Astrophysical key fusion reactions of carbon and oxygen with the high-precision STELlar Laboratory (STELLA)

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for the STELLA collaboration
IPHC Strasbourg

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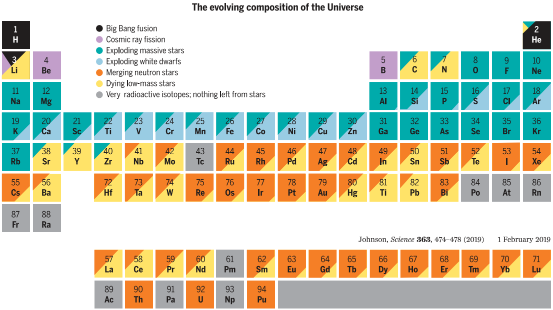
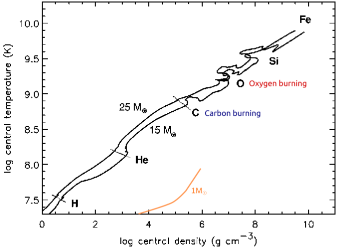
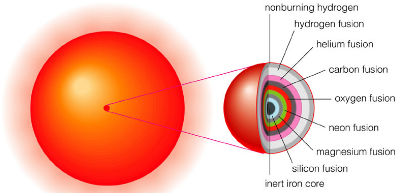
Nucleosynthesis and massive stars

- Synthesis of elements: lives and deaths of stars
- Massive stars: succession of burning phases, shell structure
- Stellar evolution driven by nuclear reactions







Carbon burning in massive stars

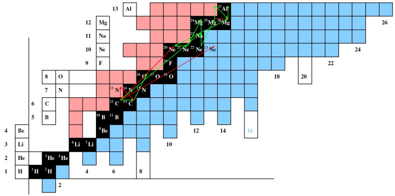
- ^{12}C+^{12}C: first heavy-ion fusion reaction to be considered for $M > M_{up} \simeq 8\, M_\odot$
  $(0.8 - 1.5) \cdot 10^9$ K

- Next natural reactions of astrophysical relevance: involving ^{16}O
  ^{12}C+^{16}O: late burning phases of C/O, shell burning, intershells mixing, SN
  ^{16}O+^{16}O: the next binary fusion ($(1.5 - 2.7) \cdot 10^9$ K)

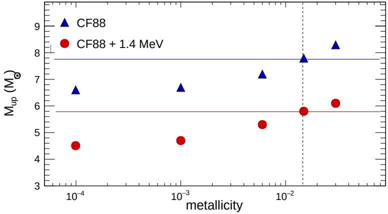
Reaction rates: $r_{xy} = N_x N_y < \sigma\nu >_{xy} (1 + \delta_{xy})^{-1}$

$$< \sigma\nu >_{xy} = (\frac{8}{\pi \mu_{xy}})^{1/2} \frac{1}{(k_B T)^{3/2}} \int_0^\infty E\, \sigma(E)\, e^{-E/(k_B T)} dE$$

$\sigma(E)$ from experiment (+ extrapolations!)

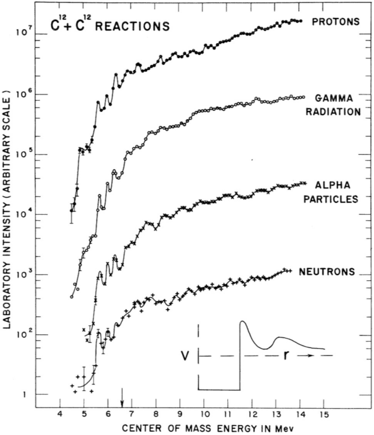


from Chieffi *et al.*, APJ **502** (1998)



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

The $^{12}C+^{12}C$ special case

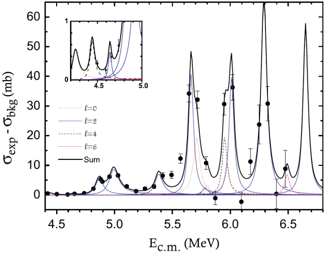


Almqvist *et al.* PRL **4** (1960)

Nuclear structure / resonances

- correspond to compound states in ^{24}Mg (14-20 MeV)
- large spacing, narrow width
- molecular/cluster states?

obstacle for extrapolation to stellar energies



Aguilera *et al.*, PRC **73** (2006)

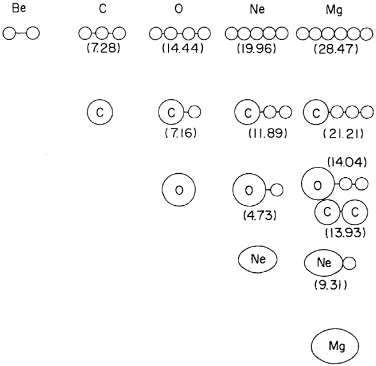
Alpha-clustering in ^{24}Mg

Theoretical predictions from first principles:

- Energy-density functionals (EDFs)
  + deformation Ebran *et al.*, Nature **487** (2012)
- Antisymmetrized molecular dynamics (AMD)
  IS monopole transition strengths from GS
  Chiba and Kimura, PRC **91** (2015)

from Ebran *et al.*, PRC **90** (2014)

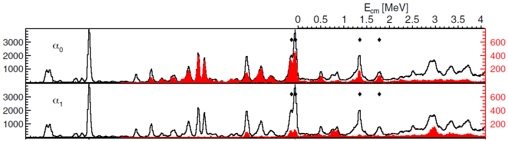
Ikeda *et al.*, Prog. Theo. Phys. Suppl. E68 (1968)



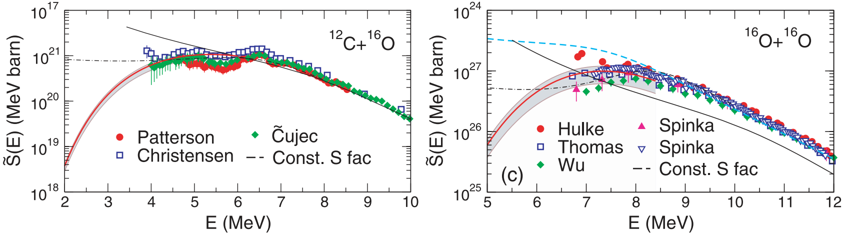
Experimental (indirect) signatures:

- Large α particle width
- Rotational bands, IS monopole
- At cluster-decay thresholds

Adsley *et al.*, PRL **129** (2022): look for candidates 0^+ cluster states with ^{24}Mg$(\alpha,\alpha_0)^{24}$Mg reaction

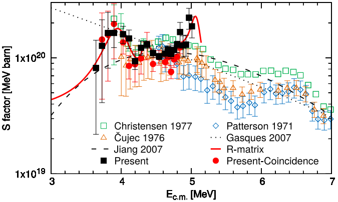


Neighboring alpha-conjugated systems



Jiang *et al.*, PRC **75** (2007)

- Large spacing and narrow width of ^{24}Mg compound levels – might be smeared out in other systems
  Jiang *et al.*, PRL **110** (2013)
- Recent mild experimental hint for resonances in ^{12}C+^{16}O system? Fang *et al.*, PRC **96** (2017)

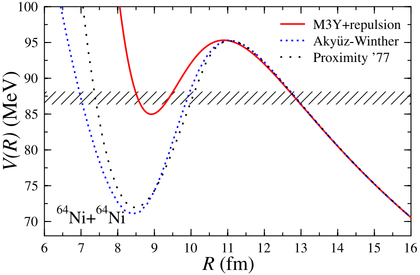


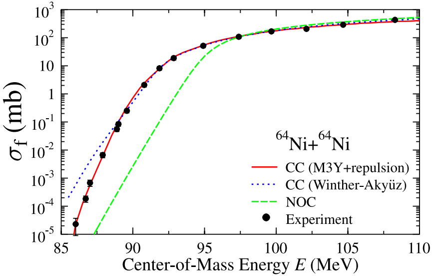
Fusion hindrance in medium-mass and light systems

Suppression of fusion in deep sub-barrier regime

Observed experimentally for a wide range of medium-mass systems.
Repulsive core in the potential which might be due to:

- Nuclear matter incompressibility
  Mişicu and Esbensen, PRL **96** (2006)
- Pauli exclusion principle
  Simenel *et al.*, PRC **95** (2017)

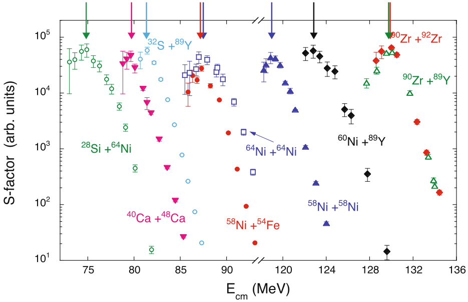


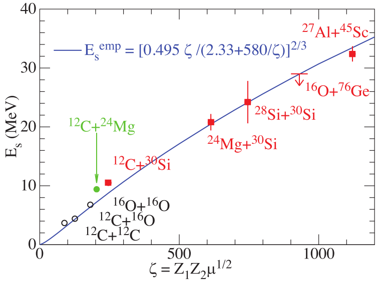


Mişicu and Esbensen, PRL **96** (2006)

Fusion hindrance in light systems?

Empirical trend of the S-factor maximum:





Montagnoli, Eur. Phys. J. A **53** (2017)

Reliability of the extrapolation for light systems?

e.g. Godbey *et al.*, PRC **100** (2019): Pauli repulsion plays minor role for ^{12}C + ^{12}C

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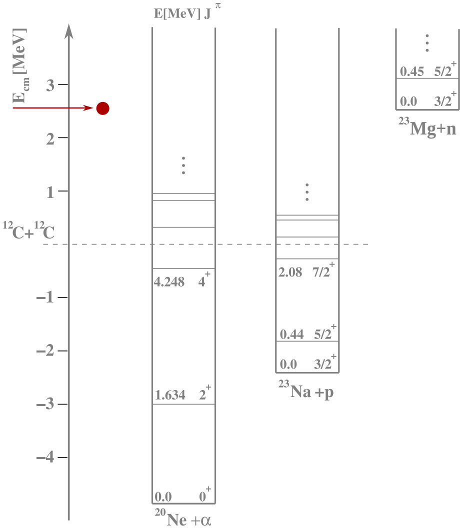
Direct measurement principle

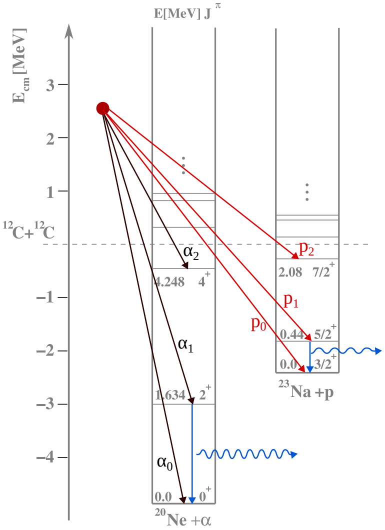


$$^{12}C + ^{12}C \rightarrow \; ^{23}Na + p \quad [\mathrm{Q = 2.24\ MeV}]$$
$$\rightarrow \; ^{20}Ne + \alpha \quad [\mathrm{Q = 4.62\ MeV}]$$
$$\rightarrow \; ^{23}Mg + n \quad [\mathrm{Q = \text{-}2.62\ MeV}]$$

Direct measurements:

- charged particles (p/α)
- deexcitation gamma-rays
- charged-particles and γ in coincidence
  $\rightarrow$ STELLA experiment!
  Selection of 1st excited state

Direct measurement principle



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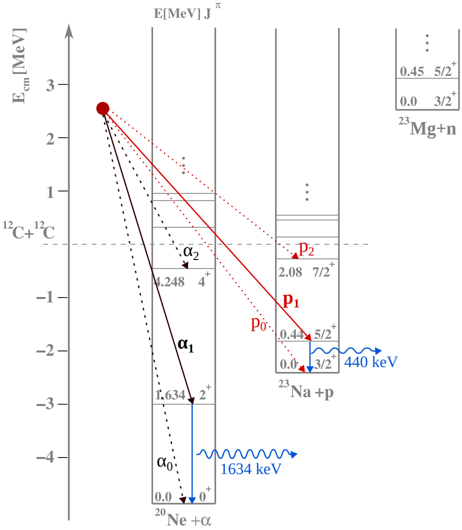

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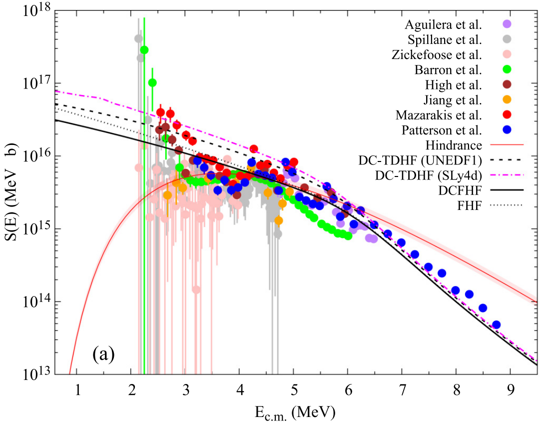
State of the art (2019)



Godbey *et al.*, PRC **100** (2019)

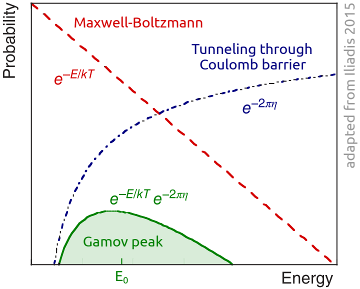
Direct measurement: challenges

At stellar temperatures: fusion via tunneling effect through the Coulomb Barrier

$\rightarrow$ Extremely small cross sections!

Experimental challenges:

- Beam intensity ($\sim$ 1-10 pμA)
- Stability (data taking weeks)
- Detection efficiency
- Background rejection
- Low statistics



Measurements expressed in terms of astrophysical S-factor:
S = E$\sigma(E) exp(2\pi\eta)$

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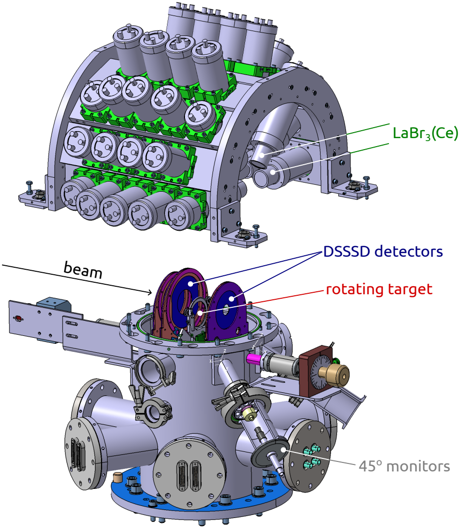
STELLA experimental setup

- Andromede facility, Orsay (France)
  4 MV, ECR source, 10 pμA

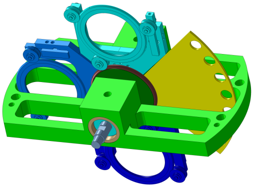
- Particle detection: annular DSSSD
  (Micron chips + IPHC conception)
  ✓ angular distribution meas.
  ✓ $d\Omega = 24\,\%$ of 4π
- Gamma detection: 36 $LaBr_3(Ce)$ detectors from UK FATIMA
  ✓ energy res.: 2.5 % @ 1.4 MeV
  ✓ sub ns-timing
  ✓ coverage: $d\Omega = 23\,\%$ of 4π



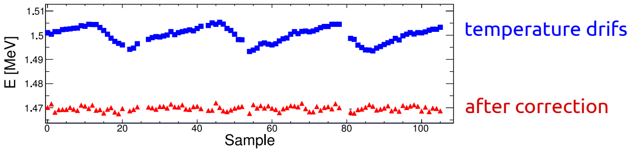
STELLA experimental setup

- DAQ: synchronization of 1 GHz gamma DAQ and 125 MHz particle DAQ
- Selection CP/γ with timing gates $\sim 15\,\mathrm{ns}$

- Intensities up to $2.5\,\mathrm{p}\mu\mathrm{A}$ on thin target foils (30-50 μg.cm^{-2})
  $\rightarrow$ heat dissipation via rotating target system
- Post-beam thickness measurements
- Carbon morphology via Raman spectroscopy

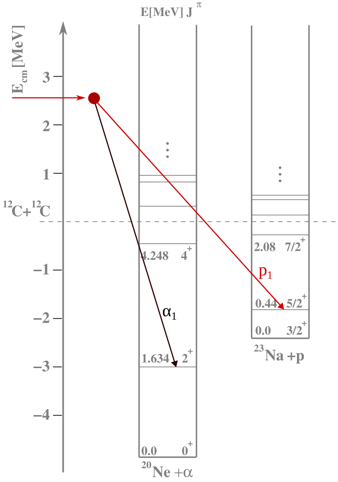


- Measurement campaigns of several weeks $\rightarrow$ stability!

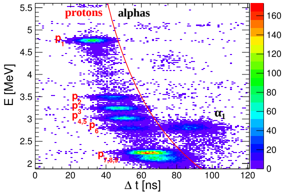


M. Heine *et al.*, NIM A **903** (2018)

STELLA data selection and background suppression

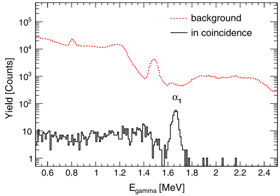


- Charged particles: energy selection + p/α discrimination from timing



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

- Gamma-rays detection in $LaBr_3$



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

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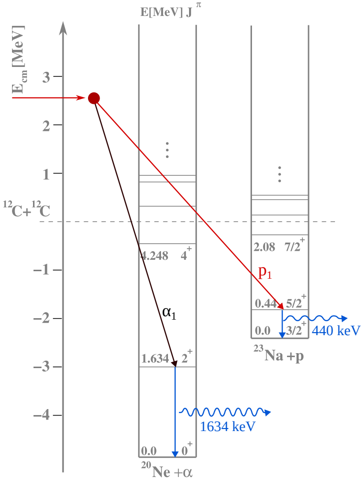

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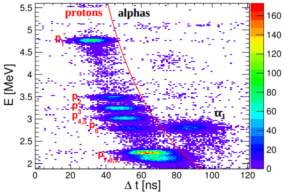

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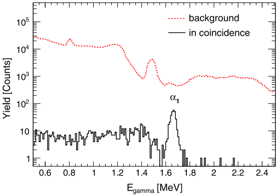

Fruet *et al.*, PRL **124** (2020)

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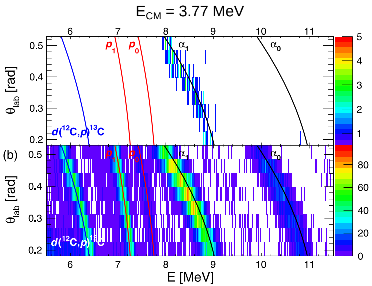
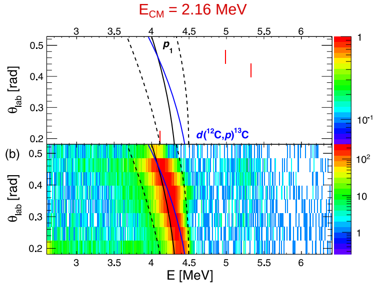




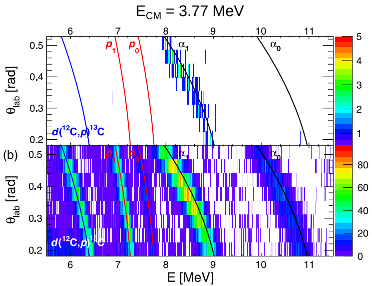
The power of coincidences with ns-timing:

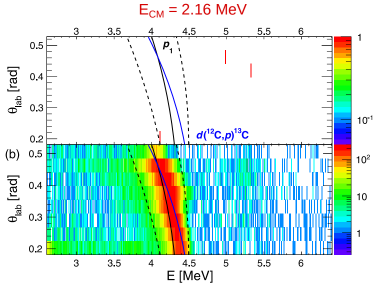
- Background (from target) suppressed
- Random background subtraction via delayed time windows

At the lowest energies: $\lesssim 100$ pb cross-sections!

- Extreme care with low statistics: Feldman-Cousins formalism

STELLA data selection and background suppression





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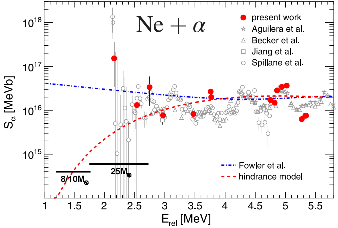
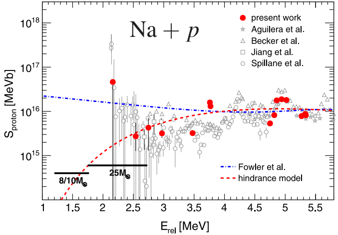
First measured S-factors from STELLA

Three regimes explored:

- Moderate sub-barrier energies: validation of experimental concept
- Deep sub-barrier energy: hindrance regime
- Gamov windows for $\sim 25 M_\odot$

Norm.: thickness measurement, charge integrator, branchings p_1/p and α_1/α derived from Becker



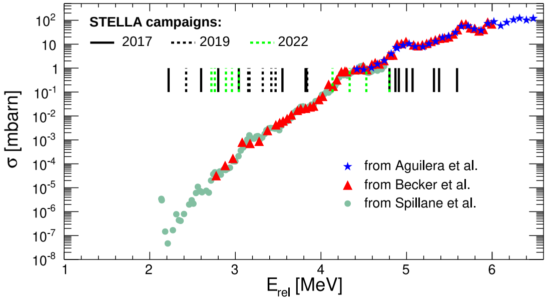


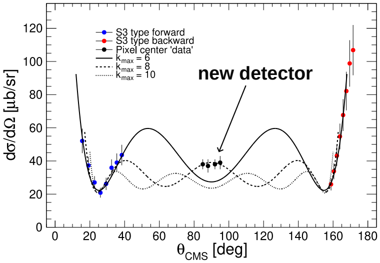
G. Fruet *et al.*, PRL **124** (2020)

$\rightarrow$ provides reliable excitation functions over 8 orders of magnitude down to 2.1 MeV (100 pb range!)

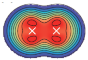
[astrophysical impact: see T. Dumont talk]

More results to come





- **2017**: exploration of three regimes
  G. Fruet *et al.*, PRL **124** (2020)
- **2019, 2022**: finer investigations
  + angular distribution studies

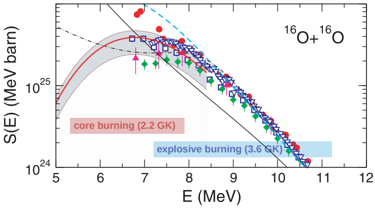


$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{24}\mathrm{Mg}^* \rightarrow ^{20}\mathrm{Ne} + \alpha_0 + \gamma$$

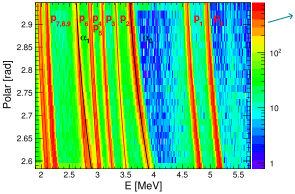
$$0^+ + 0^+ \rightarrow \quad ?^+ \rightarrow \quad 0^+ + 0^+ + \vec{L}_\alpha$$

The next steps with STELLA: $^{12}C+^{16}O$ and $^{16}O+^{16}O$

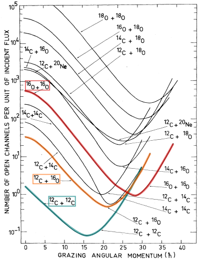
- Next natural reactions of astrophysical relevance:
  $^{12}C+^{16}O$: e.g. late carbon burning phase
  $^{16}O+^{16}O$: the next binary fusion
- Nuclear physics: fusion hindrance? Resonances?
- Scarce data in the relevant Gamov window...



→ **Measure with STELLA!** Additional challenge: increasing complexity of exit channels:



$^{12}C+^{12}C$	$^{12}C+^{16}O$	$^{16}O+^{16}O$
$^{20}Ne+\alpha$	$^{24}Mg+\alpha$	$^{28}Si+\alpha$
$^{23}Na+p$	$^{27}Al+p$	$^{31}P+p$
$^{23}Mg+n$	$^{27}Si+n$	$^{31}S+n$
$^{16}O+2\alpha$	$^{25}Mg+2p$	$^{30}Si+2p$
	$^{20}Ne+2\alpha$	$^{24}Mg+2\alpha$
	$^{23}Na+\alpha p$	$^{27}Al+\alpha p$
		$^{30}P+d$
		$^{30}P+np$



- Charged particle detectors upgrade: improved angular coverage, adapted thickness (higher energies), resolve complex final states
- Additional beam focusing element for an optimal beam spot size

Conclusion and perspectives

- Fusion reaction cross-section crucial for stellar evolution of massive stars
  intimately related to fundamental nuclear physics: resonances, hindrance?
  $\rightarrow$ Measurements essentials, microscopic understanding

- Direct measurements: challenging, complementary
  STELLA: entering Gamov windows with coincidence technique

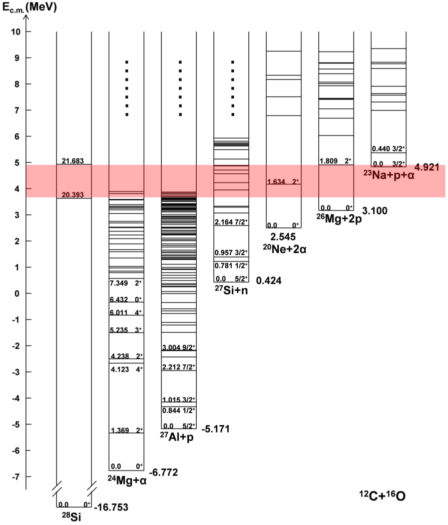
- $^{12}C+^{12}C$: new rate + astrophysical consequences
  Fruet *et al.*, PRL **124** (2020) + Montpribat *et al.*, A& A **660** (2022)

- Next steps: $^{12}C+^{16}O$, $^{16}O+^{16}O$. Increased complexity of final states, upgrades: charged particles detectors & focalisation

Thank you for your attention!

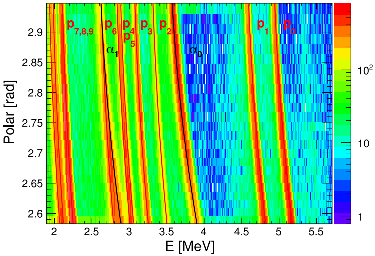
BACKUP

Specificity of the $^{12}C + {}^{16}O$ system



Much more channels and levels available than for $^{12}C+{}^{12}C$

→ increased complexity of the final state identification

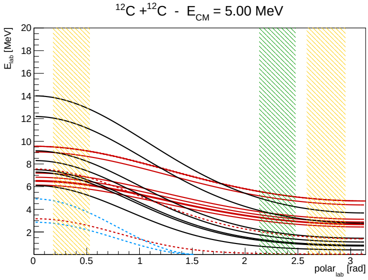


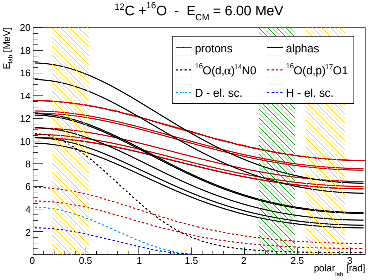
→ Accurate control of the energy resolution indispensable

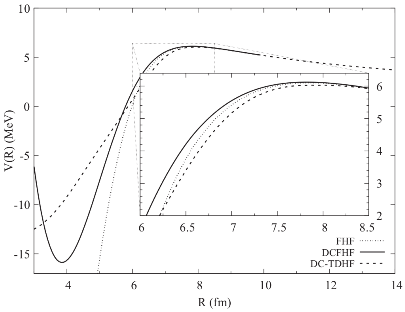
Specificity of the $^{12}C + ^{16}O$ system

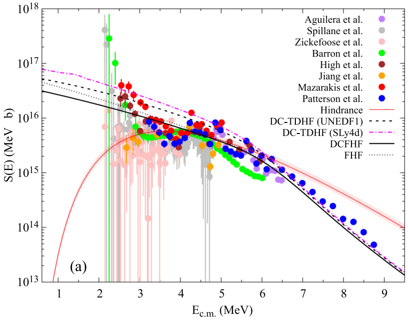
- Charged particles more energetic
- Discrimination power enhanced for large angles
- Open channels with two charged particles in the final state
- p1 and $\alpha 1$ associated γ lines close to internal contamination of LaBr3 detectors

	$^{12}C + ^{12}C$	$^{12}C + ^{16}O$
	^{23}Na	^{27}Al
p1	γ: 0.44 MeV	γ: 0.84 MeV
p2	γ: 2.08 MeV	γ: 1.01 MeV
	^{20}Ne	^{24}Mg
$\alpha 1$	γ: 1.64 MeV	γ: 1.37 MeV
$\alpha 2$	γ: 4.25 MeV	γ: 4.12 MeV



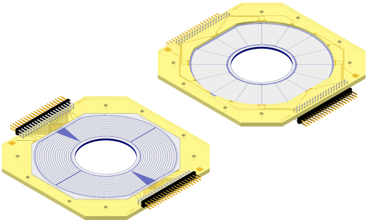



V(R) (MeV)
R (fm)
FHF
DCFHF
DC-TDHF

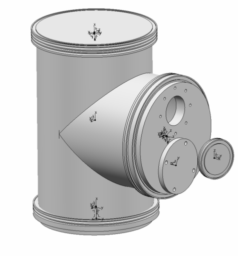

S(E) (MeV b)
E c.m. (MeV)
Aguilera et al.
Spillane et al.
Zickefoose et al.
Barron et al.
High et al.
Jiang et al.
Mazarakis et al.
Patterson et al.
Hindrance
DC-TDHF (UNEDF1)
DC-TDHF (SLy4d)
DCFHF
FHF
(a)

The CarbOx project

Upgrade 1: New light charged particle detector



- DSSSD thicker than previous version
- Better covering of backward angles
- Additional sectorisation



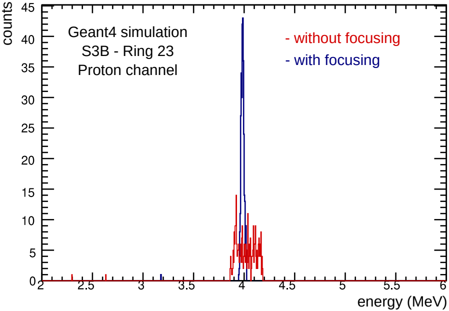
NEW test bench @IPHC in Strasbourg:

- Independent reaction chamber → extensive characterisation and testing in 2023
- DAQ improvements (easier shifter control, temperature monitoring...)
- M1 internship: geometrical caracterisation of the strips ($< 10\,\mu$m)

The CarbOx project

Upgrade 2: Focusing of the beam line

- Integration of a doublet of quadrupole just before STELLA
- Position optimization from beam optics simulation
- Goal: decrease beam spot diameter from 8 mm to 4 mm



Work ongoing: GEANT4 simulations, impact of beam size/profile