^{12}C fusion reaction at deep sub-barrier energies with the STELLA experiment

Jean Nippert

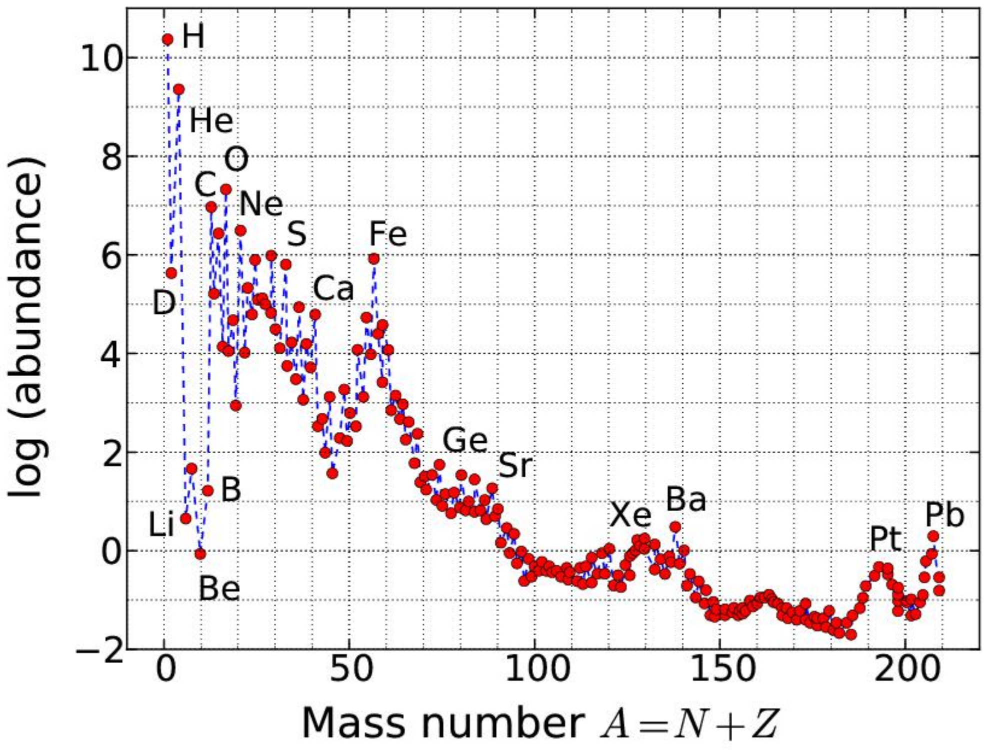
Summary:

I. $^{12}C + {}^{12}C$ Fusion reaction
   1. Astrophysical interest
   2. $^{12}C+{}^{12}C$
   3. Challenges

II. STELlar LAboratory

III. Specificities and results
   1. Angular distribution
   2. Background reduction
   3. Results and perspectives

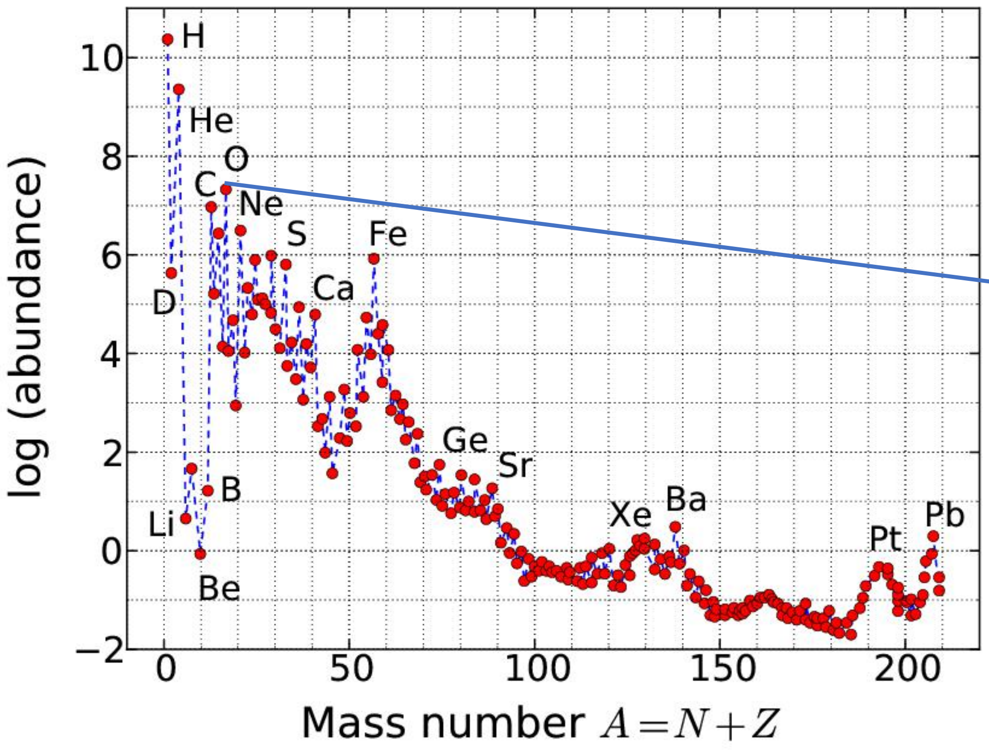
Astrophysical interest :

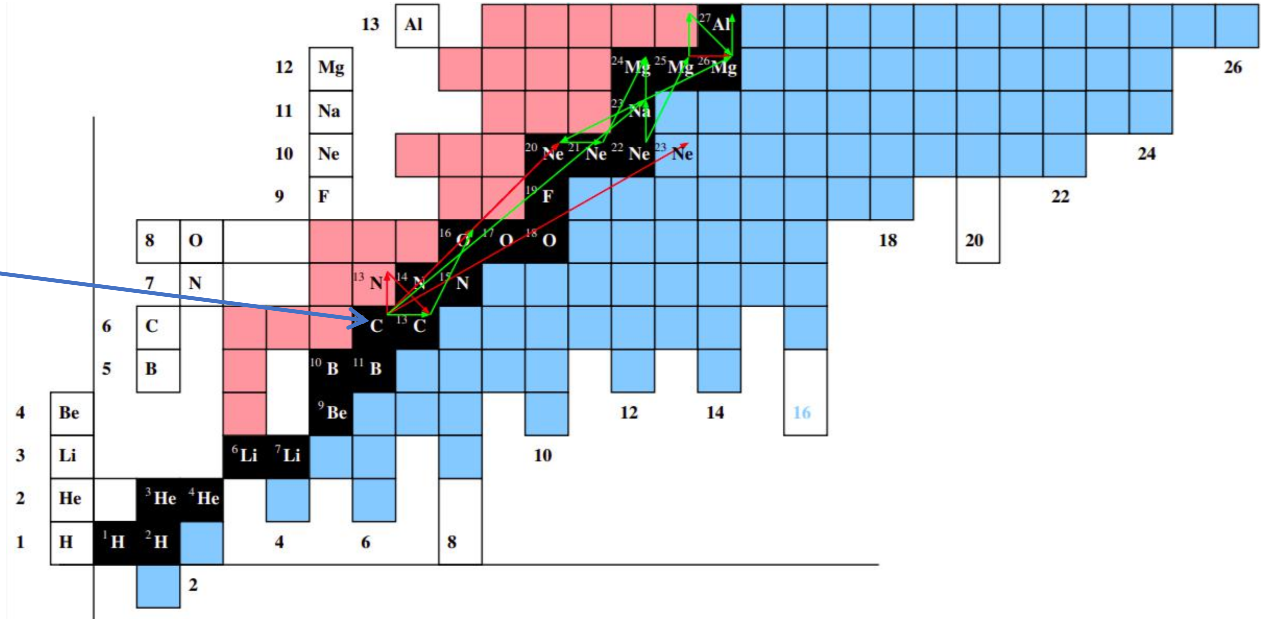


Abundance curve (chemical elements in the solar system)
K. Lodders, H. Palme, and H.P. Gail, Landolt Bornstein Encyclopedia, New Series (2009).

- BigBang -> Hydrogen and Helium
- Light elements are evolving in stars through fusion
- Nucleosynthesis :
  - H → He
  - He → ^{8}Be
    - $T_{1/2} = 8 \times 10^{-17}$ s
    - 3 α reaction → ^{12}C
- ^{12}C + ^{12}C ?

Astrophysical interest :





Chieffi et al., APJ 502, 1998

Abundance curve (chemical elements in the solar system)
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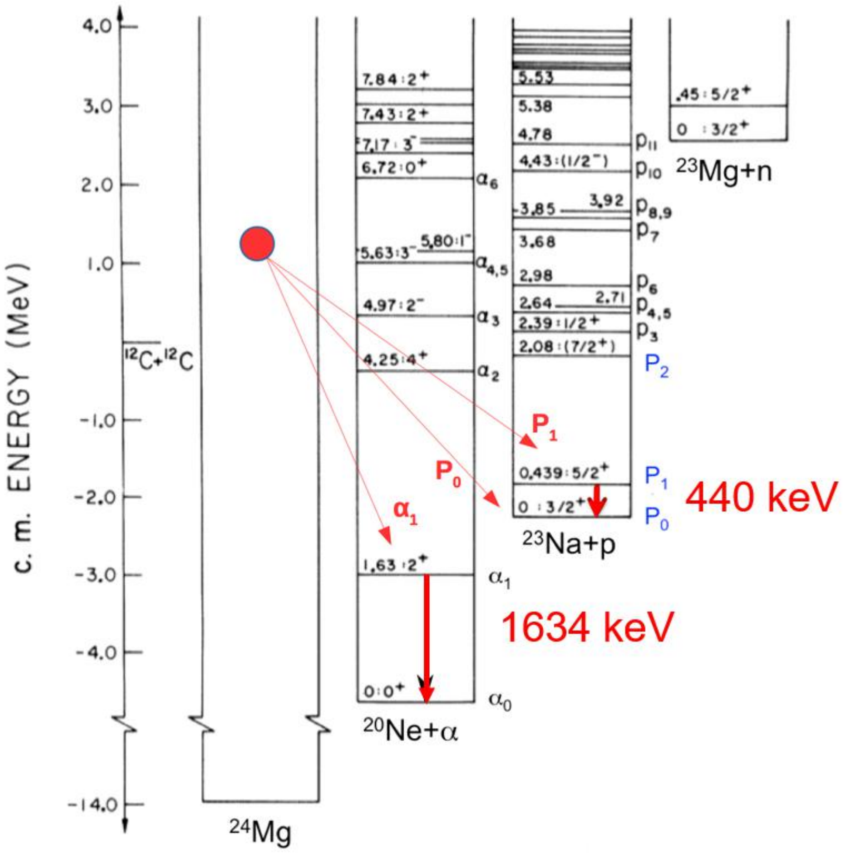
$^{12}C + ^{12}C$ Reaction :

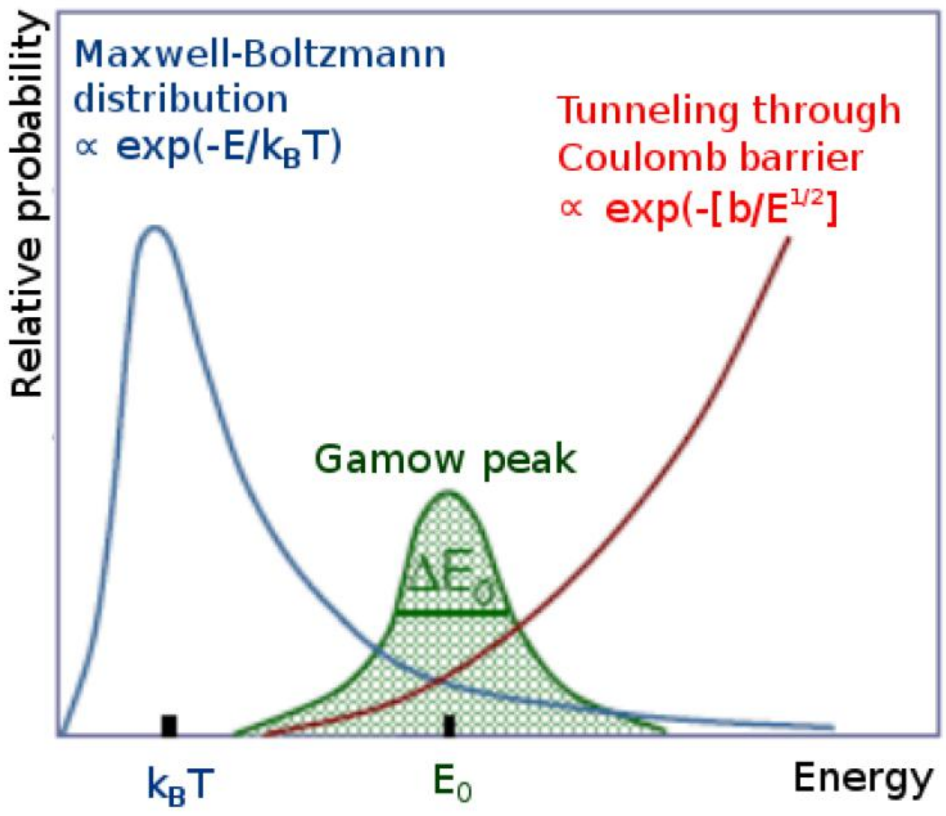


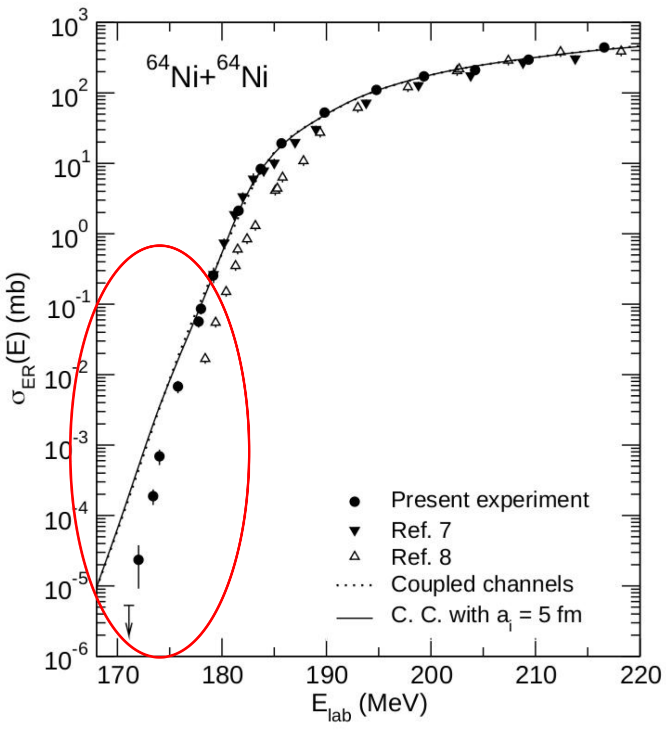
- Carbon burning
  - Reaction : $^{12}C + ^{12}C \rightarrow ^{24}Mg^*$
    - $^{24}Mg^* \rightarrow ^{23}Na^* + p$ Q = 2,24 MeV
    - $\rightarrow ^{20}Ne^* + \alpha$ Q = 4,62 MeV
    - $\rightarrow ^{23}Mg^* + n$ Q = -2,6 MeV

  - Temperature : 0,8 to 1,5 x 10^9 K
  - Stars of 8 to 10 solar masses minimum

Challenges

- ⇨ Thermal energy (Maxwell Boltzmann)
- ⇨ Low energy, challenging nuclear physics experiment
  - ⇨ Quantum tunneling
  - ⇨ ex 1,5 GK = 130 keV
  - ⇨ $^{12}C + ^{12}C \rightarrow E_c = 6{,}6$ MeV
  - ⇨ very low cross section (< nb)
- ⇨ Gamow window



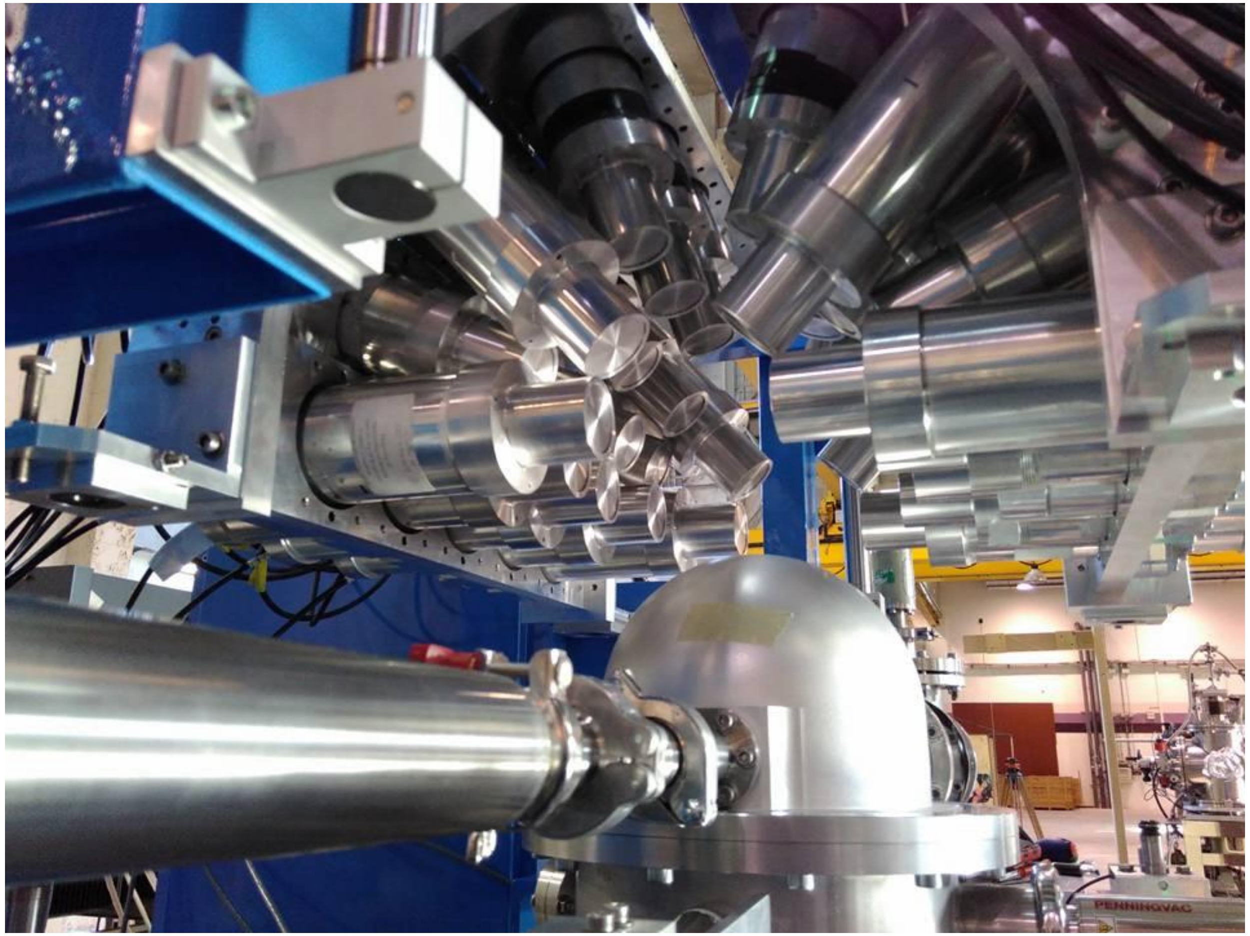


- Hindrance
  - Cross sections lower
  - seen in most of the reactions
  - Debated for ^{12}C + ^{12}C

C.L. Jiang & al. Phys. Rev. Lett. 93, 012701

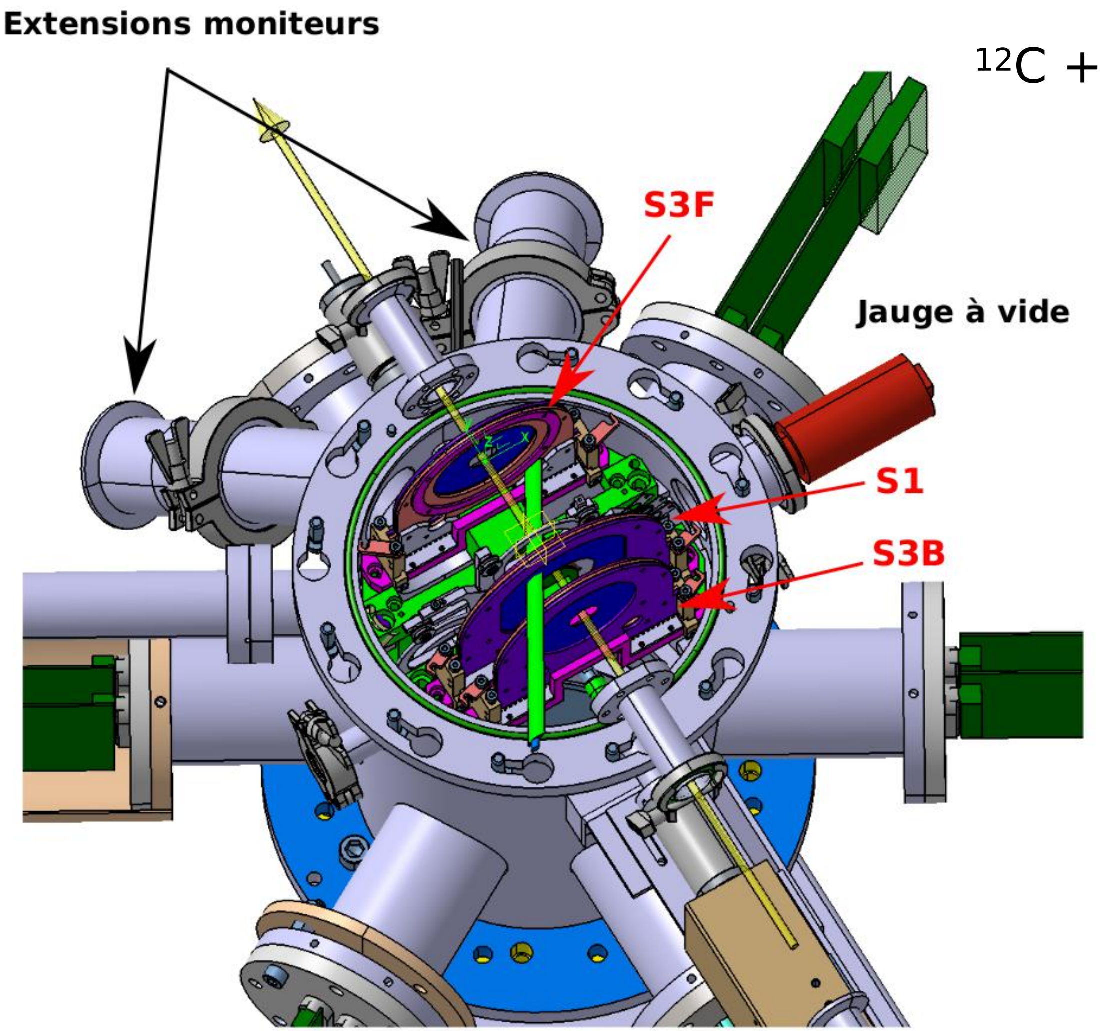
$$^{12}C + ^{12}C \rightarrow ^{23}Na + p + \gamma$$
$$\rightarrow ^{20}Ne + \alpha + \gamma$$

STELlar LAboratory



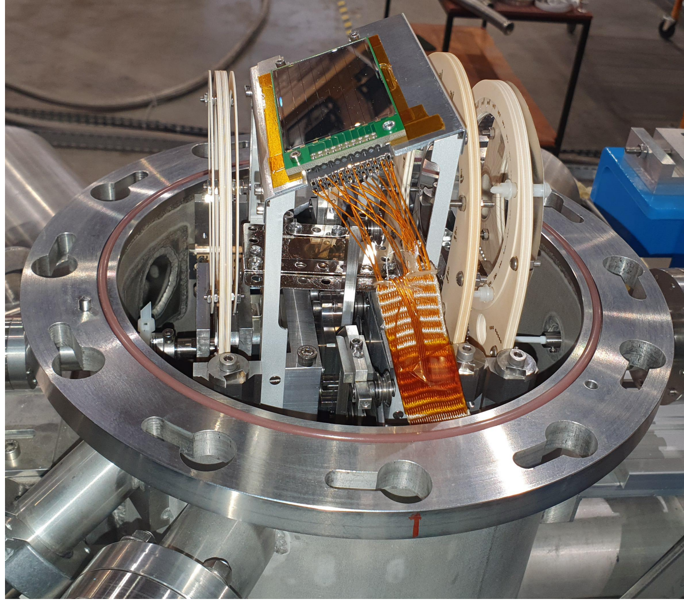
- Challenges :
  - Background reduction
  - Intense beam
    - Andromède : Stable and intense beam
  - Long measurement time (weeks)
- Coincidence technique
  - Background reduction
  - Gamma : New generation scintillators $LaBr_3(Ce)$ UK FATIMA
    - Good energy resolution and very good detection efficiency
    - Timing resolution lower than nanosecond
    - Cylindrical configuration

Reaction chamber



$^{12}C + {}^{12}C \rightarrow {}^{23}Na + p + \gamma$

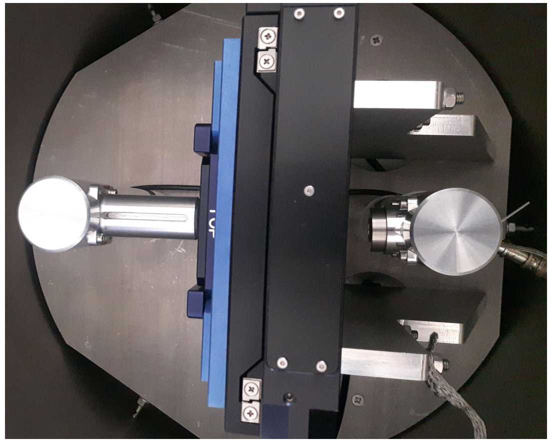
$\rightarrow {}^{20}Ne + \alpha + \gamma$



Reaction chamber

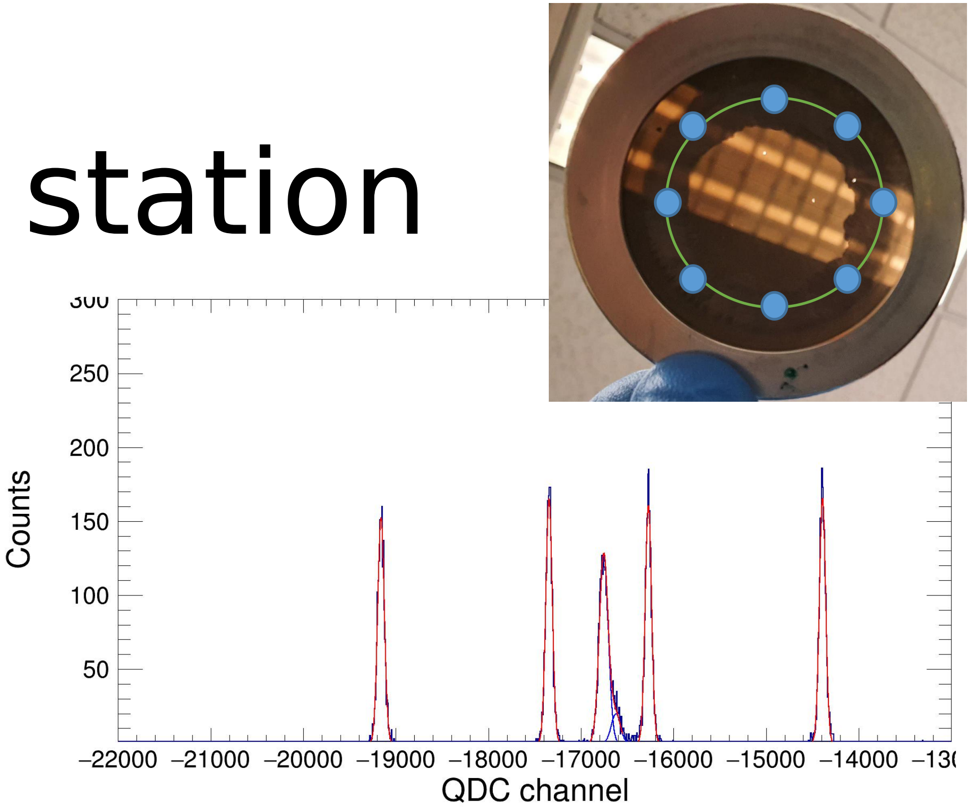
- Aluminum dome 1,5 mm thick
- Self supporting thin rotating target foils (1000 rpm)
  - **Heat dissipation**
- DSSSD S3 and S1
  - granularity allows angular distribution measurement
- Pixel : BB10 and SUPER X3
- Elastic scattering monitoring
- Cryogenic pump
  - Vacuum down to 10^{-8} mbar

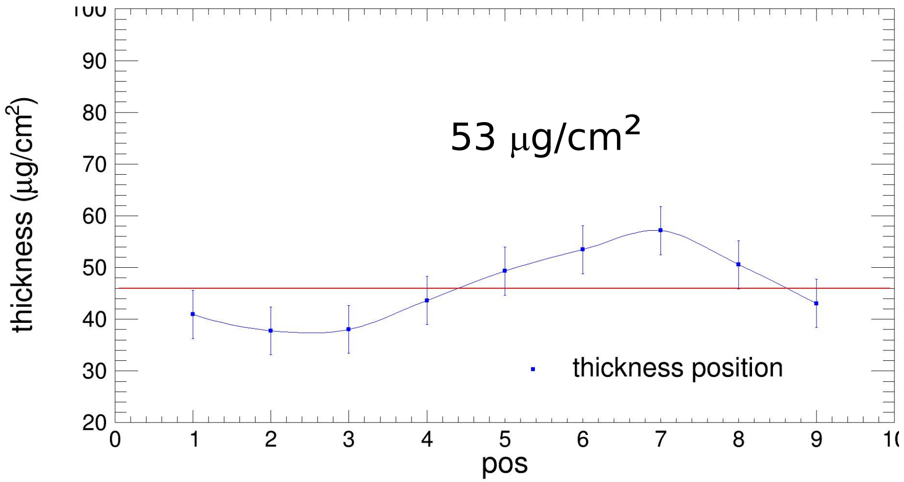
Target measurements station



- Script driven scan (LabView)
- Source : ^{241}Am intense and collimated

- Improvements :
  - noise reduction
  - Temperature stabilisation
  - Pulser method
- Results:
  - Less than 10% uncertainty
  - Sinuzoïdal variation





Angular distribution

- Angular distribution of energy in the S3 backward detector.
- E_{cm} = 5,38 MeV
- red lines : proton kinematic
- black lines : alpha kinematic
- No coincidence

$$^{12}C + ^{12}C \rightarrow ^{23}Na + p + \gamma$$
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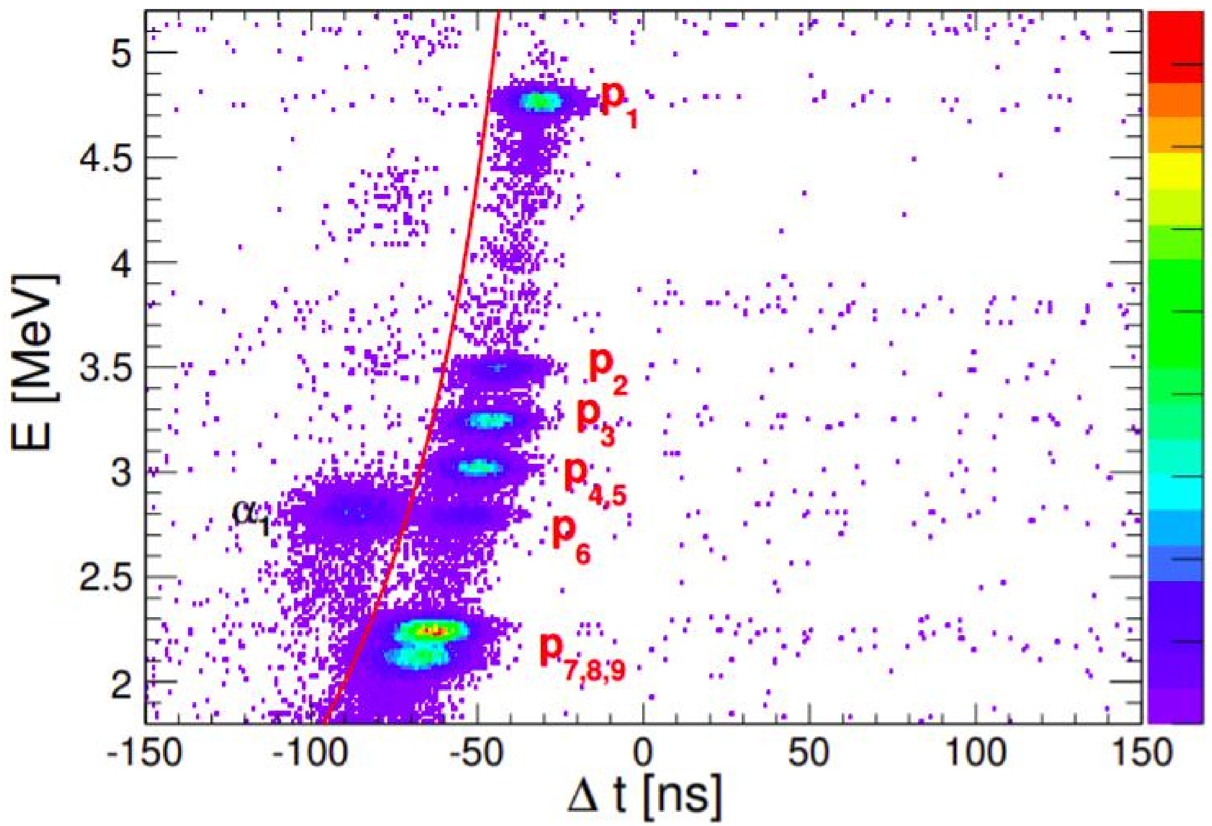
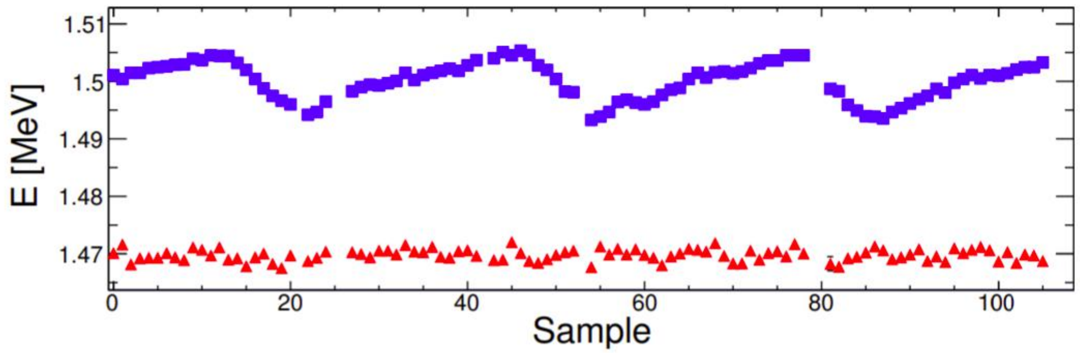
Differential cross section

- Differential cross section at E_{cm} = 5,38 MeV
  - alpha channel ground state
  - 8th order Legendre polynomial
    - need better angular coverage
  - Pixel project M.Heine
    - new detector at 90°
    - improve angular coverage
    - improve solid angle coverage
    - tested the past weeks at Andromede

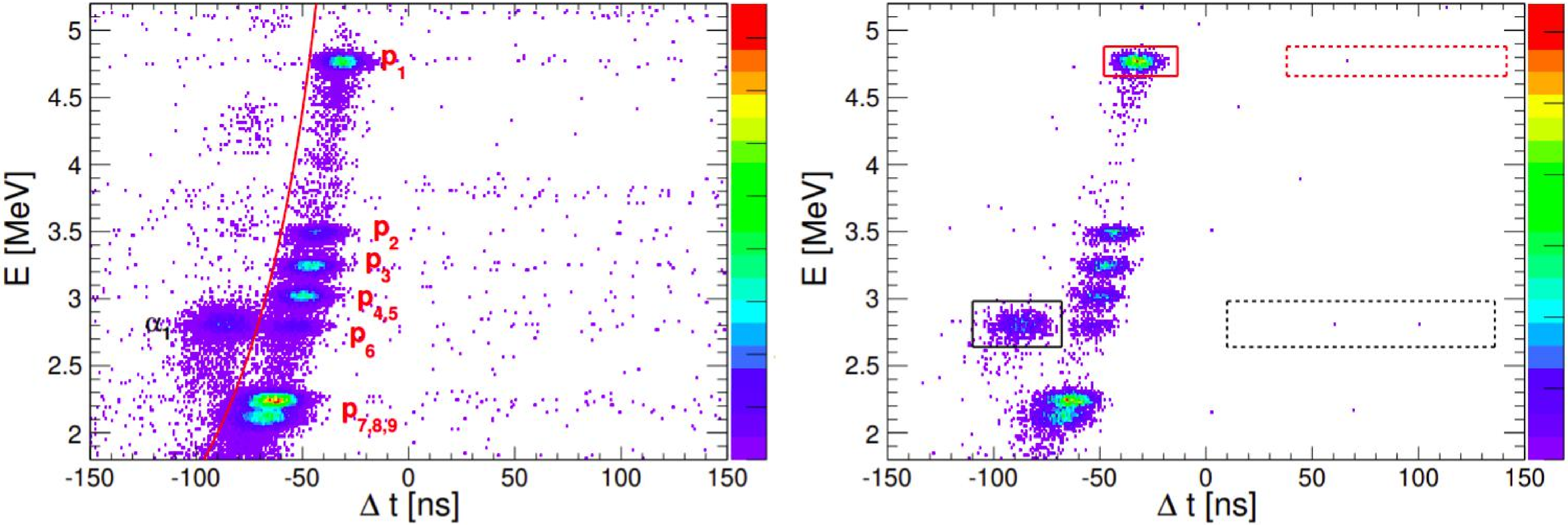
Background reduction: Coincidences with nanosecond timing with UK FATIMA



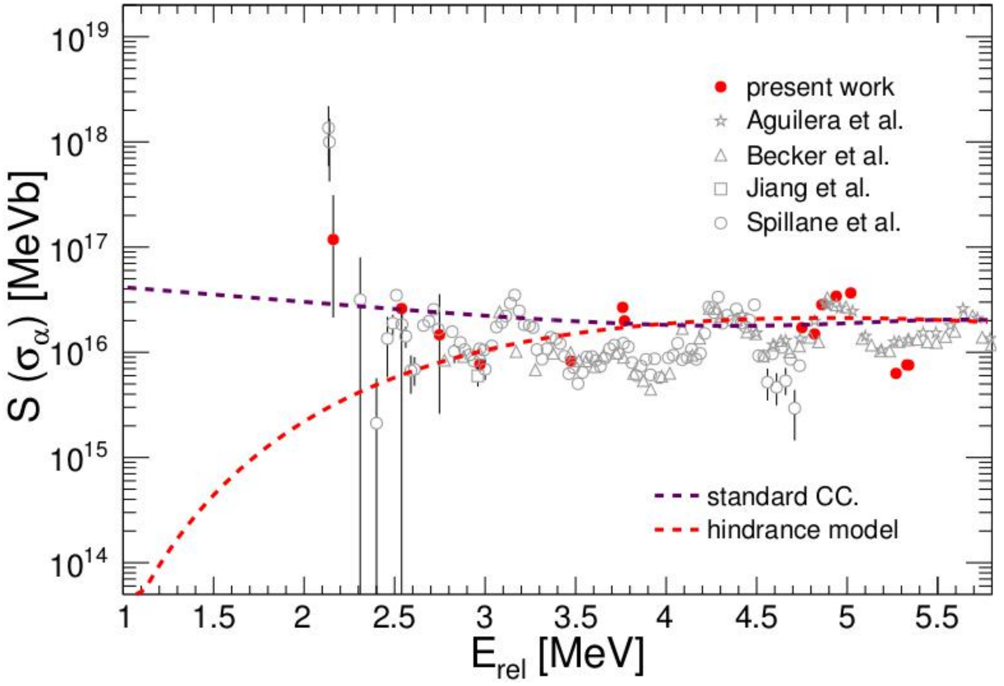
- Synchronization of 1 GHz gamma DAQ and 125 MHz particle DAQ
  - Timing gates σ ~15 ns
  - Proton-α separation
  - Self activity allows self calibration
    - Stable long time measurement

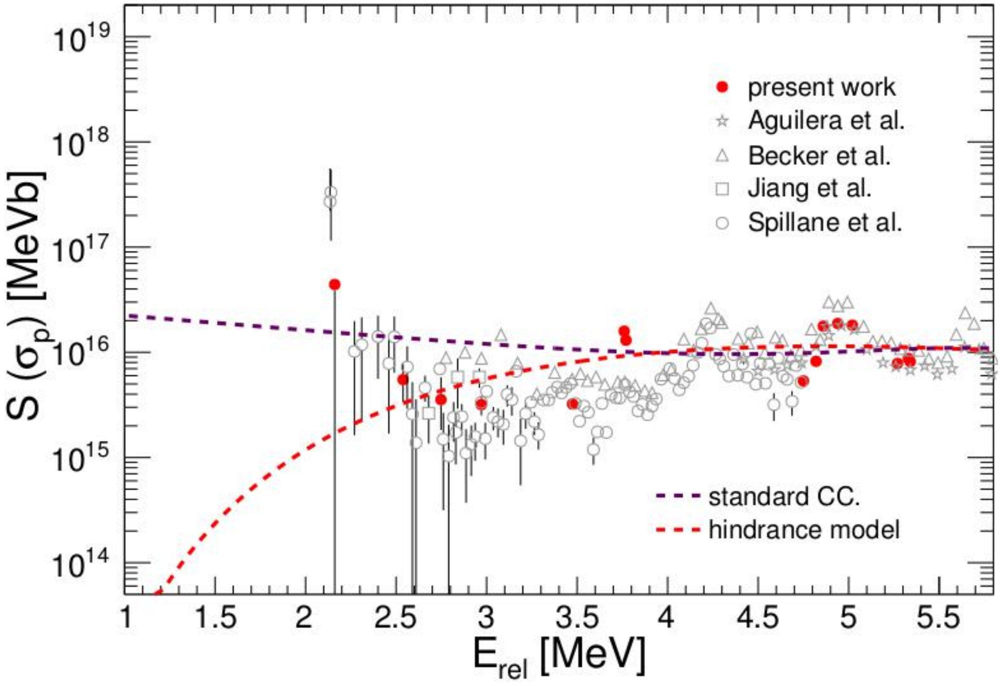


Coincidences



Cross sections





- G. Fruet et al.Phys. Rev. Lett. 124, 192701 (2/21/2020)
  - Sign of hindrance
  - Current analysis in progress
  - New experiment in progress

$$\sigma(E) = \frac{1}{E} \exp(-2\pi\eta) S(E)$$

η : Sommerfeld parameter (energy dependent)

Conclusion

- Nuclear astrophysics direct measurements are challenging
    - STELLA experiment is designed to do it
        - Background reduction

    - Possible evidence of hindrance behaviour
    - Possible identification of resonance
    - Angular distribution measurement :
        - Improvement with Pixel

    - New results to come
    - New experiment running

Thank you for your attention

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