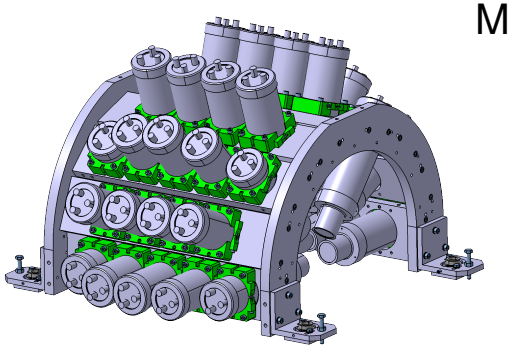
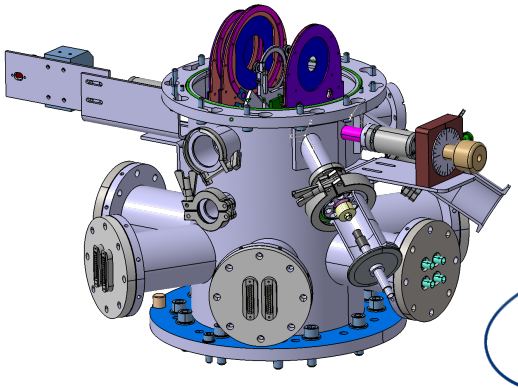
Solving the Carbon Fusion Riddle at Deep Sub-barrier Energy

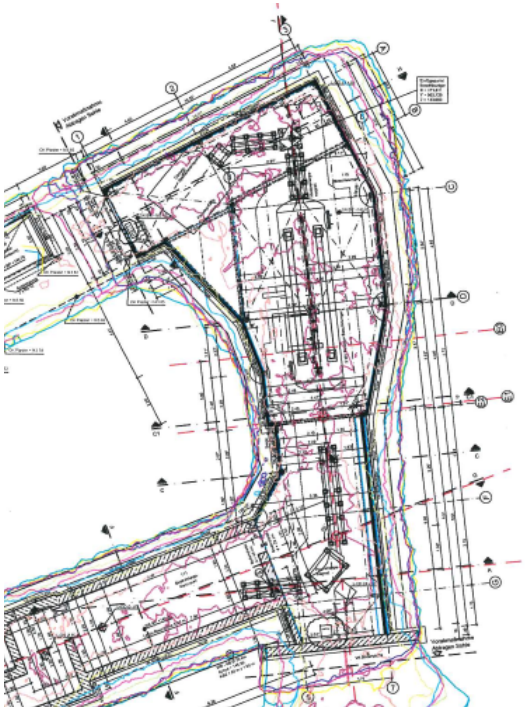


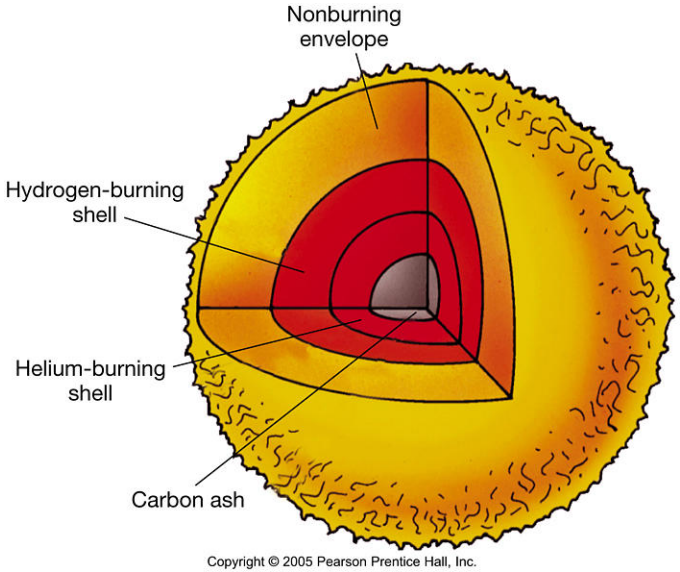


Marcel Heine for the STELLA Collaboration

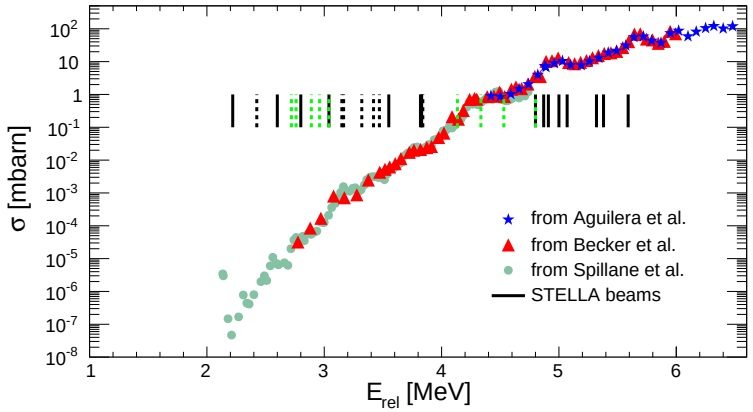
IPHC/CNRS Strasbourg

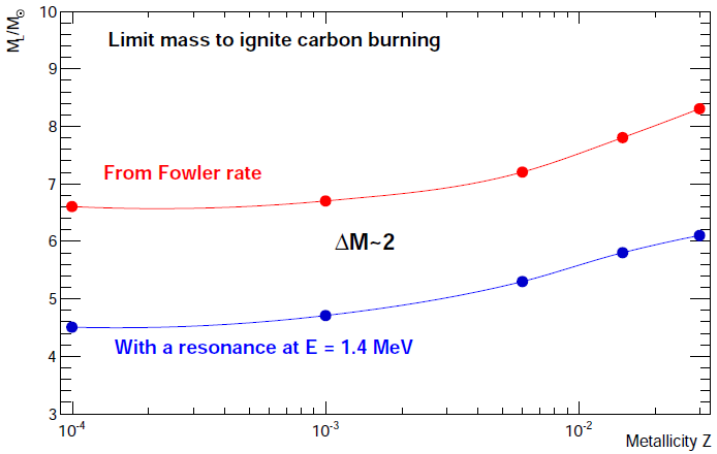
September 17, 2025



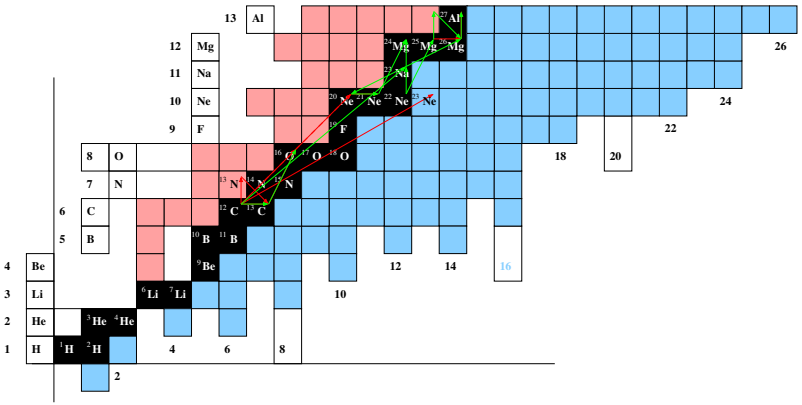


$$^{12}C + ^{12}C \rightarrow ^{24}Mg^{*} \rightarrow ^{24}Mg + \gamma$$
$$\rightarrow ^{23}Mg + n$$
$$\rightarrow ^{23}Na + p$$
$$\rightarrow ^{20}Ne + \alpha$$

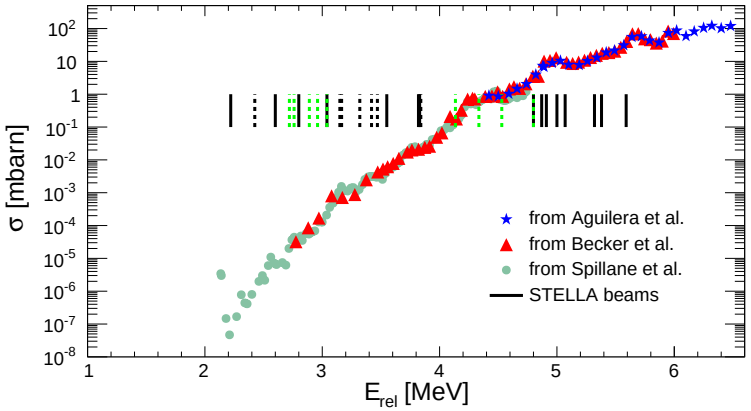




from: O. Straniero *et al.*, JPC Ser. **665** (2016), 012008



from A. Chieffi *et al.*, APJ **502** (1998), 737



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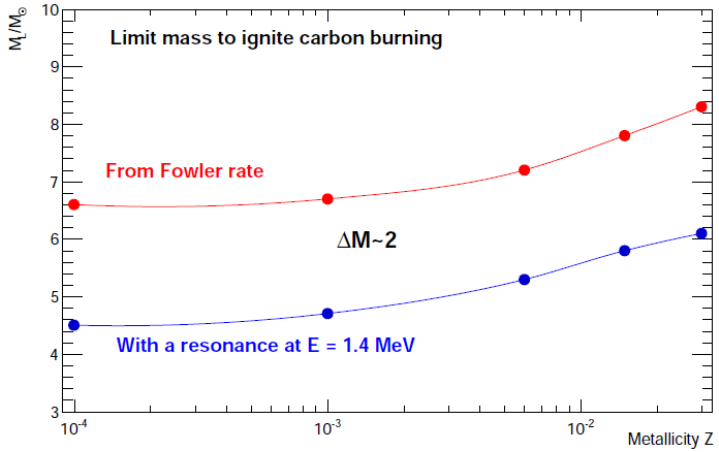

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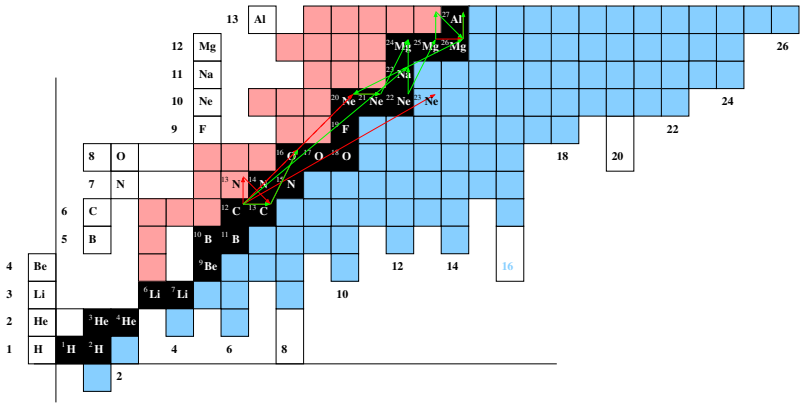

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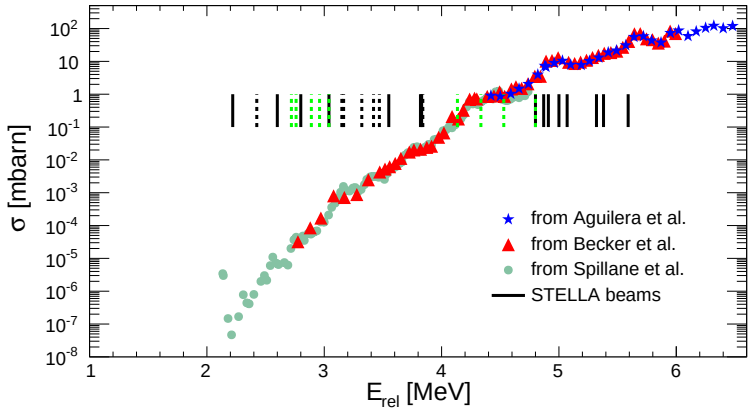

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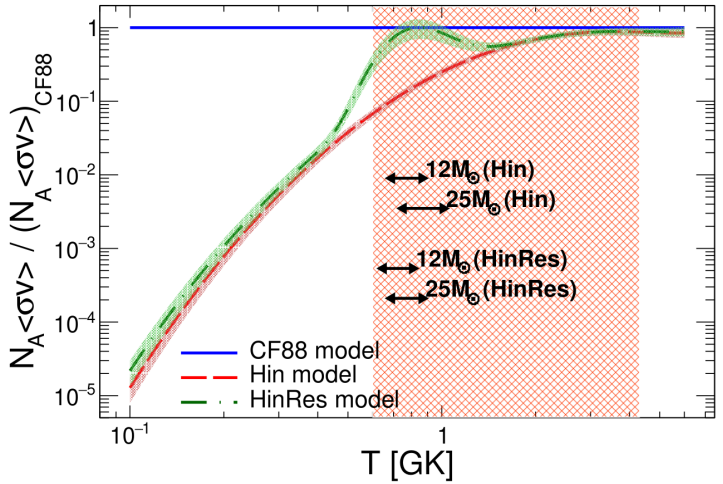

E. Monpribat *et al.*, A&A **660**, (2022) A47

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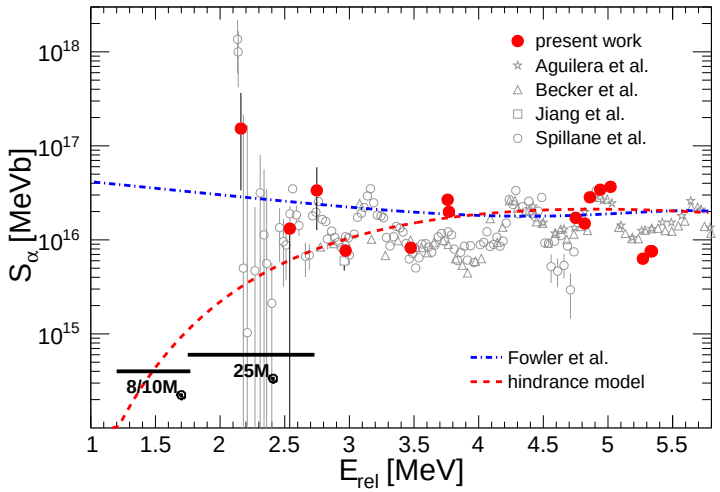

G. Fruet *et al.*, PRL **124**, (2020) 192701

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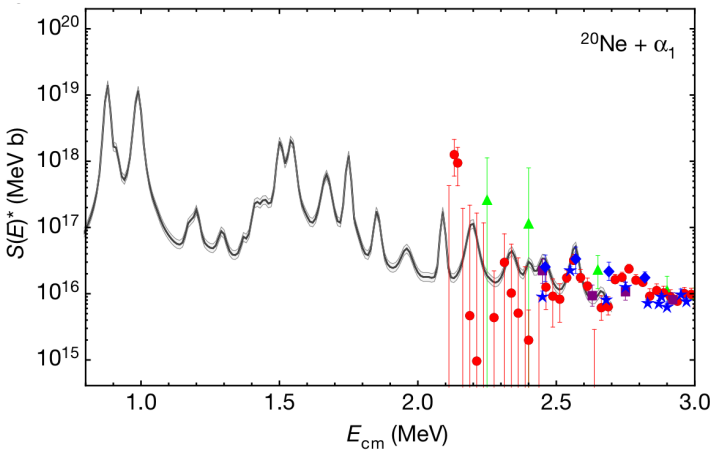

A. Tumino *et al.*, Nature **557**, (2018) 687

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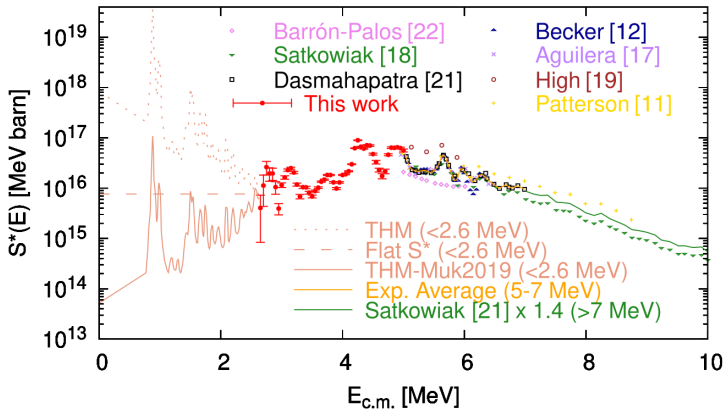

W.P. Tan *et al.*, PRC **110**, (2024) 035808

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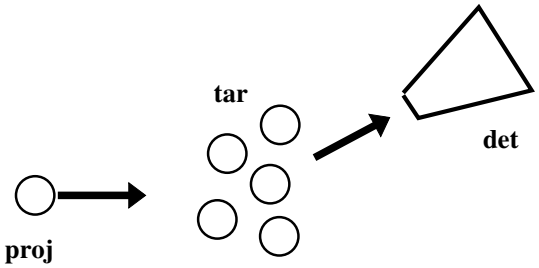
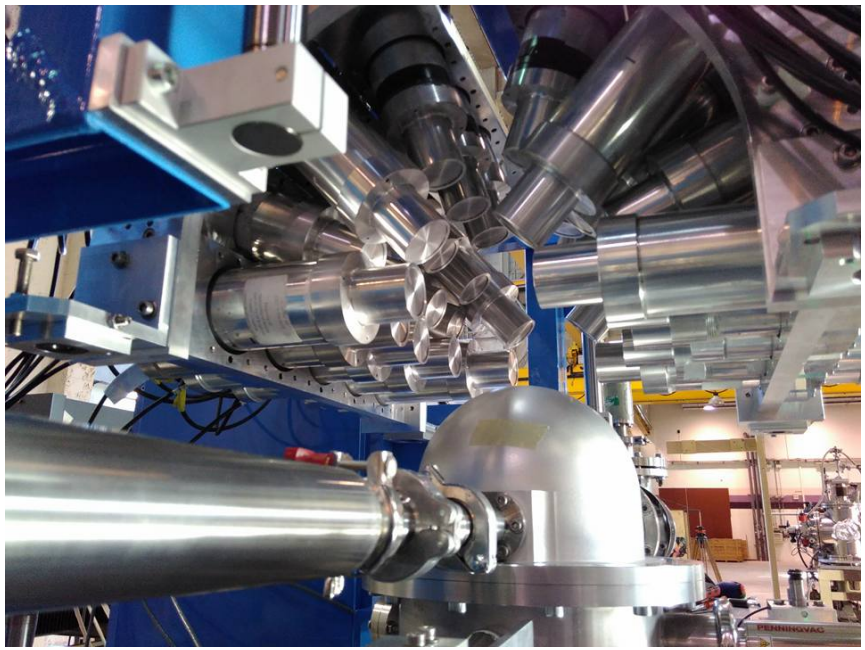
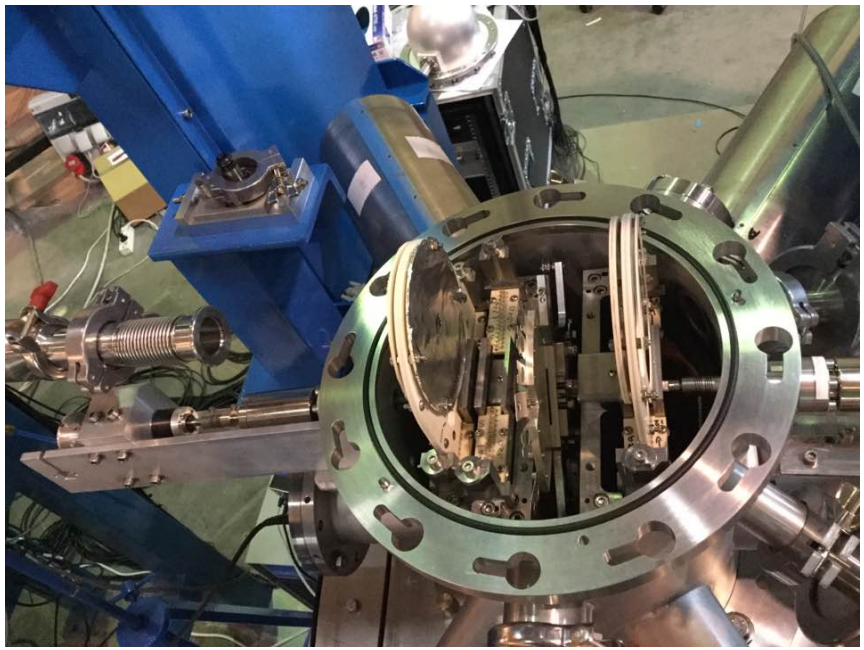
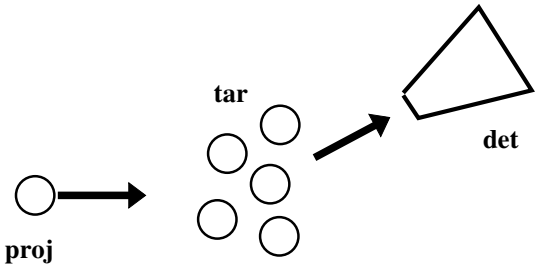


1. beam intensities of a few pμA
2. data taking for weeks
3. γ-particle coincidences, granularity
4. low counting statistics analysis







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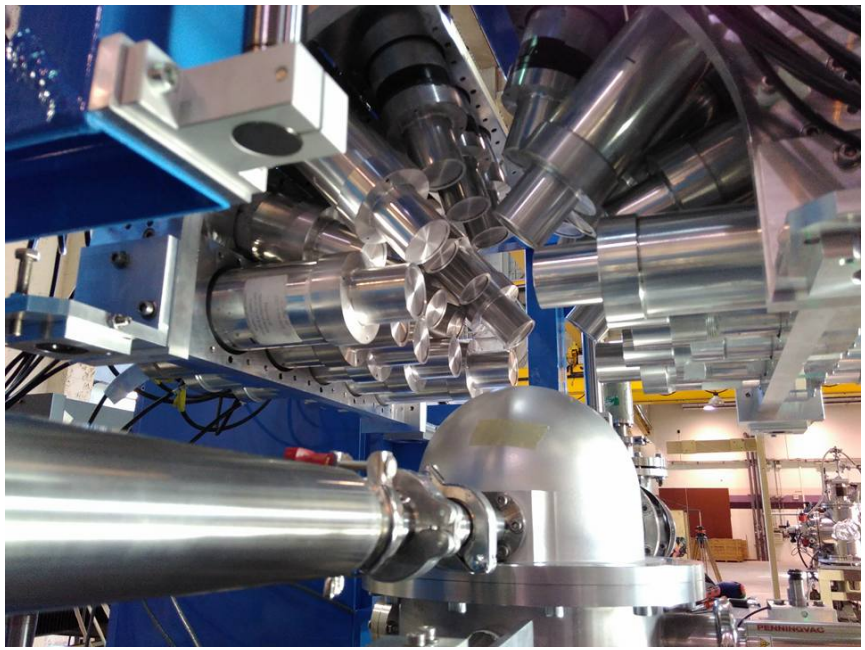
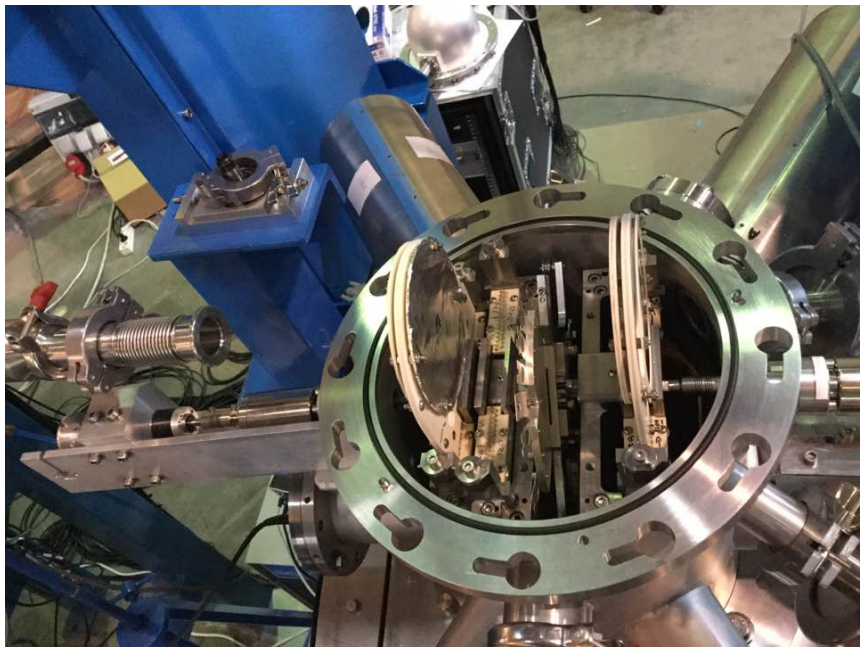
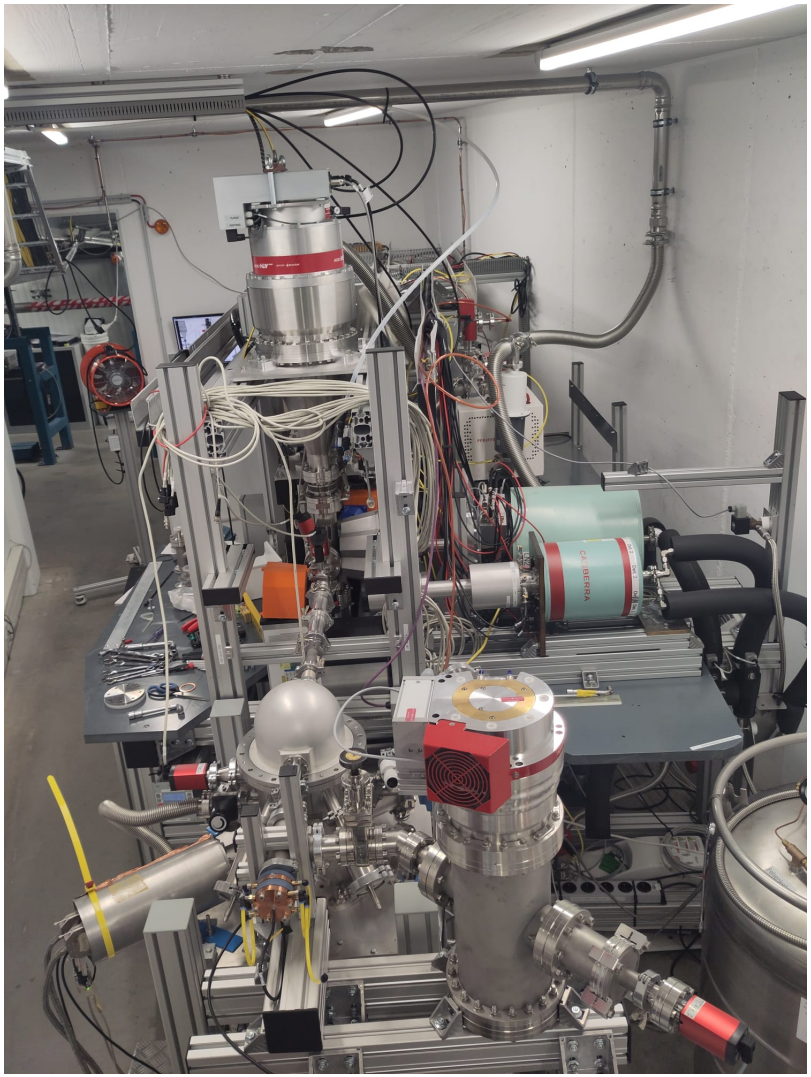
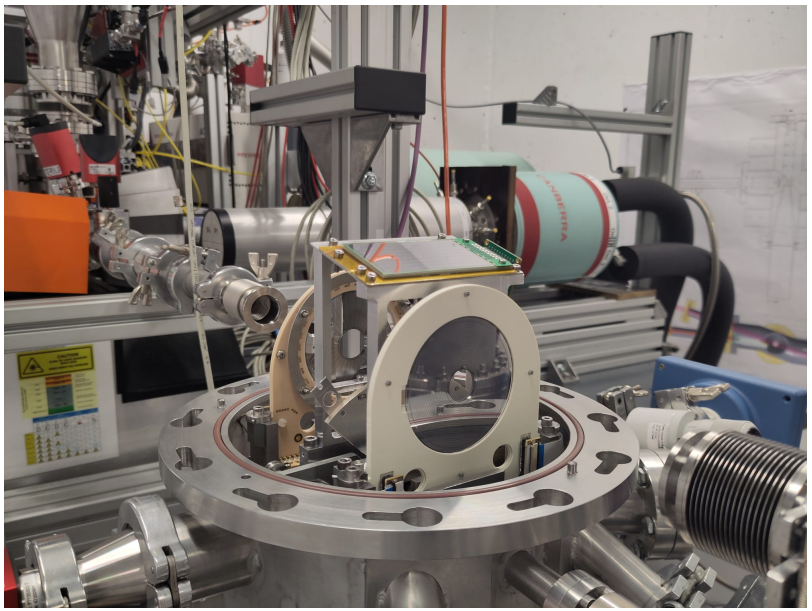


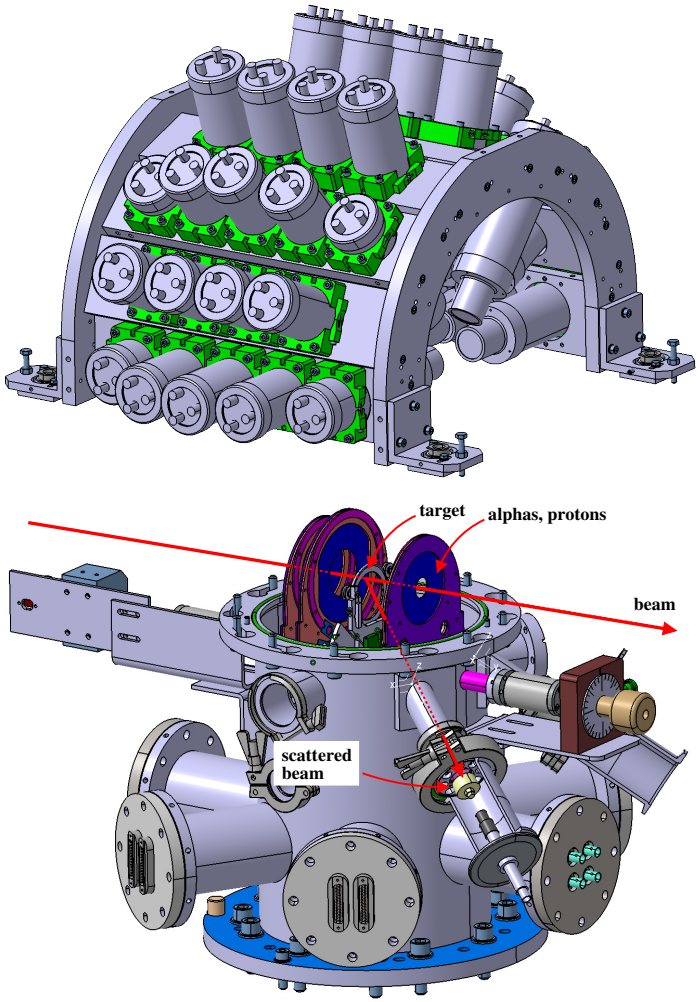




setup at the Felsenkeller laboratory provided:

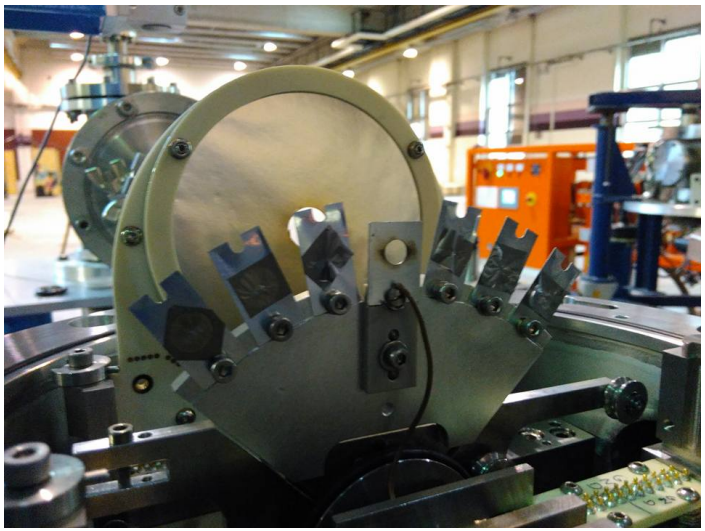
- Faraday cup
- pumps/venting
- DAQ



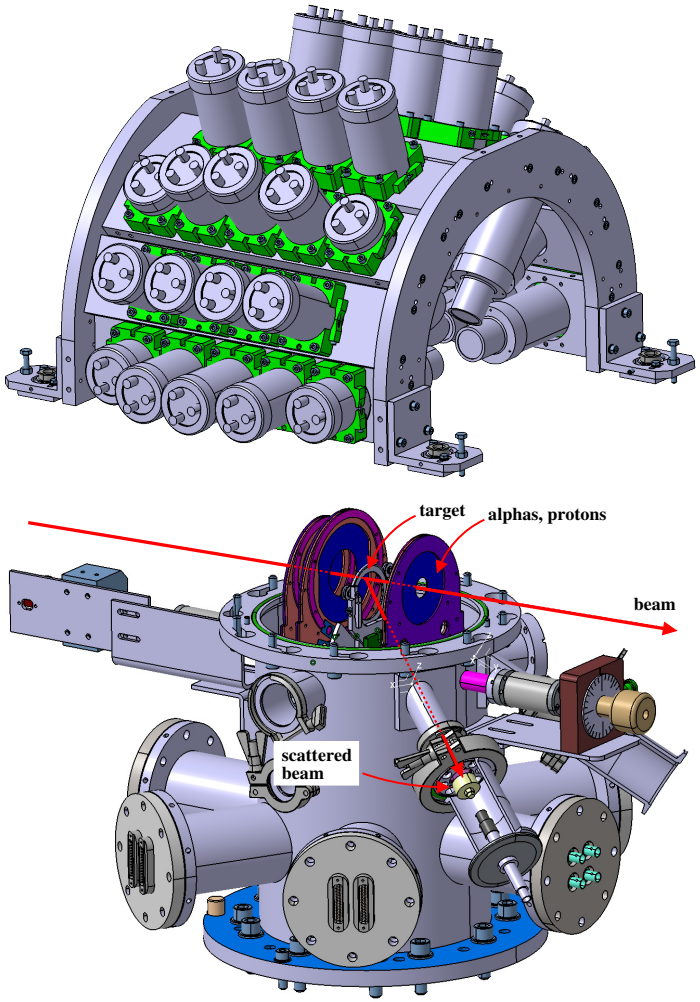


monitoring of target state:

- elastic scattering
- beam integral
- alpha source runs



M. Heine *et al.*, NIM A **903**, (2018) 1–7
J. Nippert *et al.*, APPB **17**, (2024) 3-A33



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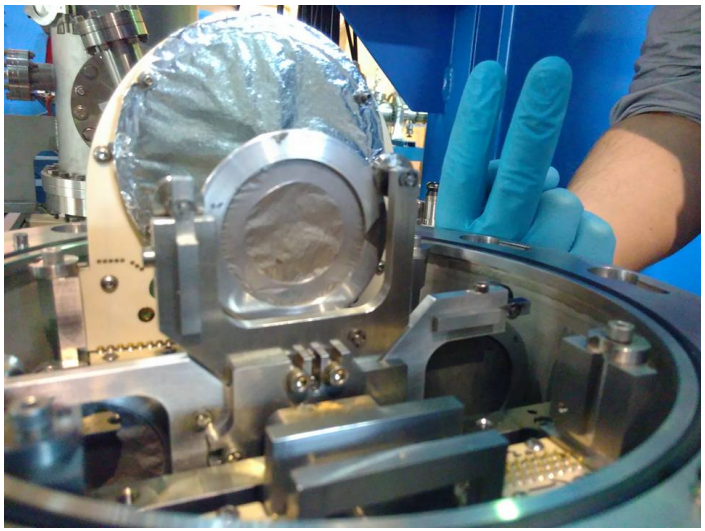

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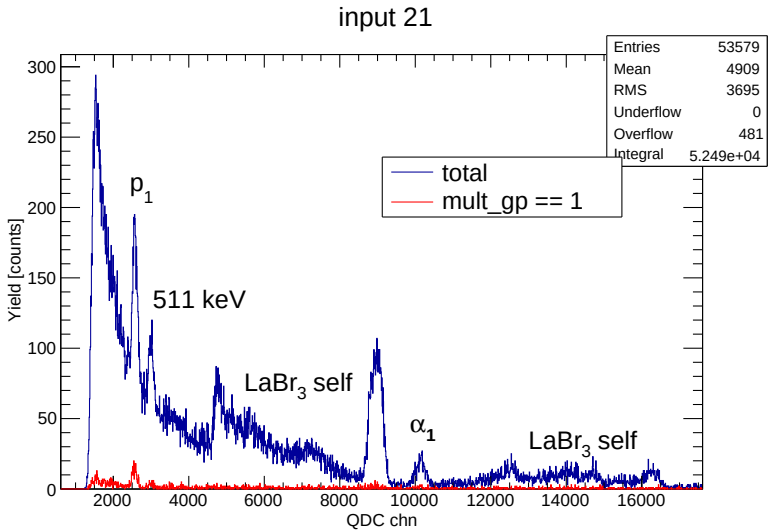
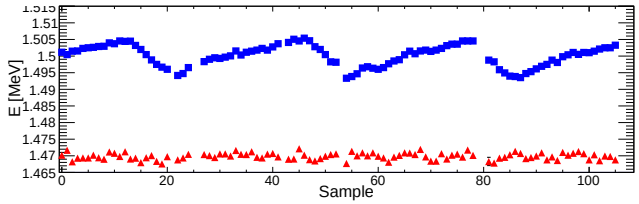


- 3 days of data; 45 min blocks
- drift of 1.47 MeV line: 1.5 keV
- since calibration: 30 keV



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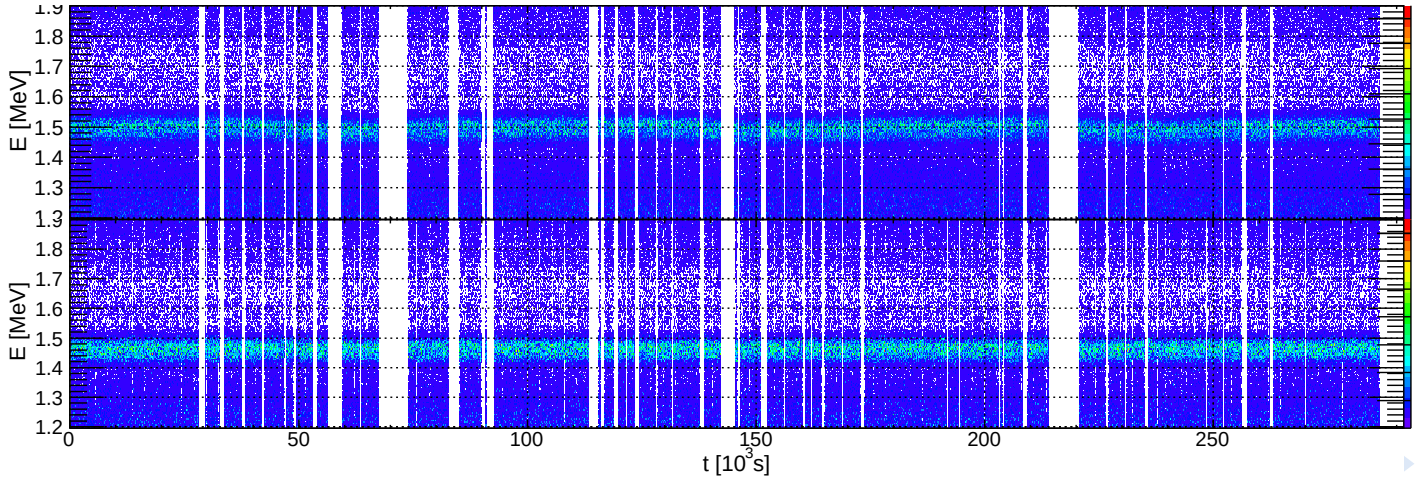
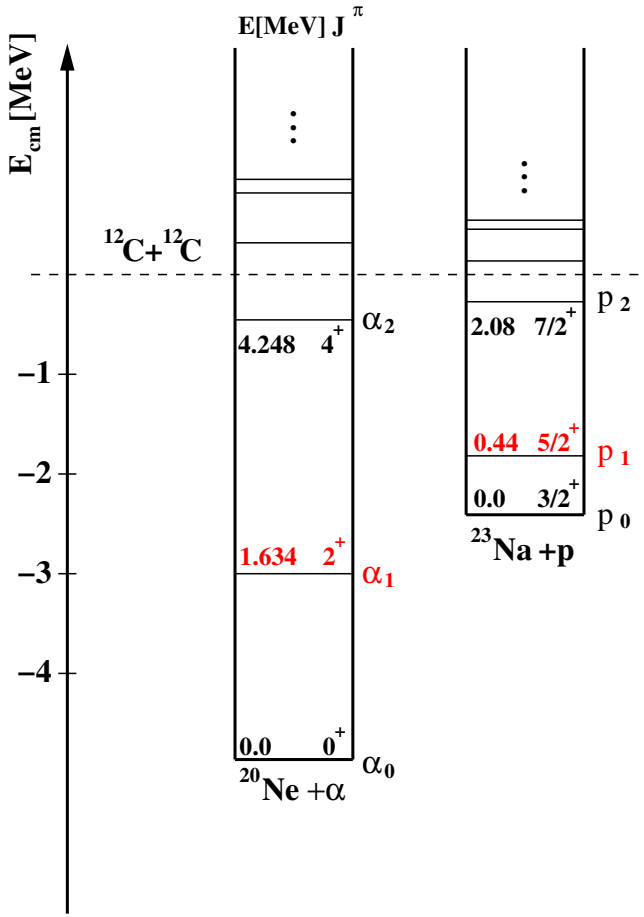
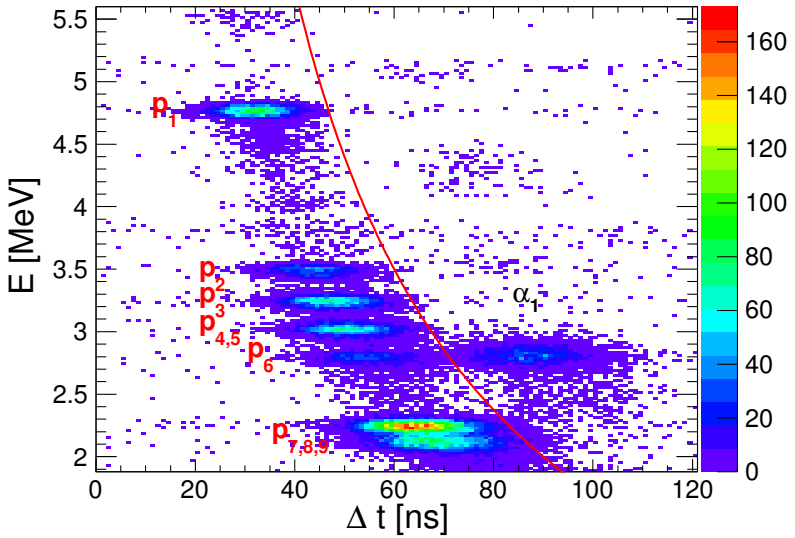


- synchronization of 1 GHz gamma DAQ and 125 MHz particle DAQ
- energy-deposition in silicon substrate: triggering on pulse shape



- timing gates σ ~15 ns
- proton-α separation



M. Heine *et al.*, NIM A **903** (2018), 1

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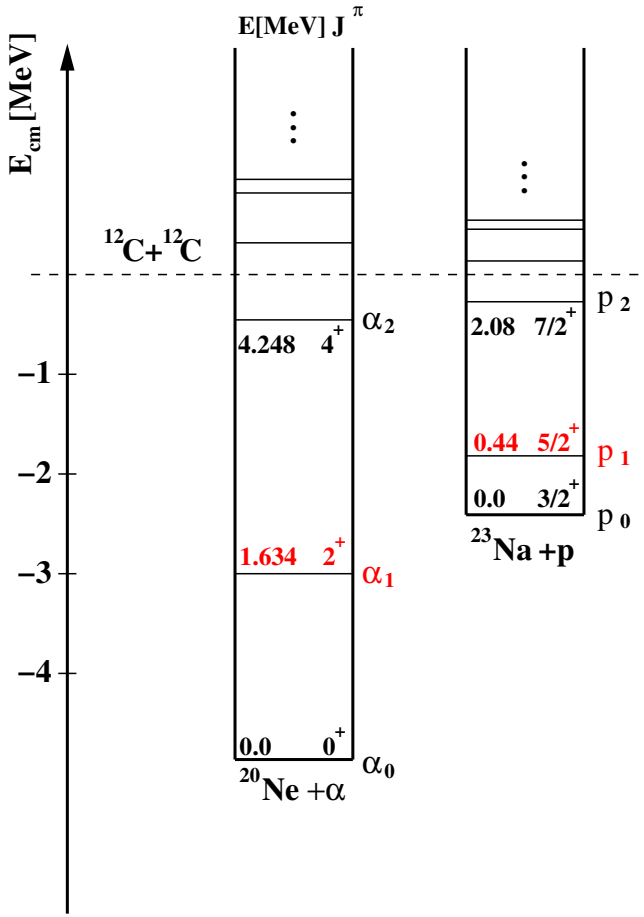
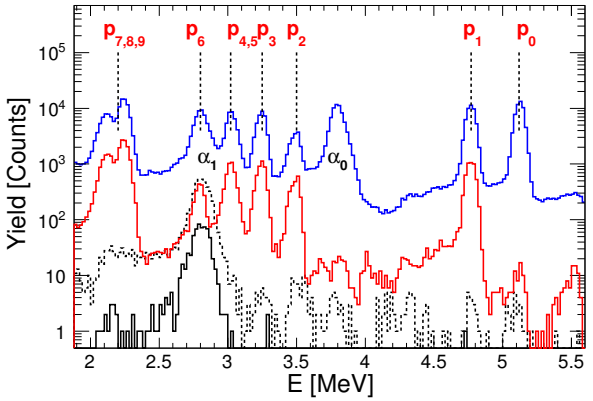
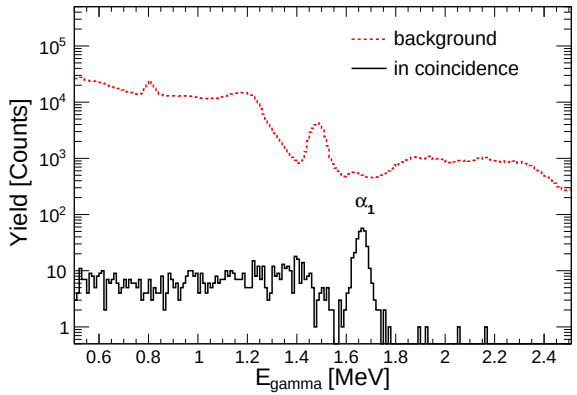
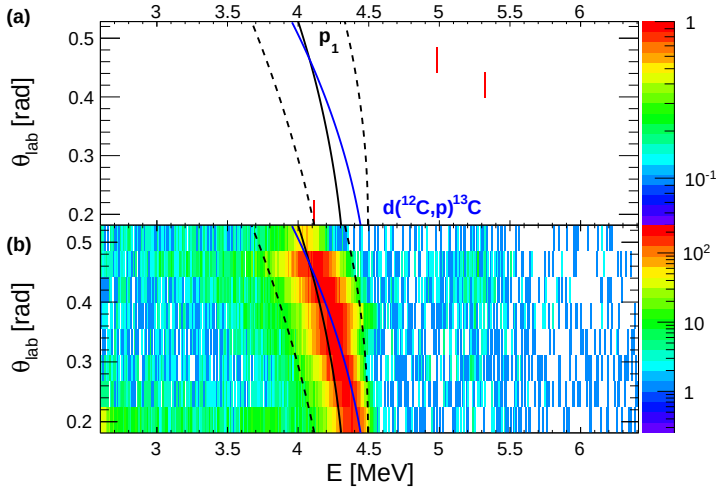


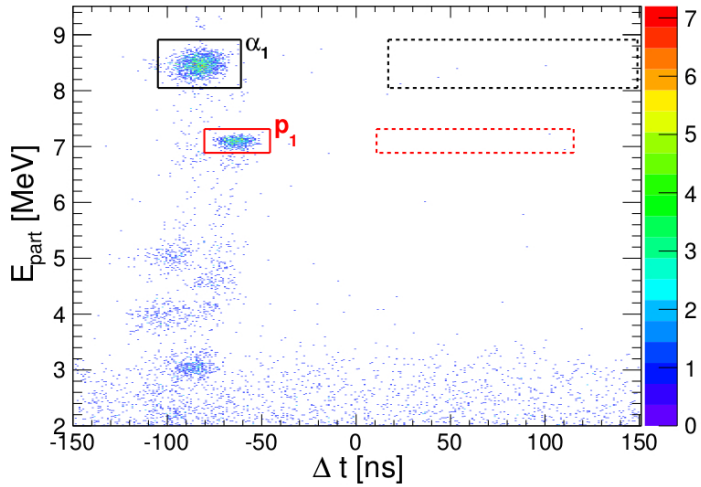




G. Fruet *et al.*, PRL **124**, (2020) 192701

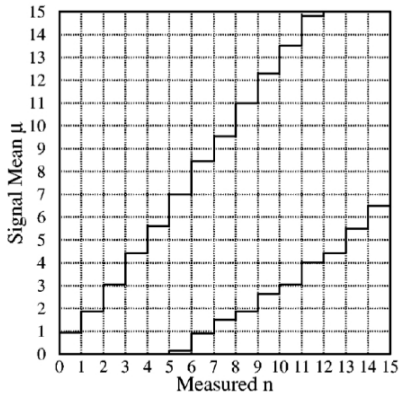


G. Fruet *et al.*, PRL **124** (2020), 192701



M. Heine *et al.*, EPJ Web Conf **260** (2022), 01004

- avoid negative physics counts:



G.F. Feldman & R.D. Cousins, PRD **57** (1998), 3873

$$n = 1\ (\text{observed}), b = 1\ (\text{background}), \mu = n - b$$

$$\frac{\Delta\mu}{\mu} = \sqrt{\left(\frac{\Delta n}{n}\right)^2 + \left(\frac{\Delta b}{b}\right)^2}\ \text{N.A.N.}$$

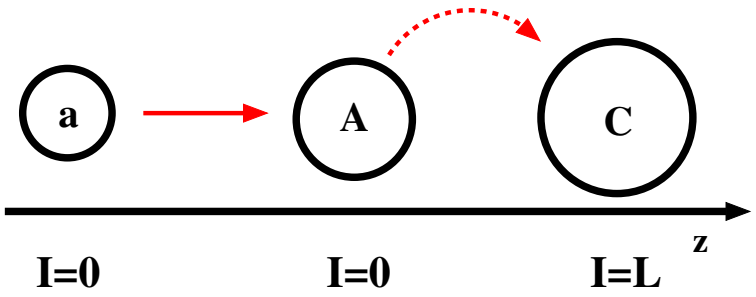
$$n = 1, b = 1 \rightarrow \mu \in [0.00, 1.75]$$

$$n = 2, b = 2 \rightarrow \mu \in [0.00, 2.25]$$

N. Bohr hypothesis of independence: compound formation and decay are independent

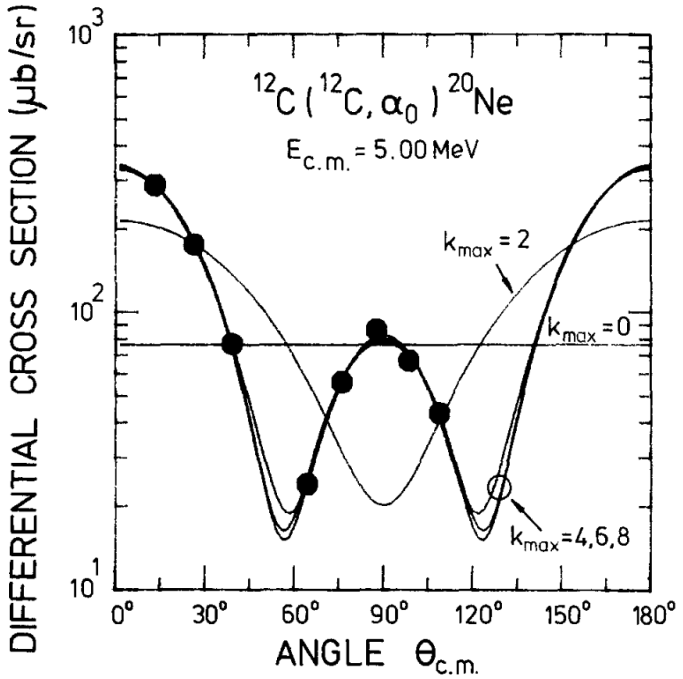
but angular momentum conservation

fusion of spinless particles:



- L perpendicular to z
- equal probability ± z

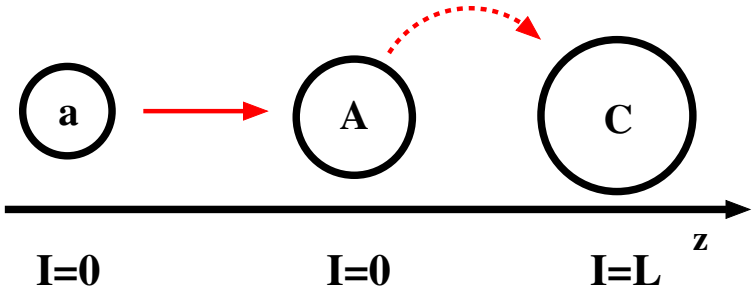
$$\left(\frac{d\sigma}{d\Omega}\right) = \sum_{k=0}^{k_{max}} a_k P_k(\cos(\theta)),\ k = 0, 2, 4, ..$$



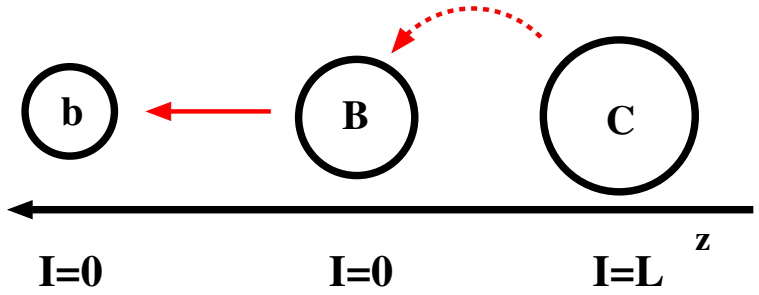
N. Bohr hypothesis of independence: compound formation and decay are independent

but angular momentum conservation

fusion of spinless particles:



- L perpendicular to z
- equal probability ± z



→ compound state spin from fusion measurements

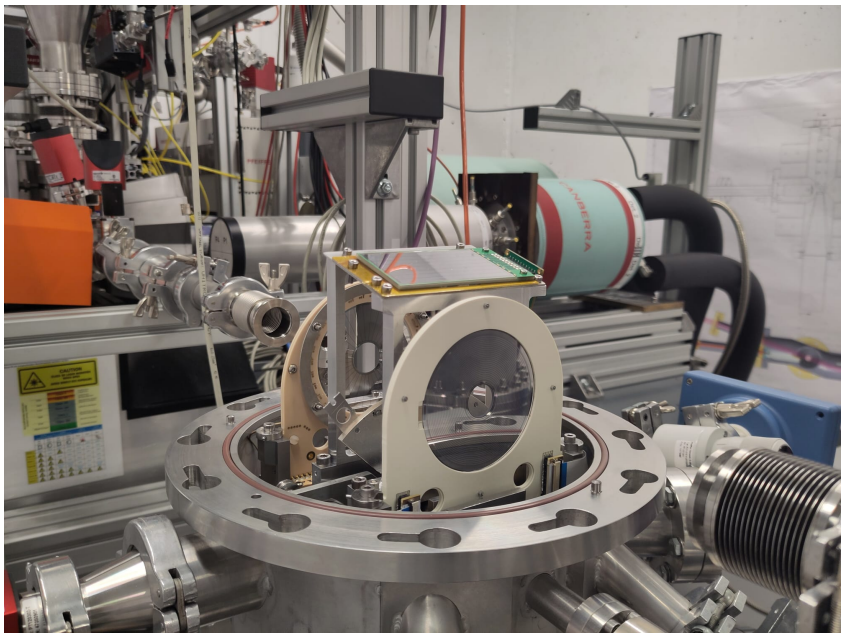
- normalisation of cross sections: $P_0(\cos(\theta))$

$$\left(\frac{d\sigma}{d\Omega}\right) = \sum_{k=0}^{k_{max}} a_k P_k(\cos(\theta)),\ k = 0, 2, 4, ..$$

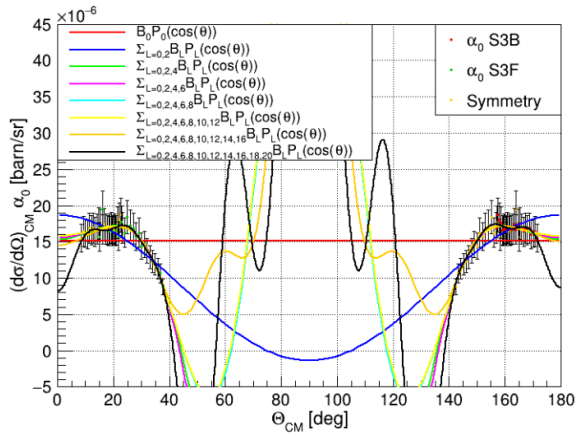
E/p conversation: angular distribution α, p:

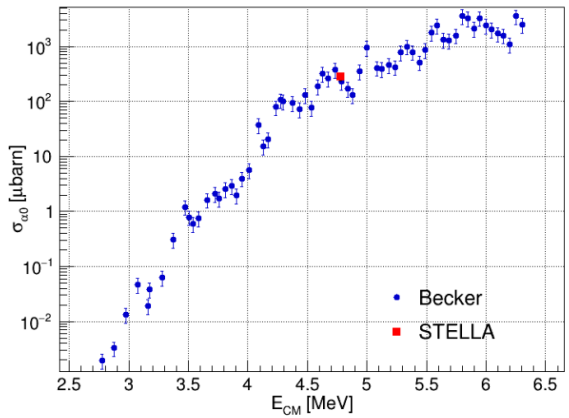
- accurate normalisation
- spin parity of compound nucleus ^{24}Mg

- effective beam energy



- χ^2 and uncertainty analysis
- spin-parity conservation





courtesy: G. Harmant

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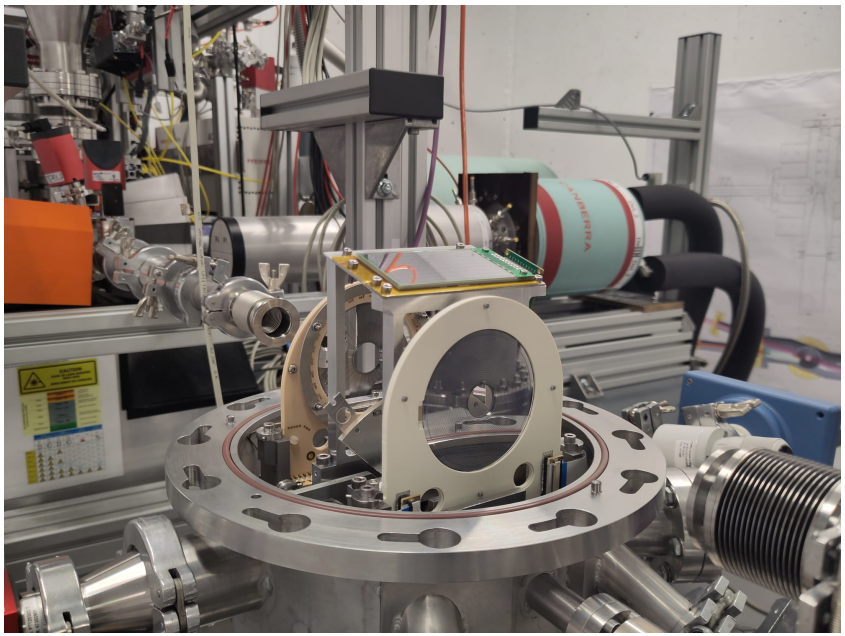

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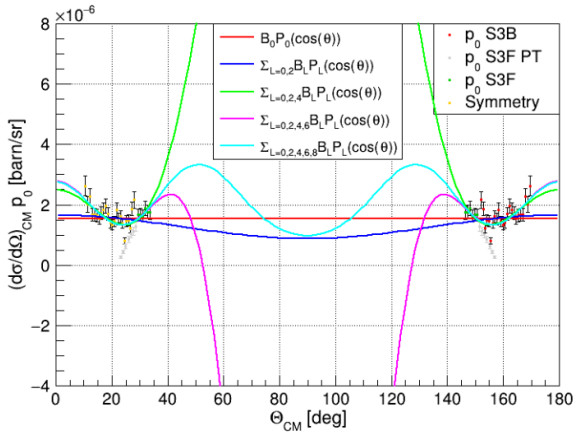

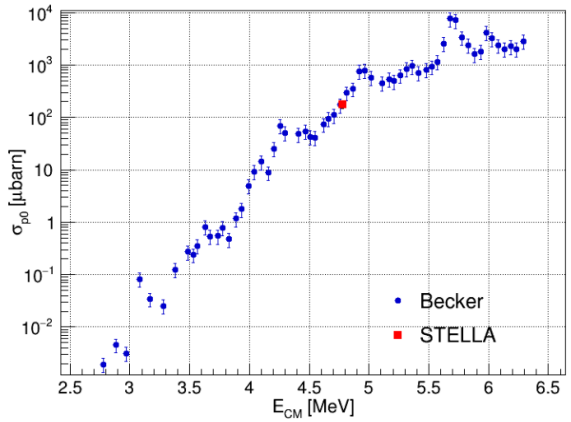

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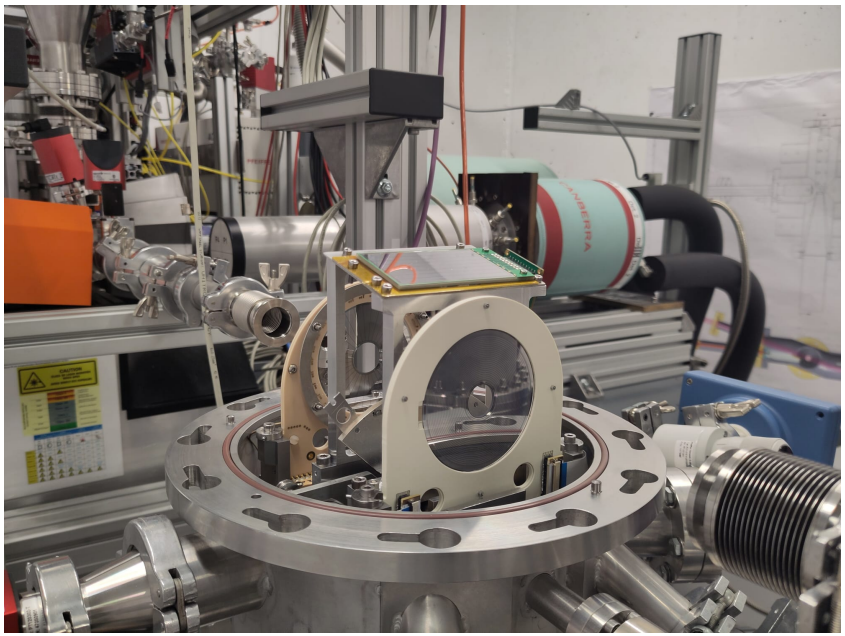

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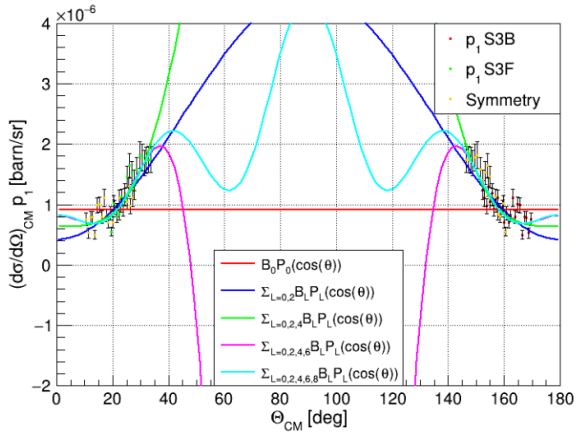

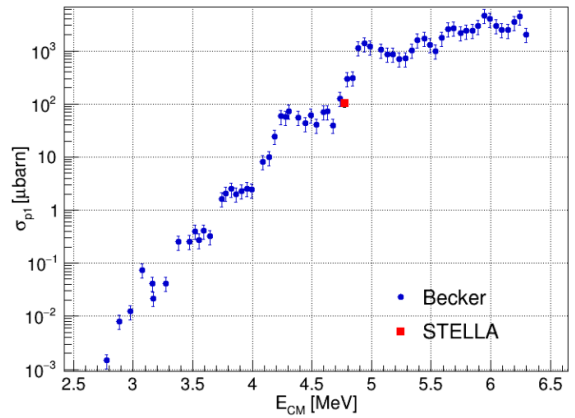

courtesy: G. Harmant

Thank You Very Much for Your Attention

- carbon burning in massive stars
  - cross sections below nano barns
  - oscillating excitation function
- direct measurements of carbon fusion with STELLA
  - high duty experimentation
  - long term stability
  - low count statistics
- resonance determination with STELLA
  - scan of known resonances: $0^+, 2^+, 4^+$
  - alpha, proton detection at steep angles