Present $^{12}C(\alpha,\gamma)^{16}O$ reaction knowledge for astrophysical purposes Perspectives for future improvements

Problematics

Present status

Perspectives

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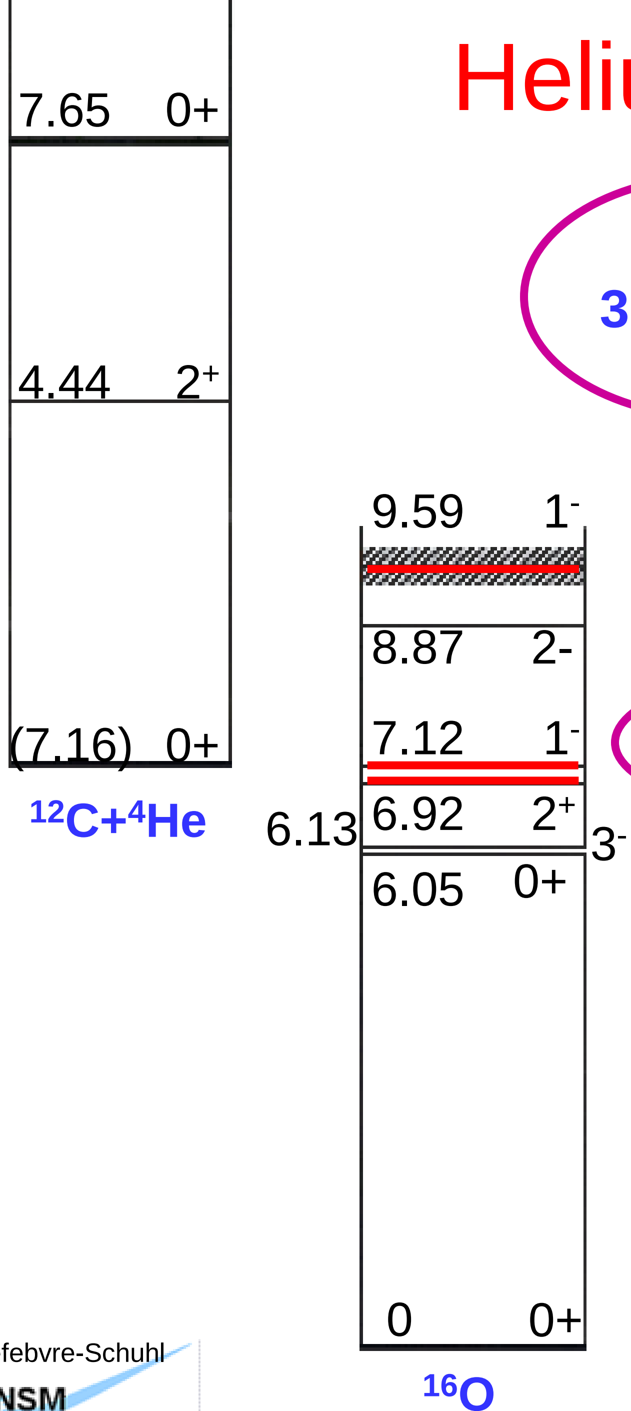
CSNSM Orsay

November 24th 2011

THERRAA, Athens

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

W.A. Fowler, S.E. Woosley, T.A. Weaver, T.S. Metcalfe, G. Imbriani, A. Chieffi, C. Tür, O. Straniero,…

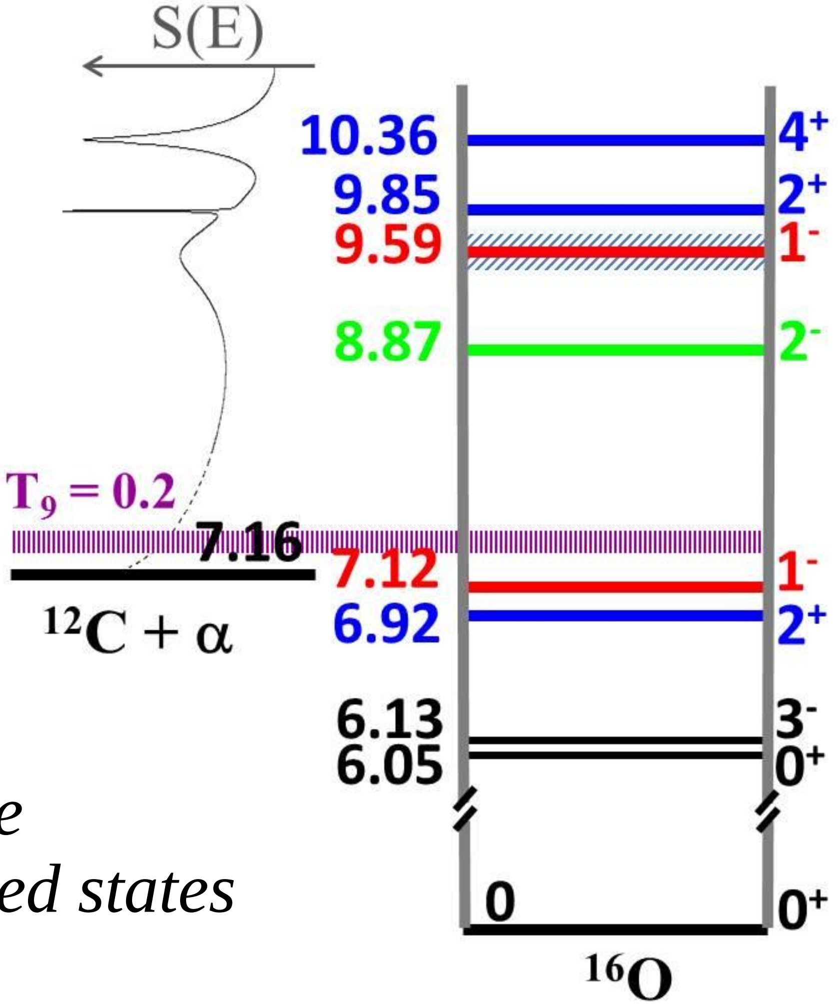
$^{12}C(\alpha,\gamma)^{16}O$

T~ 0.2 x 10^9 K

→ E(Gamow peak) ~ 300 keV

σ(300 keV) ≈ 10^{-17} barn !

$$S(E) = E\,\sigma(E)\,e^{(2\pi Z_1 Z_2 e^2/\hbar v)}$$



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_{DC} → ground state

(γ-ray angular distributions)

and for E_{DC} → excited state

Indirect methods :

To get nuclear informations:

α spectroscopic factors, reduced α–widths, ANCs…

→ Nuclear models : R-matrix, microscopic cluster models…

- ✓ 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

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

$S_{E1}(300)$ in keVb

*[Z. Zhao et al. PRL**90**(1993)2006]*

95±6(stat)±28(syst)

*[R.E. Azuma et al. PRC**50**(1994)1194]*

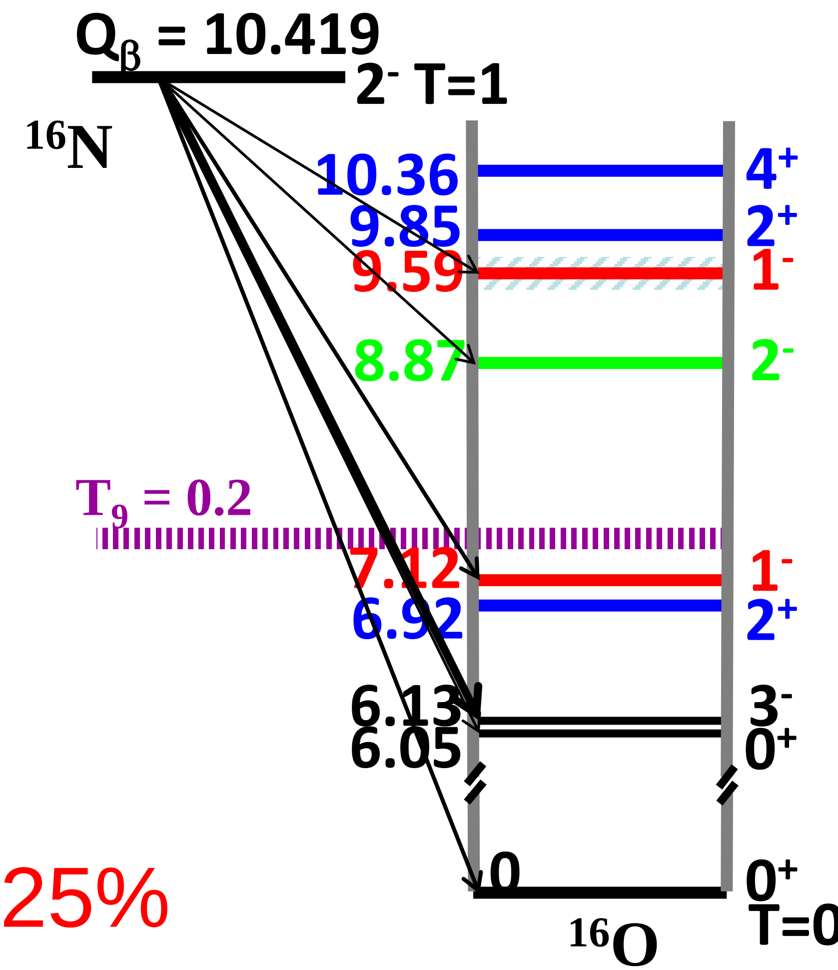
79 ± 21 (R)

82 ± 26 (K)

*[X.D. Tang et al. PRC**81**(2010)045809]*

86 ± 22

~25%



→ M. Gai talk

Indirect methods :

^{16}O Coulomb breakup

2 crucial points:

- to extract the Coulomb contributions
- to separate dipolar and quadrupolar contributions

Requires a high precision in angular distribution measurements

[F. Fleurot et al. PLB615(2005)167 and ref. therein]

S(300) in keVb

α-transfer $^{12}C(^{6}Li, d)^{16}O$

$S_{E1}(300)$: **81±17** *[A. Belhout et al. NP **A793**(2007)178 and ref. therein]*

α-transfer $^{12}C(^{7}Li, t)^{16}O$

$S_{E1}(300)$: **100±28** *[N. Oulebsir et al. NIC X1(2010) and ref. therein]*

$S_{E2}(300)$: **52±19** $S_{tot}(300)$: **177±63**

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) → *reduced uncertainties*

background suppression: shieldings
or coincidences with pulsed beams

γ-ray angular distributions :

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

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

Ex : *M. Assunção et al. PRC 73 (2006) 055801* :

« Eurogam » setup

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

→ very good energy resolution

→ reduced uncertainties

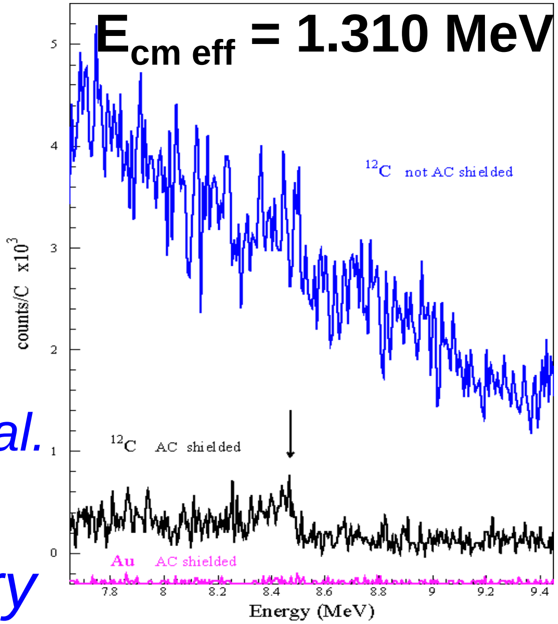
Compton suppression (active BGO shields)

↘ E_{cm} = 1.310 MeV

↘ *E_{cm} = 0.9 MeV M. Fey et al.*

Turn table, 4 Ge detectors

High efficiency, closer geometry



Total γ efficiency at 10 MeV : 1.2×10^{-3} in experimental conditions

($7\ 10^{-3}$ at 1.33MeV)

Present S_{E1} results to the ground state

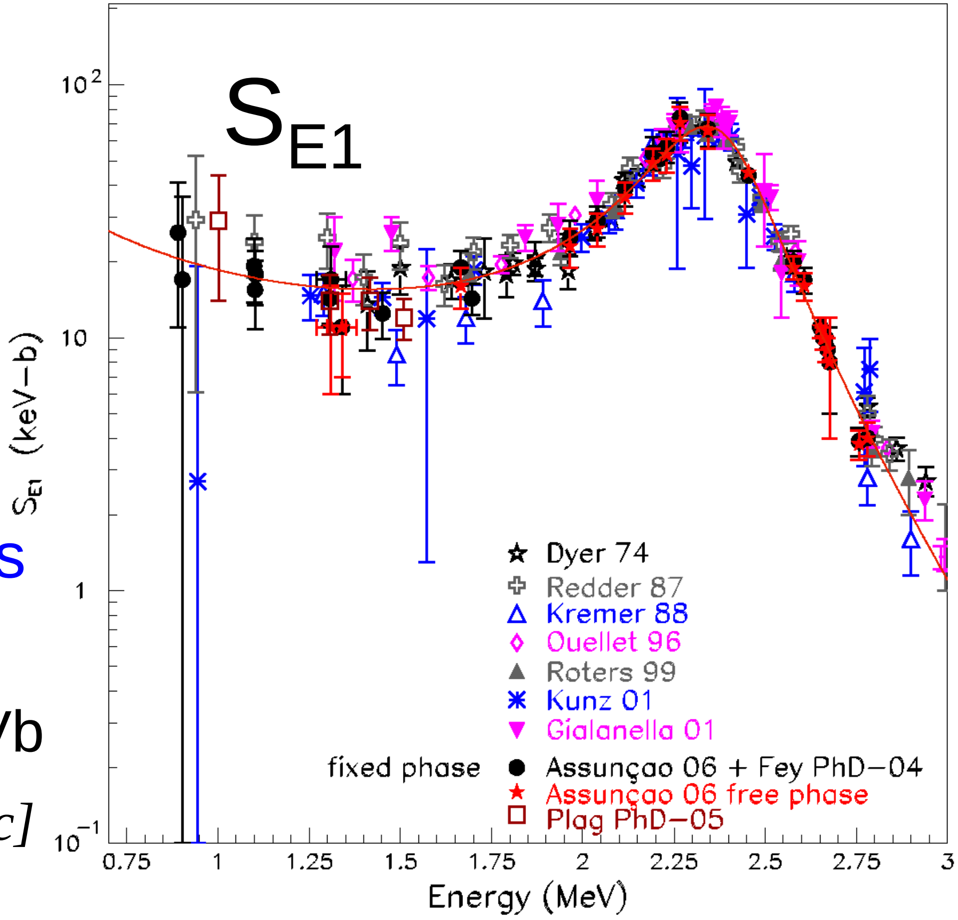
$$S(E) = E\,\sigma(E)\,e^{(2\pi Z_1 Z_2 e^2/\hbar v)}$$

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

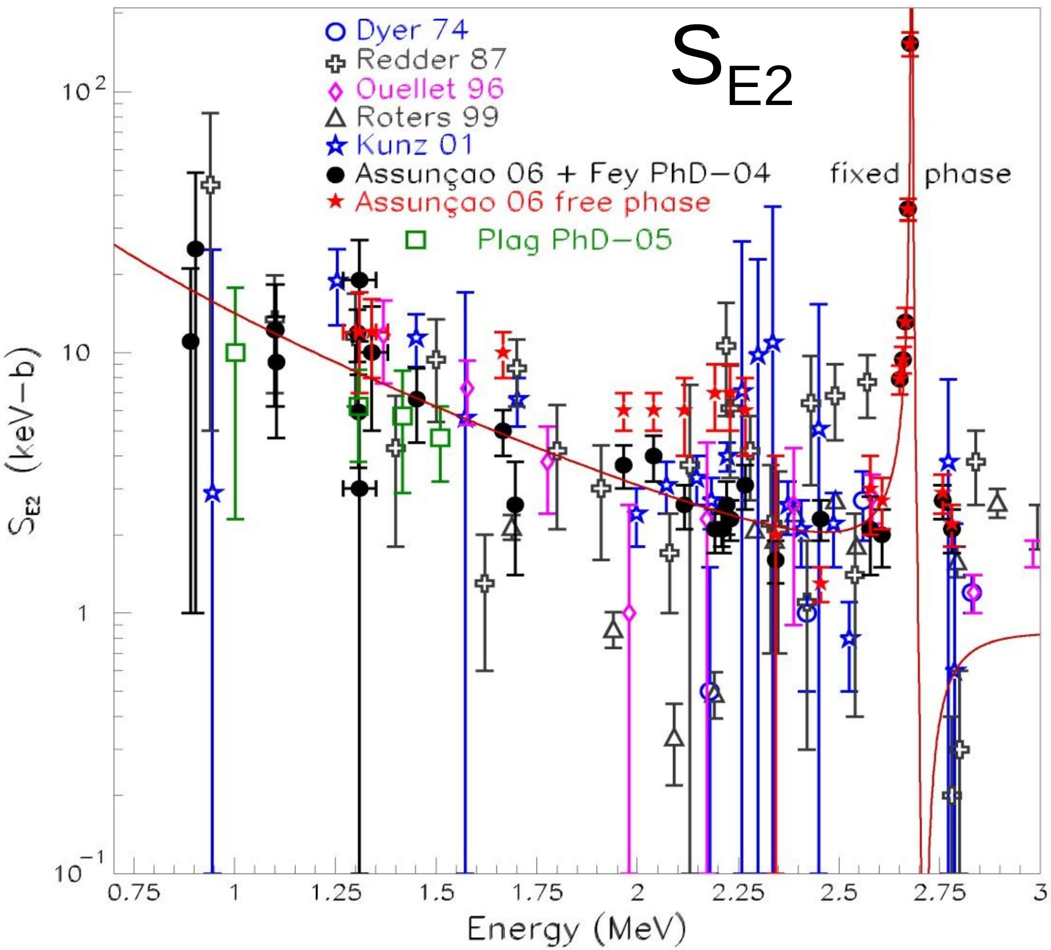
Best χ^2-> $S_{E1}(300) = 77\pm17$ keVb

[Hammer et al. NP ***A758*** *(2005) 363c]*



Present S_{E2} results to the ground state

$$S(E) = E\,\sigma(E)\,e^{(2\pi Z_1 Z_2 e^2/\hbar v)}$$



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. NP **A758** (2005) 363c]*

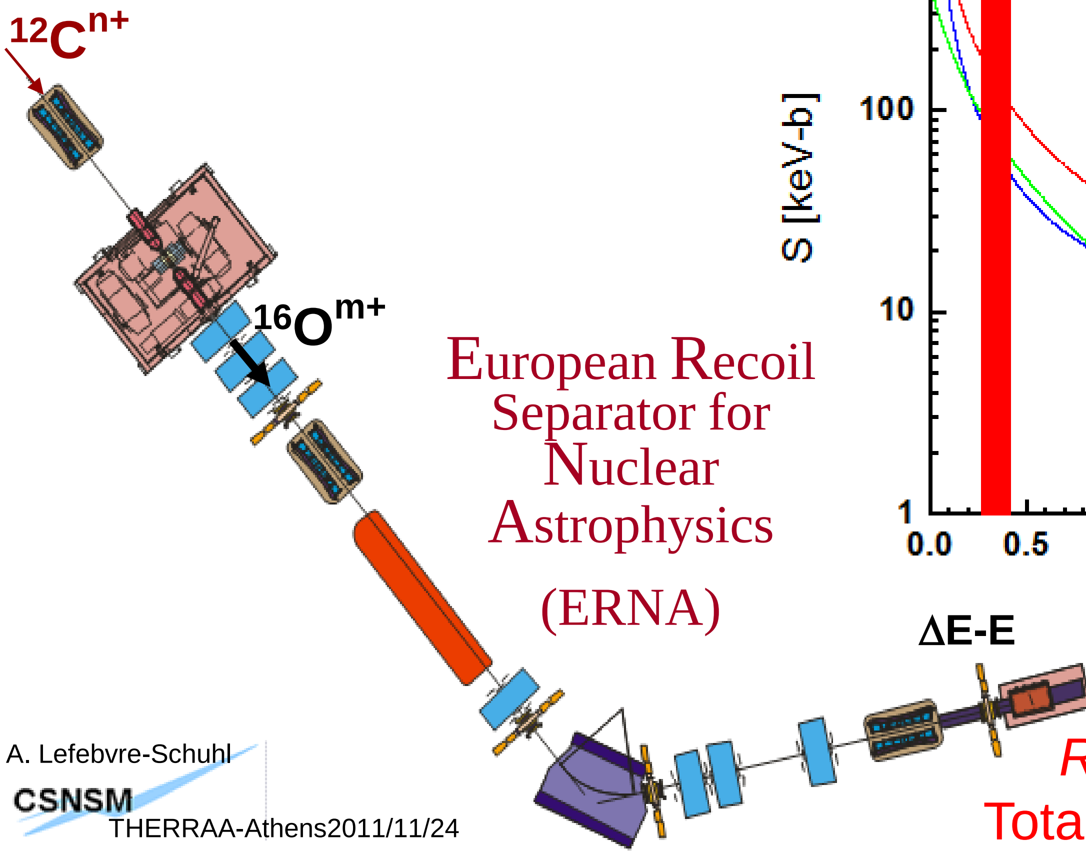
Direct methods in inverse kinematics:

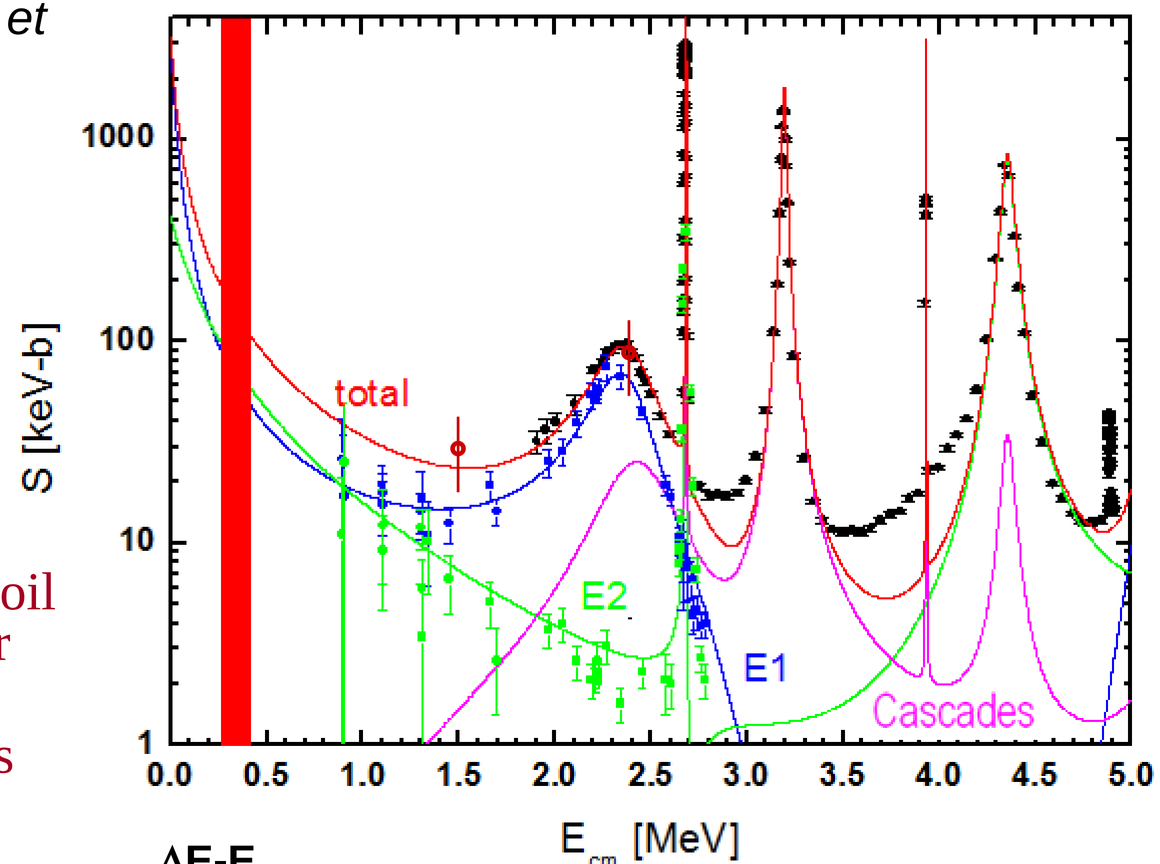
^{12}C-beam, ^{4}He-gas target, γ-ray detection, ^{16}O-recoil measurement

Total S factor *[D. Schürmann et al. EpJA**26**(2005)301]*

[K. Fujita et al. NIC11(2010)]

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





R-Matrix calculation:
*R. Kunz et al. Ap.J. **567**(2002)643*
Total = E1+ E2+ cascades (6.92+7.12)

New R-matrix fit with a new R-Matrix code

[D. Schürmann, Nuclei in the Cosmos 9, June 2006]

- classical formalism OR C. Brune's alternative parametrization
- all relevant channels included: ^{16}N, (α,α), (α,γ) [external (direct) capture]

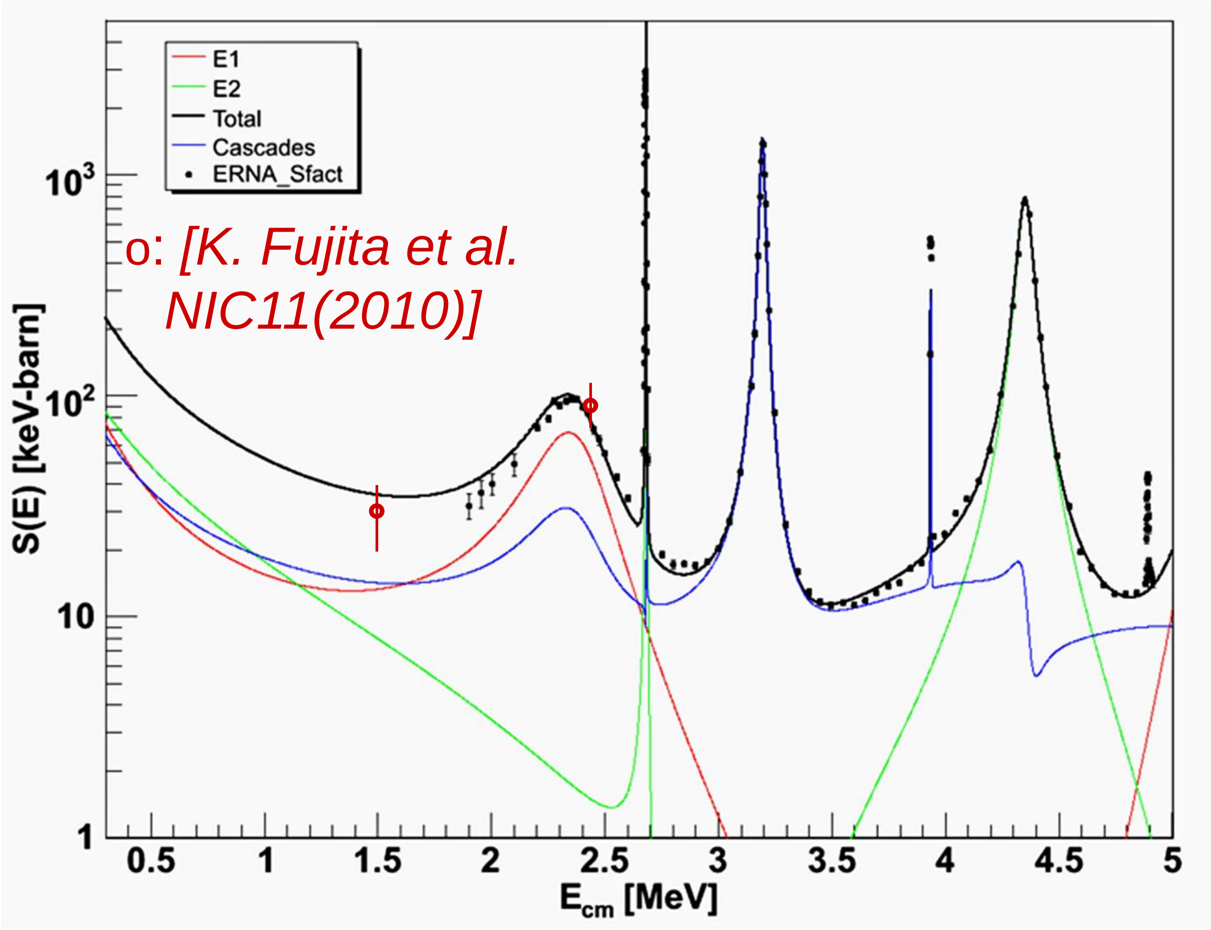
From the curves, in keVb:

$S_{E1}(300) \sim 73$

$S_{E2}(300) \sim 82$

$S_{cas}(300) \sim 65$

$S_{tot}(300) \sim 210$



Cascades:
Radiative capture to ^{16}O excited states

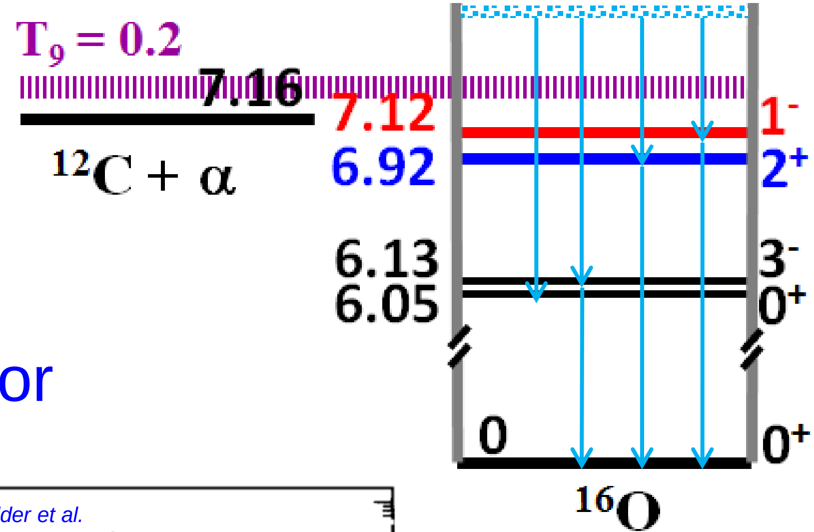
$J^\pi = 1^-$, 7.12 MeV

$J^\pi = 2^+$, 6.92 MeV

$J^\pi = 3^-$, 6.13 MeV (negligible ?)

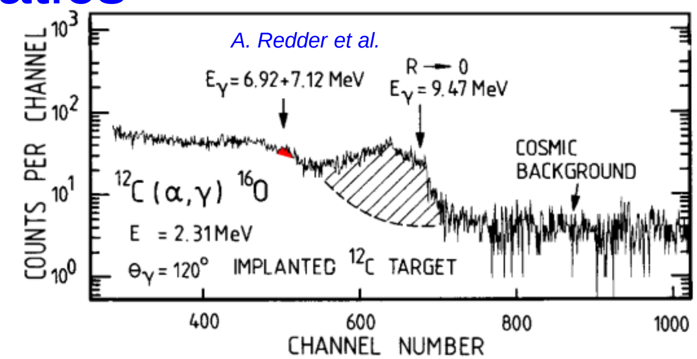
$J^\pi = 0^+$, 6.05 MeV

E1, E2



Results obtained either in direct or inverse kinematics

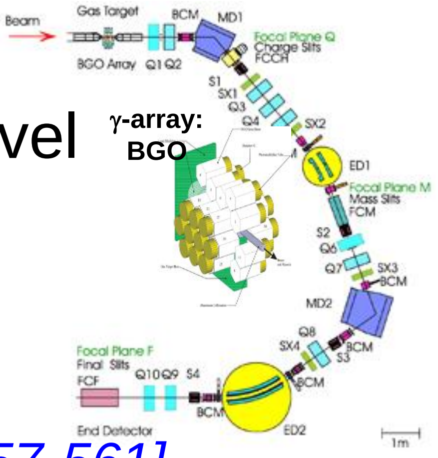
In direct kinematics:
high γ-ray background



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

*[K.U. Kettner et al. Z. Phys. A **308** (1982) 73]*
*[A. Redder et al. NP **A462** (1987) 385]*

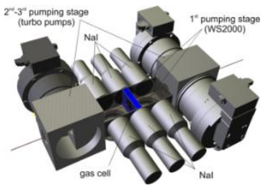
Cascades



Since 2006, new results on DC to the 6.05 MeV level

Sophisticated setups in inverse kinematics

Dragon at Triumf or Erna at Bochum



*[C. Matei et al. PRL **97** (2006) 242503]*

[D. Schürmann et al. Phys. Lett. B703 (2011) 557-561]

$S_{7.1}$(300) in keVb

$1.3^{+0.5}_{-1.0}$ *A. Redder et al. NP **A462**(1987)385*

0.3 *L. Buchmann & C.A. Barnes NP **A777** (2006) 254*

1-2 *F.C. Barker & T. Kajino Aust.J.Phys.**44**(1991)369*

$S_{6.9}$(300) in keVb

6 ± 3 *A. Redder et al. NP **A462**(1987)385*

7^{+13}_{-4} *L. Buchmann & C.A. Barnes NP **A777** (2006) 254*

$S_{6.05}$ (300) in keVb

25^{+16}_{-15} *C. Matei et al. PRL **97** (2006) 242503*

< 1 *D. Schürmann et al. Phys. Lett. B703 (2011) 557-561*

Some recent R-matrix calculations of S(300)

in keVb

	a(1999)	*b(2004)*	*c(2006)*	*d(2006)*	*e(2008)*	*f(2011)*
$E1_0$	79 ± 21	77 ± 17	80 ± 20	~ 73	70 ± 20	
$E2_0$	120 ± 60	81 ± 22	53^{+13}_{-18}	~ 82	45^{+15}_{-35}	
6.92		4 ± 4				
6.92+7.12			7^{+13}_{-4}	~ 65	10 ± 6	*& 6.13*
6.05			25^{+16}_{-15}		25 ± 16	< 1 *(l = 2 only)*
Total		162 ± 39	165^{+62}_{-57}	~ 210	150^{+57}_{-77}	

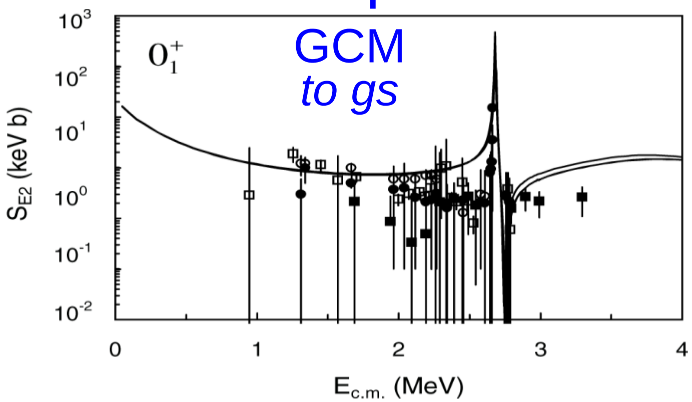
a – Nacre (1999); b - M. Fey et al.(2004), Ecm: 0.89-2.8 MeV, «Stuttgart» data; c - L. Buchmann & C.A. Barnes (2006); all available data; d - Schürmann, NIC9 (2006); e - L. Buchmann, NIC10 (2008); f - D. Schürmann et al., PLB703(2011), Ecm: 3.3-4.5 MeV

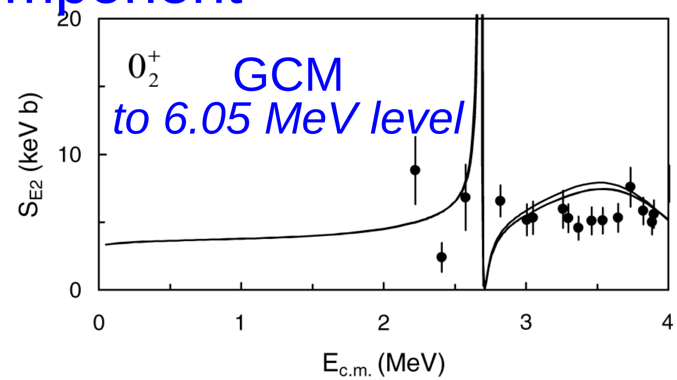
Improvements in the accuracies of all values are needed in order to reduce the uncertainty on S(300)

Microscopic cluster calculation

*M. Dufour & P. Descouvemont PRC**78**(2008)015808*

α+^{12}C microscopic cluster calculation: in the framework of the Generator Coordinate Method with 3 nucleon-nucleon interaction performed for the E2 component





●, ○ *M. Assunçao et al. PRC **73**(2006)055801*

■ *G. Roters et al. EPJA(1999)451*

□ *R. Kunz et al. PRL**86**(2001)3244*

● *C. Matei et al. PRL**97** (2006) 242503*

$S_{E2,6.05}(300) \approx 3.5$keVb

$S_{E2,gs}(300) \approx 50$keVb

→ P. Descouvemont

R-matrix fits combined with a microscopic cluster model

From current phase shifts and capture data: high uncertainty on S +constraint: 2^+_1 ANC from the GCM→$S_{E2}(300) = 42 \pm 2$ keVb

Improvements in the accuracies of all values + values at lower E_{cm} are needed in order to reduce the uncertainty on S_{E2}

Perspectives

Time-inverse reaction: $^{16}O(\gamma,\alpha)^{12}C$

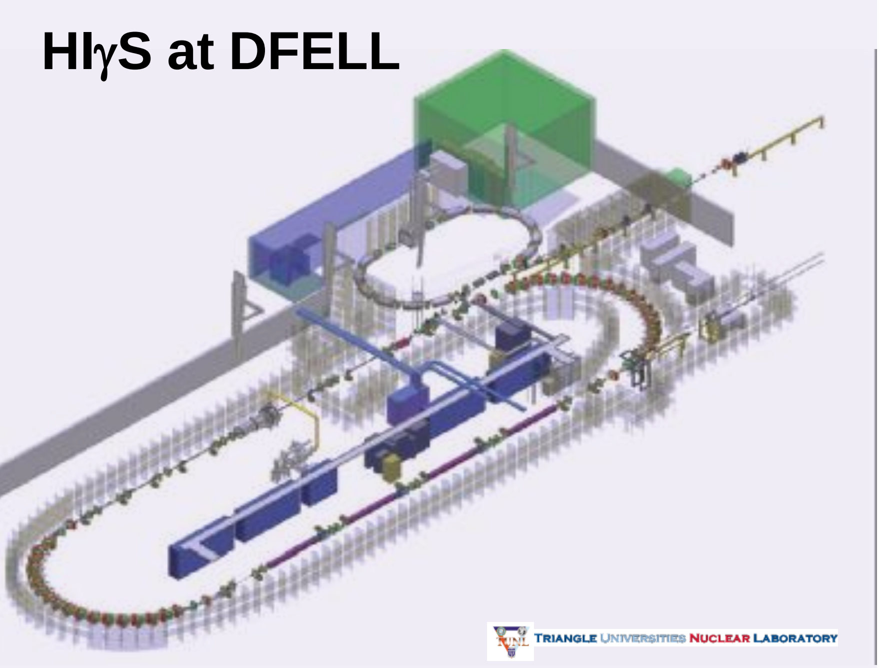
γ-beam (Duke University)

α and ^{12}C recoil measurement

Cross section enhancement

High Intensity Gamma Source (HIgS) facility
at the *Duke* Free Electron Laser Laboratory (DFELL)

E_γ = 8 – 11 MeV, $I_\gamma \sim 5 \times 10^7$ photons/s



Targets

* Bubble chamber (H_2O)
K.E. Rehm et al., NPA-V, Eilat, Israël 2011

* O-TPC (CO_2+ N_2)
M. Gai et al., NPA-V, Eilat, Israël 2011

→ M. Gai presentation

Perspectives

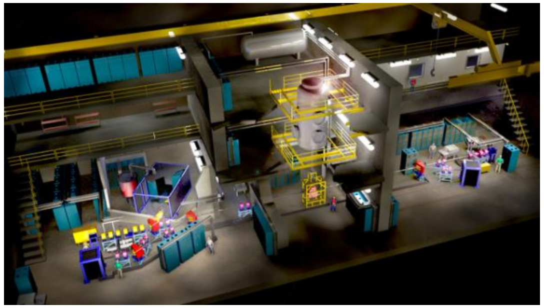
Accelerator of intense $^{4}He/^{12}C$ beam

3 to 5 MV with intense source
with pulsed beams?

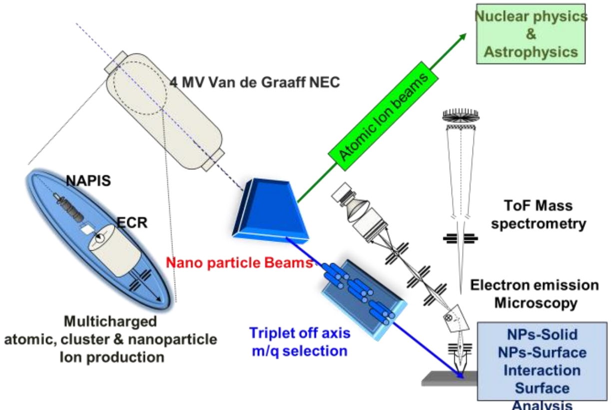
Elena project at Boulby, *M. Aliotta, CANFRANC Workshop (2009) Barcelona*
3 MV single-ended machine (e.g. Pelletron by NEC) with ECR source (e.g. for high intensity ^{12}C beam at high charge states)

Underground or not ?

Diana project
at Homestake
D. Leitner, Particle Accelerator Conference (2011)New York



Two accelerators → 50-400kV [300-3MV] with high ion beam currents: 100 mA proton, 50 mA helium [≥ 1mA]
High density super-sonic jet-gas target (up to 10^{18} atoms/cm^{2}).



Andromede equipex at Orsay:
a 4 MV Van de Graaff NEC
with Nacis and ECR sources
S. Della-Negra, IPNO

Perspectives

Gas (^{4}He) vs solid (^{12}C) targets

(Coincidences with) a new γ-ray detector array (angular distributions, cascades)

+ recoil separator (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

DENSE jet gas target: supersonic?, cooled?

A new γ-ray array

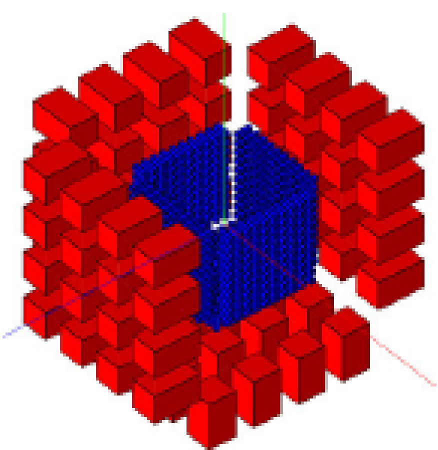
energy resolution vs efficiency

to separate the transitions

With Ge detectors ?

LaBr3 array ?

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, 40 institutions from 17 countries and principally : *IFJ PAN-Kraków,* ATOMKI-Debrecen, CSNSN-Orsay and Univ.-Warsaw