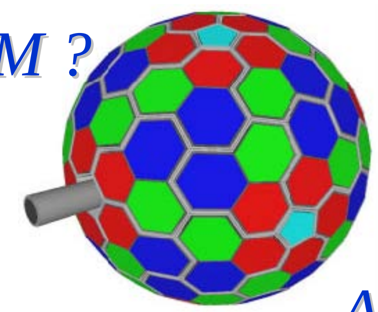
to separate the transitions — enough statistics

With Ge detectors ?

EUROBALL ?

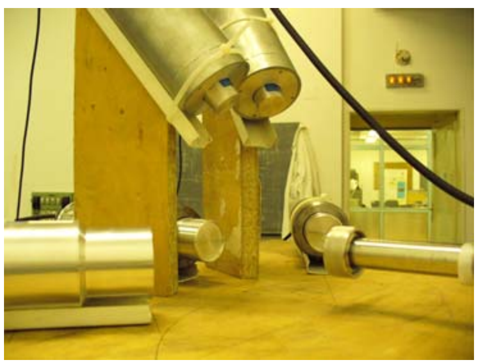


EXOGAM ?



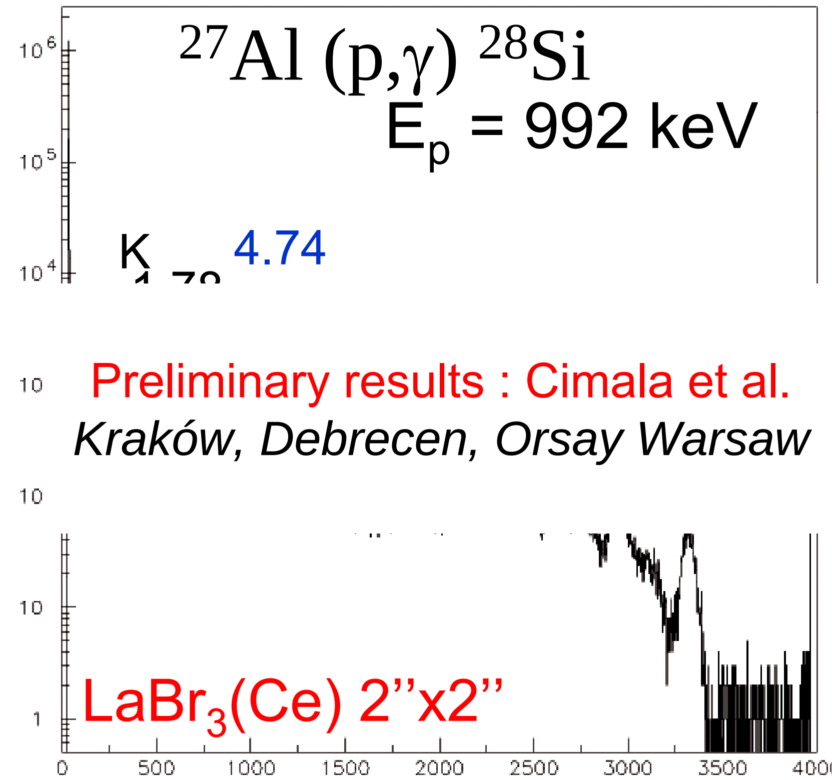
AGATA ?

or new ones : LaBr3 array ?



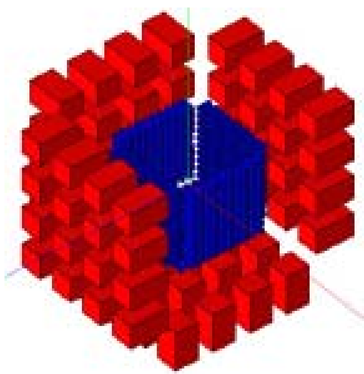
Preliminary results : Cimala et al.

Kraków, Debrecen, Orsay, Warsaw



A Paris detector ?

(LaBr3 + CsI)



Eurogam-detector collaboration

M. Assunção, M. Fey, A. Lefebvre-Schuhl, J. Kiener, V. Tatischeff, J.W. Hammer, C. Beck, C. Boukari-Pelissie, A. Coc, J.J. Correia, S. Courtin, F. Fleurot, E. Galanopoulos, C. Grama, F. Haas, F. Hammache, F. Hannachi, S. Harissopulos, A. Korichi, R. Kunz, D. Ledu, A. Lopez-Martens, D. Malcherek, R. Meunier, Th. Paradellis, M. Rousseau, N. Rowley, G. Staudt, S. Szilner, J.P. Thibaud, and J.L. Weil

CSNSM-Orsay; IfS-Stuttgart; IPHC/IReS-Strasbourg; KVI-Groningen; INP-Athens; GSI-Darmstadt (IPN-Orsay); PI-Tübingen; DP-Lexington (II-Budapest)

ERNA's collaboration

D. Schürmann, A. Di Leva, L. Gialanella, D. Rogalla, F. Strieder, N. De Cesare, A. D'Onofrio, G. Imbriani, R. Kunz, C. Lubritto, A. Ordine, V. Roca, C. Rolfs, M. Romano, F. Schümann, F. Terrasi, and H.-P. Trautvetter

INFN & Univ.-Naples; IE3-Bochum;

PARIS collaboration

100 physicists, engineers and PhD students, 38 institutions from 16 countries and principally : *IFJ PAN-Kraków,* ATOMKI-Debrecen, CSNSN-Orsay and Univ.-Warsaw