New $^{12}C + {}^{12}C$ sub-barrier fusion cross section measurements within the STELLA project

Guillaume Fruet

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Contents

Nucleosynthesis

- Carbon burning :

$\rightarrow \quad {}^{12}C + {}^{12}C \quad$ and $\quad {}^{12}C + {}^{16}O$

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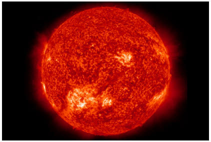
Key reaction : ${}^{12}C + {}^{12}C$

- Nucleosynthesis of heavier elements



Massive stars

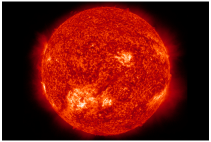
Nucleosynthesis

- Carbon burning :

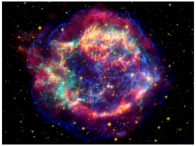
$\rightarrow \quad {}^{12}C + {}^{12}C \quad$ and $\quad {}^{12}C + {}^{16}O$

Key reaction : ${}^{12}C + {}^{12}C$

- Nucleosynthesis of heavier elements
- Explosive scenario



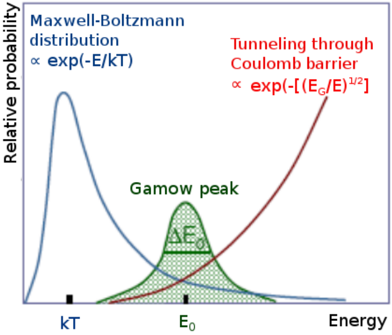
Massive stars



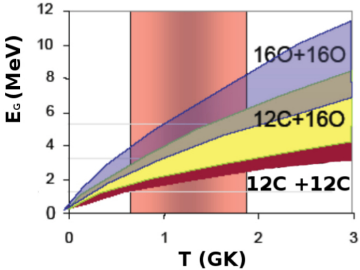
Supernova Cassiopeia A

Gamow window

- Thermal energy distribution
- Quantum tunneling



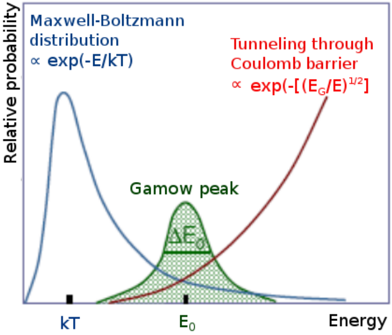
The Gamow window



Gamow energy for different light systems at various temperature

Gamow window

- Thermal energy distribution
- Quantum tunneling



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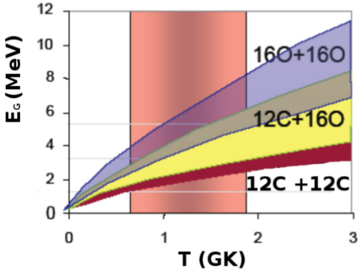
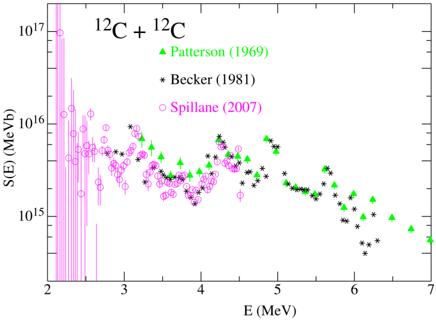


Gamow energy for different light systems at various temperature

- $^{12}C+^{12}C$: $E_0 = 1.5 \pm 0.3$ MeV at $T = 5 \cdot 10^8$K ($E_C \sim 6.6$ MeV)
- $\sigma_{fus} \sim$ pb

Resonances

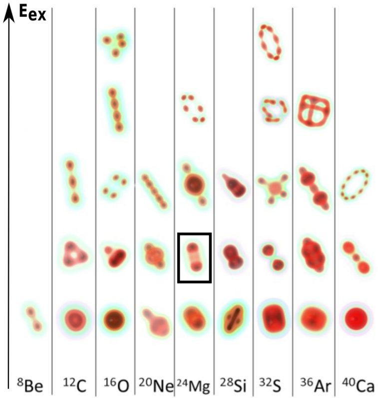


Astrophysical S-Factor for the ^{12}C+^{12}C reaction

- $\sigma(E) = \frac{1}{E} exp\left(-2\pi\eta\right) S(E)$, where $\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$
- Behavior known since 1970's
- ^{12}C+^{12}C exhibits a lot of resonances

Cluster states

- Possible interpretation for resonant states



Modified Ikeda diagram - J.-P. Ebran et al., PRC 90 (2014)

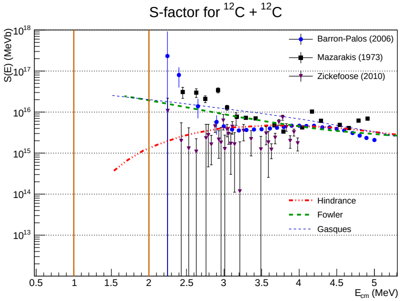
- Resonances in ^{12}C + ^{12}C

  → Di-nuclear molecule in ^{24}Mg ?

- Influence on nuclear reaction rate ?

Previous measurements

- Uncertainty + deviation in between data set
- No data inside the Gamow window



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

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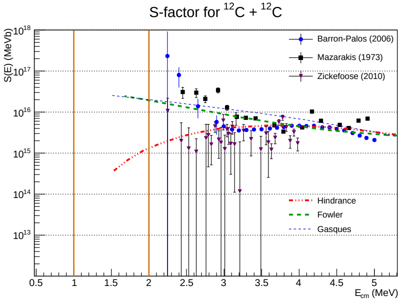

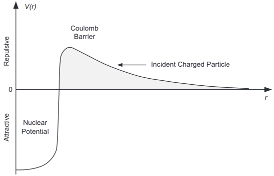

Standard nuclear potential

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

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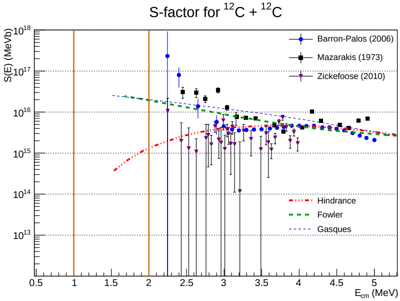

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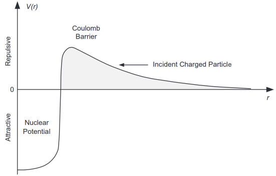
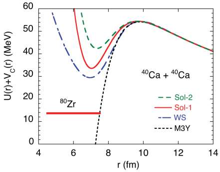


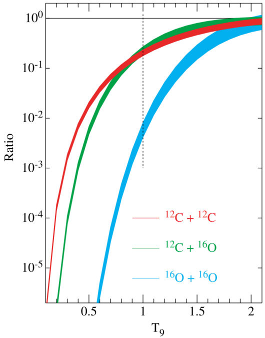
Standard nuclear potential



G. Montagnoli et al., PRC 85 (2012)

Reaction rates

$$R \propto N_i \cdot N_j \cdot \int_0^{\infty} \sigma(E) \cdot E \cdot \exp\left(-\frac{E}{kT}\right)$$



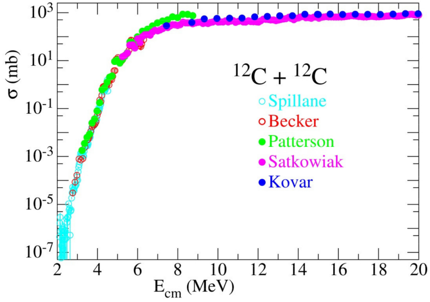
Ratio in between two different extrapolations - C.L. Jiang et al., PRC 75 (2007).

- Ratio $= \frac{R_{hind}}{R_{fowl}}$
- Astrophysical region of interest

  $\rightarrow$ (0.15 - 1) 10^9K
- Several orders of magnitude

Experimental approach

- Previous measurements :

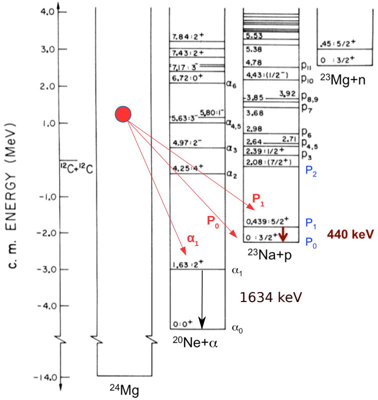


Previous fusion cross section measurements of $^{12}C + {}^{12}C$

- Single particle or γ measurements
- Exponential drop towards low energies
- Contaminations : cosmic rays, ^{13}C, d, ...

Experimental approach

- γ-particle coincidence technique



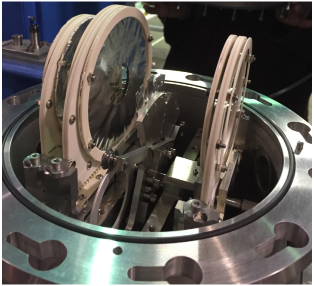
Experimental challenges

- Efficiency : $\epsilon_{tot} = \epsilon_\gamma \times \epsilon_{part}$
- Carbon build-up
- Thin target under high beam intensity

Experimental set-up

Particle detectors

- Annular silicon strip detectors



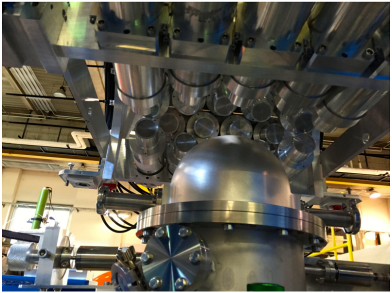
Design and build in IPHC - Strasbourg

- New PCB design with R04003C material
- New pin connection system
- $\Delta\Omega_{tot} \sim 24\%$ of 4π

Experimental set-up

γ detectors

- $LaBr_3(Ce)$ scintillators from the UK FATIMA collaboration



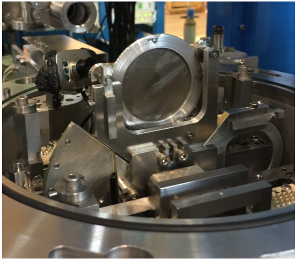
Design and build in IPHC - Strasbourg

- Up to 36 $LaBr_3(Ce)$ detectors
- Self activity as background
- $\epsilon \sim 8$ % for $E_\gamma = 440$ keV
- $\epsilon \sim 3$ % for $E_\gamma = 1634$ keV

Experimental set-up

Targets and carbon build-up

- Ultra High Vacuum chamber
- Thin rotating target



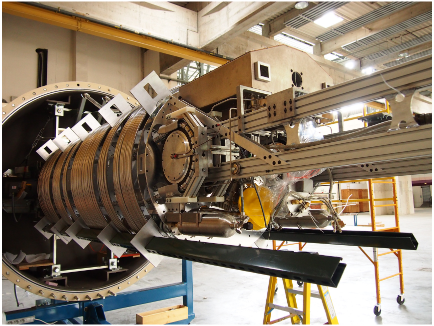
IPHC and GANIL collaboration

- Cryopump $\rightarrow$ P $\sim 3 \cdot 10^{-8}$ mbar
- Target $\varnothing \sim 5$ cm
- Rotation ≥ 1000 rpm
- Designed to sustain up to 10 pμA

The Andromède facility

Andromède

- 4 MV Pelletron accelerator



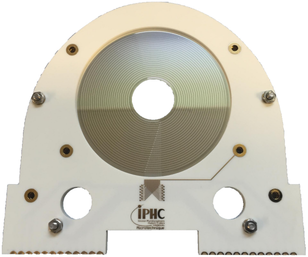
Located at IPN Orsay - France

- Long running period
- E_{lab} from 11 to 4.45 MeV
- Intensities from 40 pnA to $\sim$2 pμA
- Fix targets of 20 to 50 μg/cm^2
- Rotating targets of 30 to 75 μg/cm^2

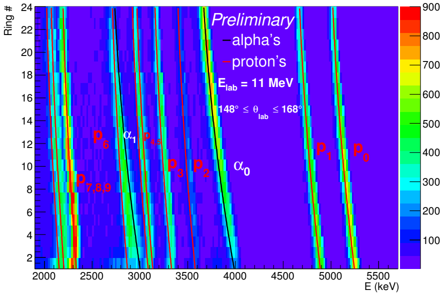
Single particle analysis

Angular matrix

- 24 rings $\leftrightarrow$ polar angle in the lab. frame
- Strip width $\sim$ 886 μm



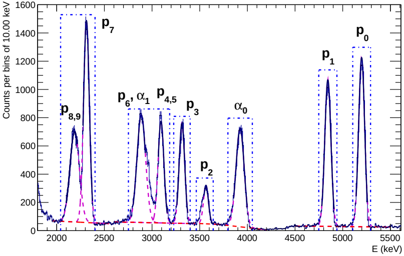
S3 design



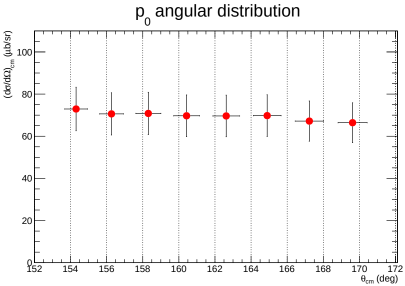
Typical angular matrix (S3B) - E_{lab} = 11 MeV

Angular distribution

- 24 rings → 8 'coupled' rings
- Linear background + gaussian peak



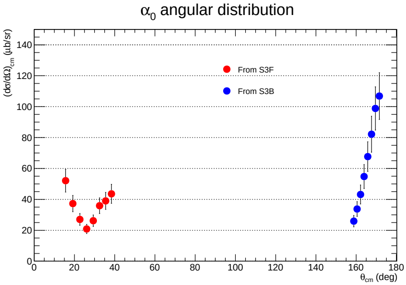
No coincident particle spectrum from S3B - E_{lab} = 11 MeV



Angular distribution for the p_0 exit channel - E_{lab} = 11 MeV

Angular distribution

- 24 rings $\rightarrow$ 8 ‘coupled’ rings
- Linear background + gaussian peak

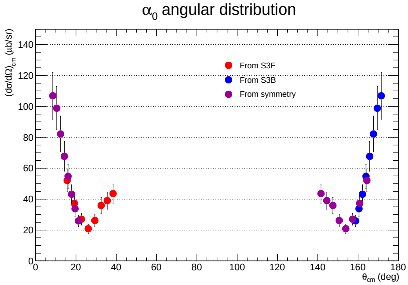


Angular distribution for the α_0 exit channel - E_{lab} = 10.8 MeV

- Symmetric around 90°
- Analysis consistent for the two detectors used
- Average and integrate over 4π for the first

Angular distribution

- 24 rings $\rightarrow$ 8 'coupled' rings
- Linear background + gaussian peak



Angular distribution for the α_0 exit channel - E_{lab} = 10.8 MeV

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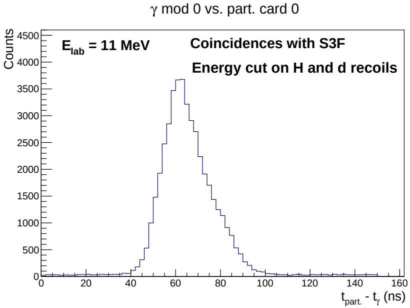
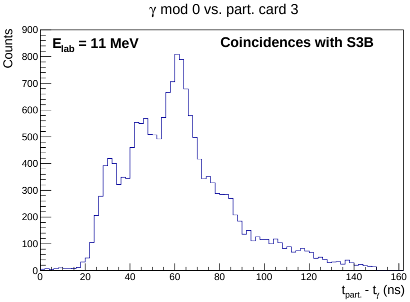
Particle-γ coincidences

Time correlation

- Between γ and particles acq. modules



Time correlation between one γ module and the S3F card

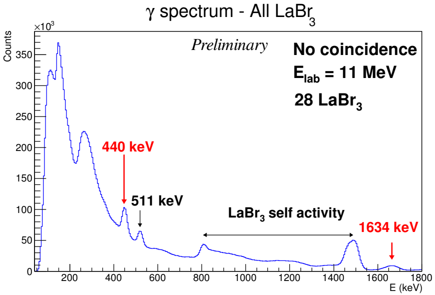


Time correlation between one γ module and the S3B card

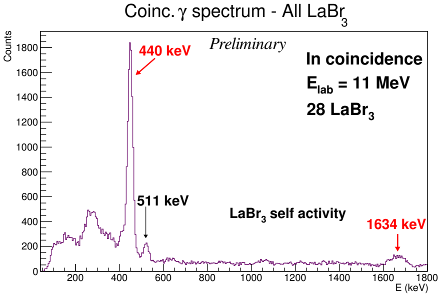
Particle-γ coincidences

Effect on γ spectra

- Suppression of self-activity



Gamma spectrum summed over 28 $LaBr_3$ - Without coincidences

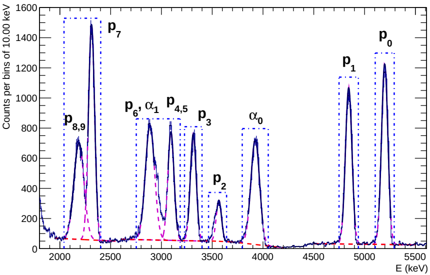


Gamma spectrum summed over 28 $LaBr_3$ - Coincidences with S3B

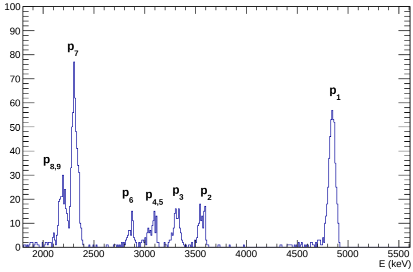
Particle-γ coincidences

Effect on particle spectra

- Suppression of p_0 and α_0 contributions



Particle spectrum from S3B - Without coincidences



Particle spectrum from S3B - Coincidences with $E_\gamma = 440$ keV

Particle-γ coincidences

Effect on particle spectra

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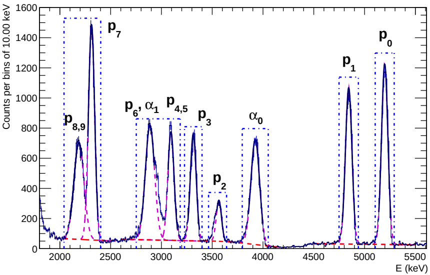

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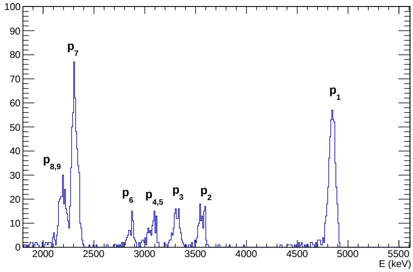


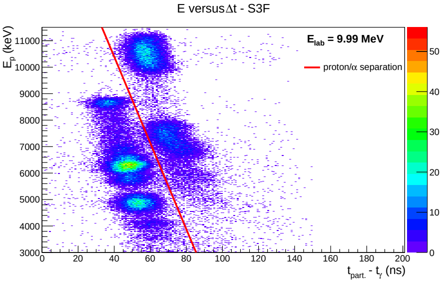
Particle spectrum from S3B - Coincidences with $E_\gamma = 440$ keV

$\rightarrow$ Estimation of the $E_\gamma = 440$ keV efficiency : $\sim 6\%$

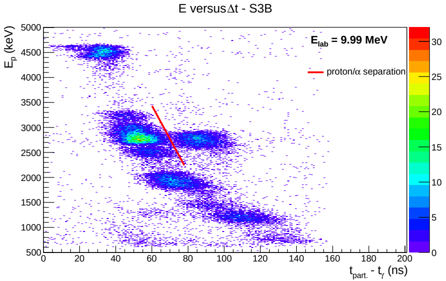
Proton/α selection

Pulse shape consideration

- proton/α can have the same energies
- Rising time of the pulse depends on the particle



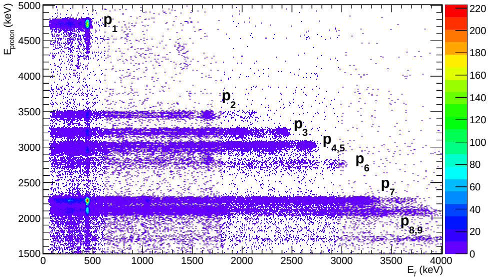
(E_p,Δt) matrix for S3F



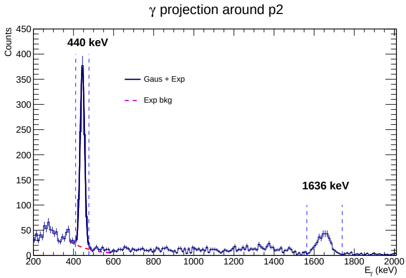
(E_p,Δt) matrix for S3B

Particle/γ matrix

- Projection on γ axis
- Exponential bkg + gaussian peak



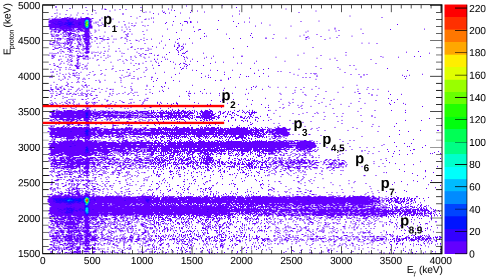
Proton/γ matrix - S3B (E_{lab} = 10.8 MeV)



Projection on γ axis around p_2

Particle/γ matrix

- Projection on γ axis
- Exponential bkg + gaussian peak



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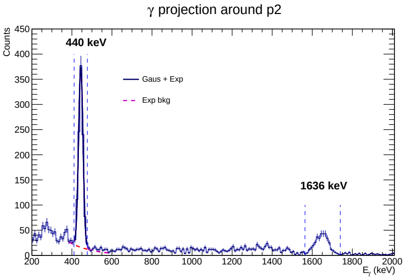
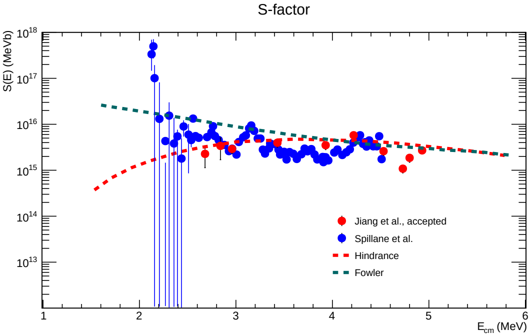


Projection on γ axis around p_2

Just accepted...

C.L. Jiang et al., Argonne data

- Coincidence technique
- Hindrance at low energy ?



Outlook and Perspectives

Hindrance systematics

- Shift carbon ignition towards higher temperatures
- More neutron are then produced
- Enhancement of long-lived γ emitters ^{26}Al and ^{60}Fe
- Agreement with recent observations in deep see sediments (A. Wallner et al.) and at the lunar surface (L. Fimiani et al)

The STELLA near future

- Extend to other nuclear reactions important for astrophysics :

$$\rightarrow \quad {}^{12}\mathrm{C} + {}^{16}\mathrm{O}, \quad {}^{16}\mathrm{O} + {}^{16}\mathrm{O}, \quad \ldots$$

Thanks for your attention