

The $^{12}\text{C}+^{12}\text{C}$ Saga : From Hvar (1977) to Split (2011)

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- International Conference on Resonances in Heavy-Ion Reactions,
Hvar, May 30 – June 3, 1977

- Proceedings :
“Nuclear Molecular Phenomena”, Edited by N. CINDRO
First talk in the Conference :

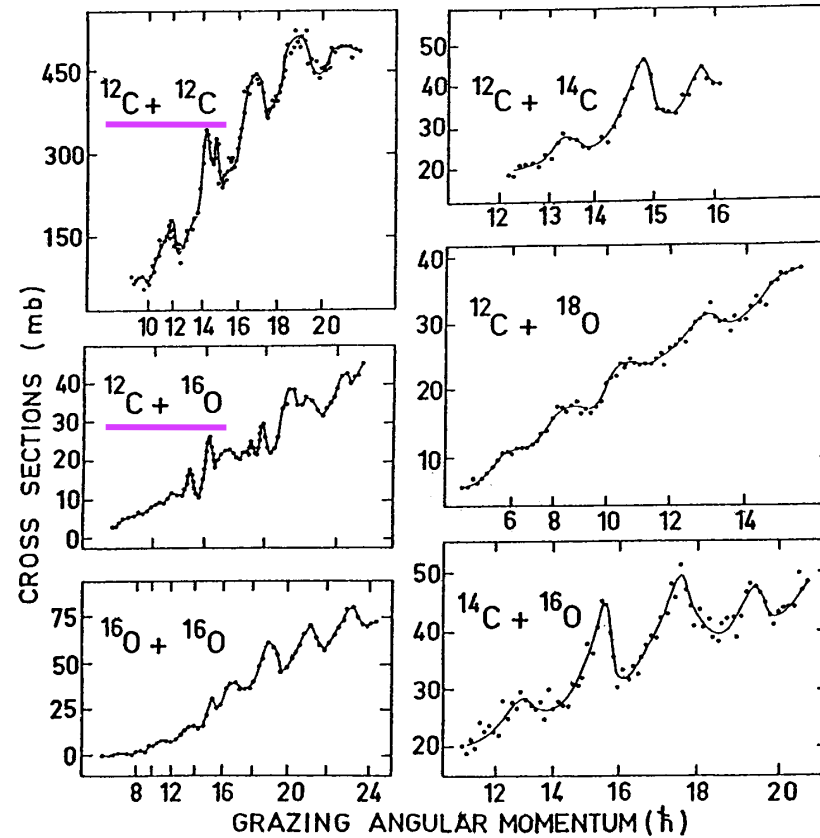
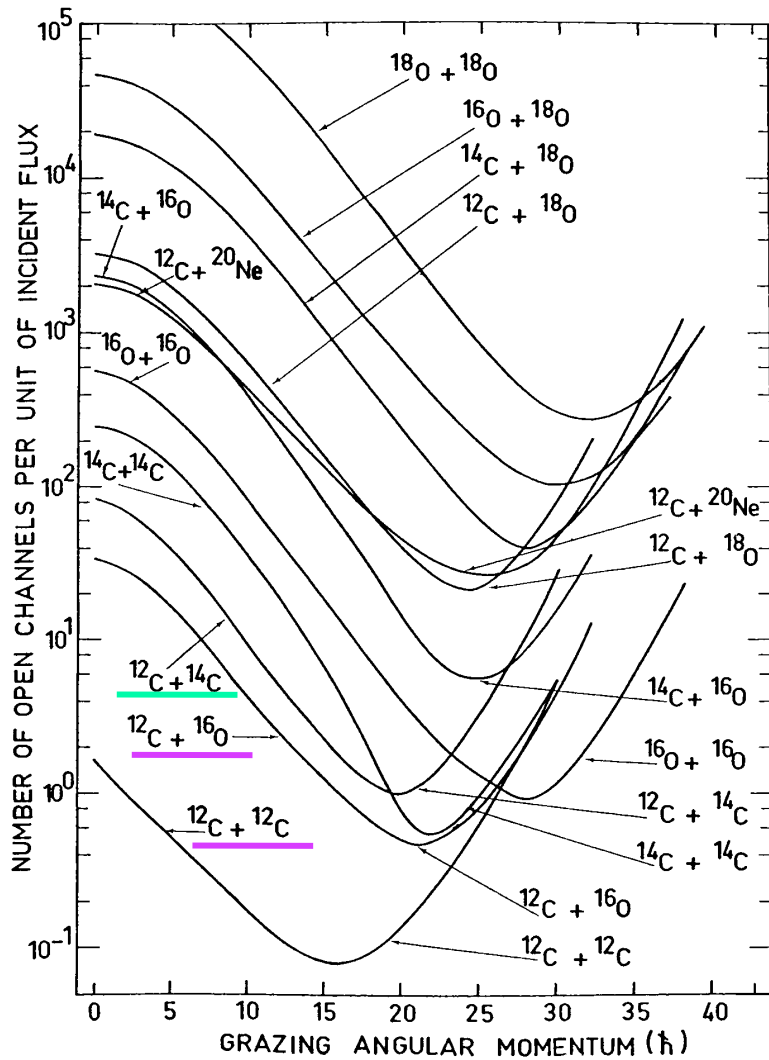
- The Carbon-Carbon Nuclear System, D.A. Bromley

- $^{12}\text{C}+^{12}\text{C}$ ~ 1000 references in NNDC

Resonances

- Resonances in the collisions of light heavy-ions
- From CB to ~ 5 MeV per nucleon
Collisions between identical bosons
 $^{12}\text{C}+^{12}\text{C}$, $^{14}\text{C}+^{14}\text{C}$, $^{16}\text{O}+^{16}\text{O}$, $^{24}\text{Mg}+^{24}\text{Mg}$, $^{28}\text{Si}+^{28}\text{Si}$
- Observation in these systems: number of open channels (weak absorption)

Resonances and NOC



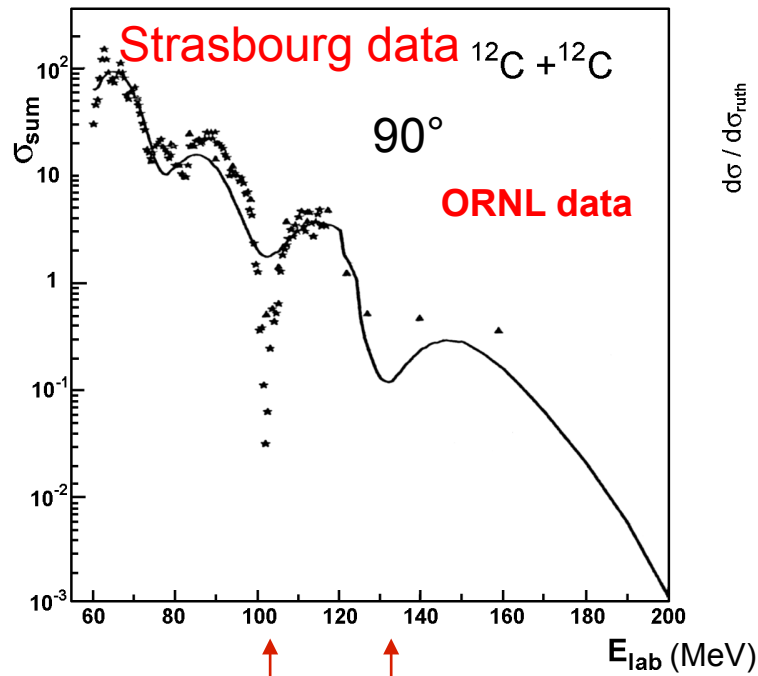
F. Haas and Y. Abe, Phys. Rev. Lett. 46 (1981) 1667

The $^{12}\text{C}+^{12}\text{C}$ reaction : a unique example of a “WEAK ABSORPTION” collision

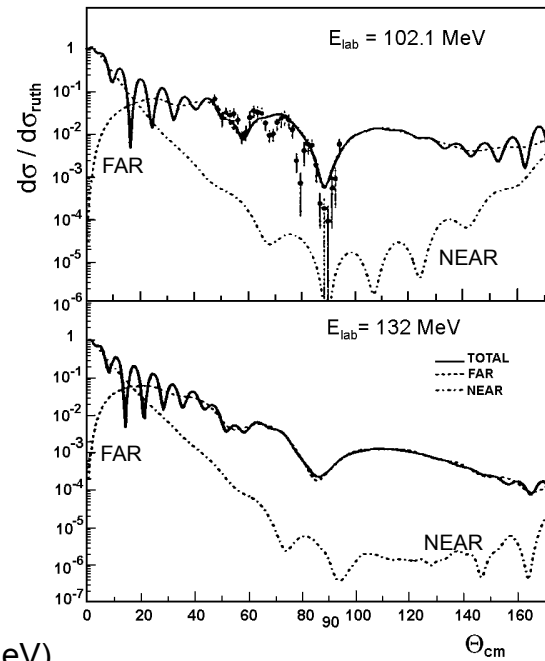
- ❑ Resonant Phenomena
- ❑ Resonances observed from well below the CB (0.5 MeV/n) to ~ 5-6 MeV/n.
Widths from ~ 100 keV to 1 MeV (cm)
Spins from $J = 0$ to $J = 16$ with clustering of states with the same J (the Feshbach coupling picture)
- ❑ Resonances in the elastic, inelastic, fusion and transfer channels
- ❑ No resonances above $J = 16$ (fission limit for ^{24}Mg)

Higher energies

- What happens above 5 MeV per nucleon ?
 - narrow structures to wider ones
 - resonant to refractive effects
 - molecules to **rainbows** ...

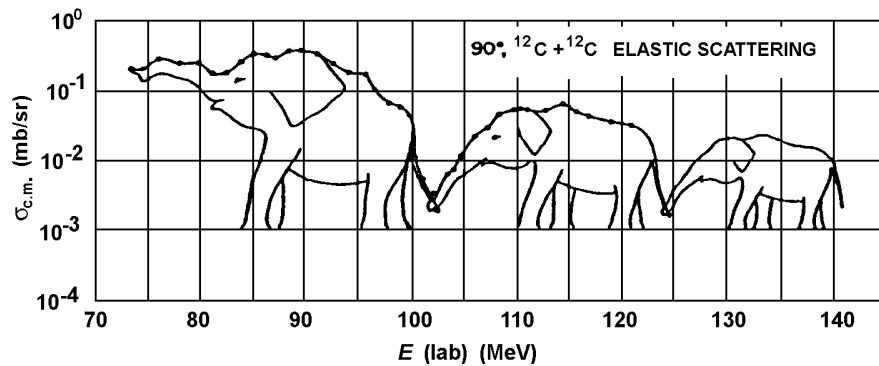


102.1 MeV 132 MeV



Potential analysis

PhD Thesis S. Sziler



Resonant structures vs molecular states

Experimental signature ↔ decay of the resonances

- Widths, spins, fragment emission ...
- Molecules and deformed shapes
 - Gamma decay of the resonant structures
 - But Γ_γ / Γ (very) weak : $10^{-4} - 10^{-6}$

The gamma decay of molecular states

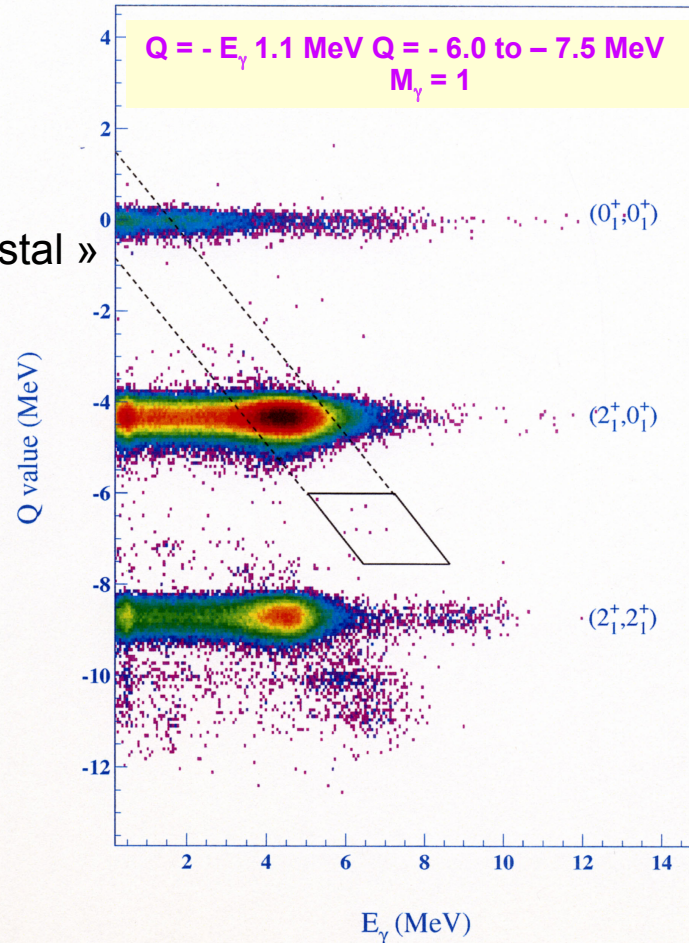
- The ^{16}O cluster band : $^{12}\text{C} + \alpha \leftrightarrow 4\text{p-4h}$
 $^{16}\text{O}(0^+, 2^+, 4^+)$ at $E_x = 6.05, 6.92, 10.36$ MeV
 $E2(2^+ \rightarrow 0^+) : 27$ W.u., $E2(4^+ \rightarrow 2^+) : 65$ W.u.

- The $^{12}\text{C}+^{12}\text{C}$ case

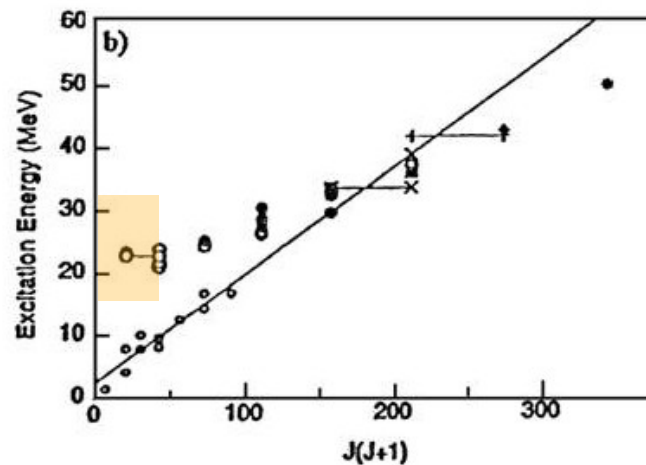
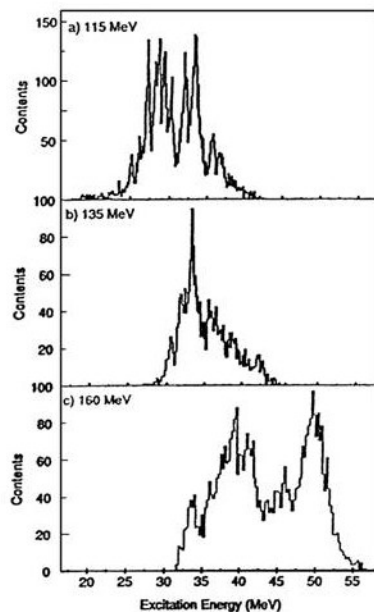
Experiment at the « Château de Cristal »

$E_{\text{CM}} = 15.45$ MeV

$J\pi = 10^+$ resonance



$^{12}\text{C}+^{12}\text{C}$ breakup states in ^{24}Mg

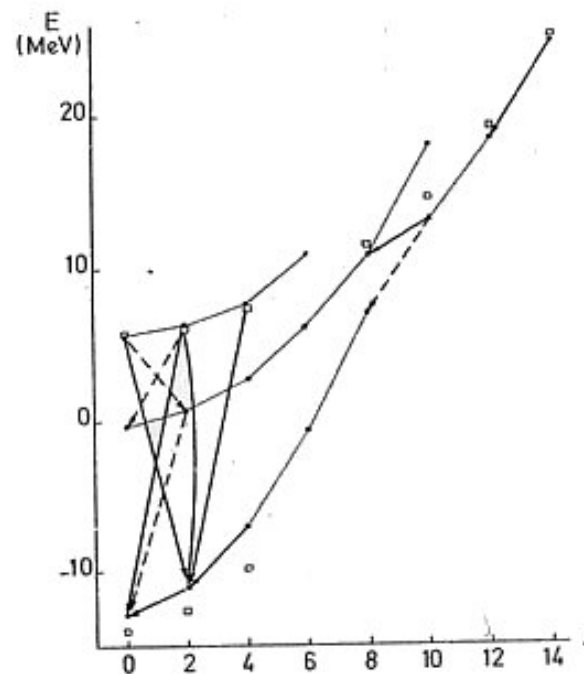


RC

- $^{12}\text{C}+^{12}\text{C}$ breakup states in ^{24}Mg up to $E^* = 50$ MeV
C.J. Metelko et al., Phys.Rev. C68 (2003) 0544321
- Reaction $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C}^{12}\text{C})\alpha$
- Position Sensitive Double-Sided Silicon Strip Detectors for coincident particle detection

The $^{12}\text{C}+^{12}\text{C}$ clustering in ^{24}Mg

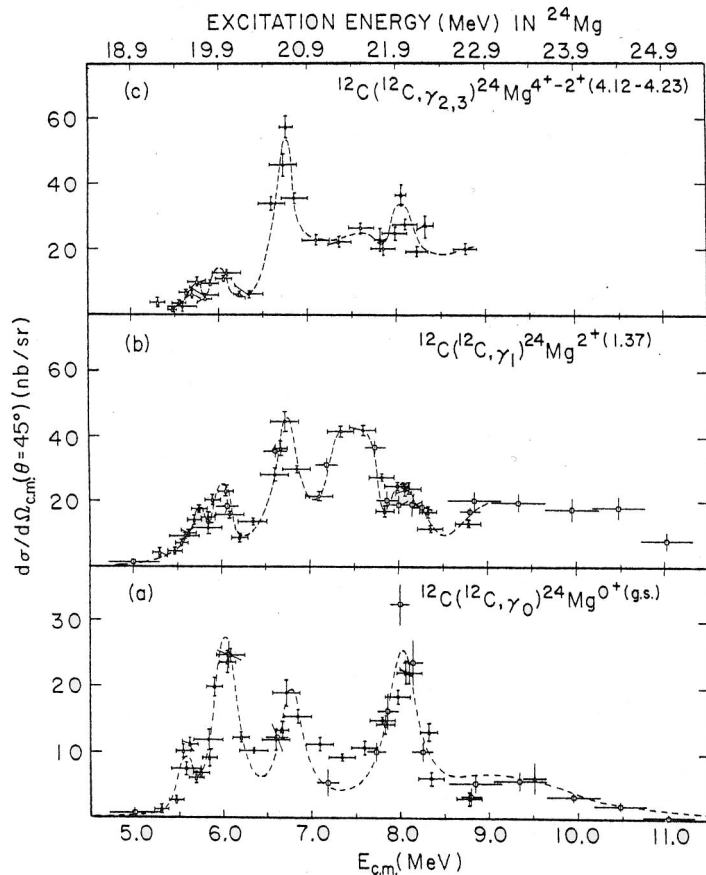
The $^{12}\text{C}-^{12}\text{C}$ molecule *à la* Descouvemont and Baye
(PL 169B (1986)143) with GCM : 3 bands in ^{24}Mg



The $^{12}\text{C}+^{12}\text{C}$ radiative capture as a tool to study the γ decay of molecular states at CB

The $^{12}\text{C}+^{12}\text{C}$ Radiative Capture Reaction

- The radiative capture in light-heavy ion collisions
- The pioneering Sandorfi experiments
Treatise on Heavy Ion Science, Vol.2 (1984) and references therein.

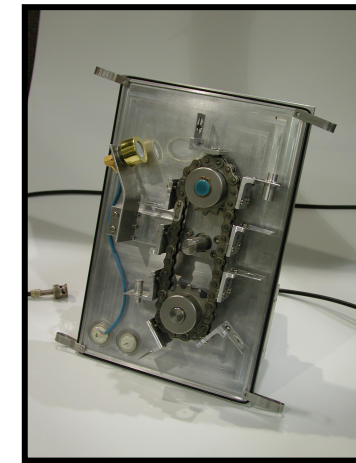
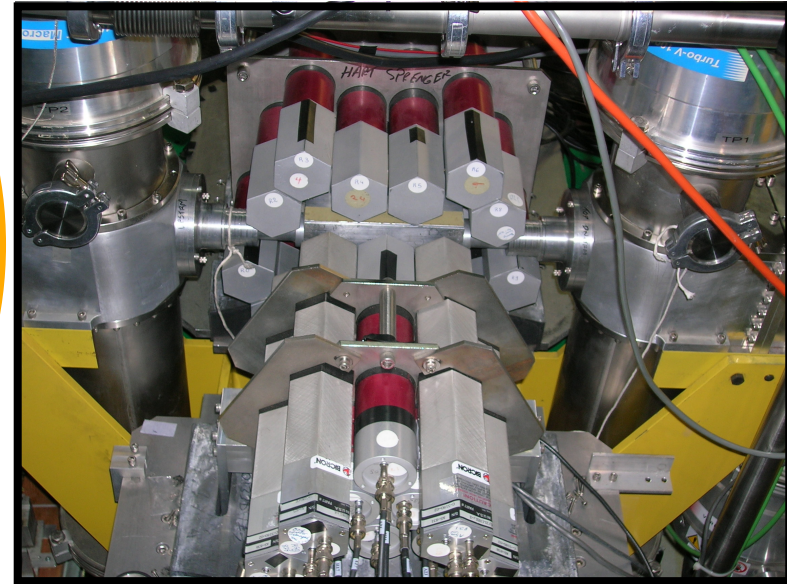
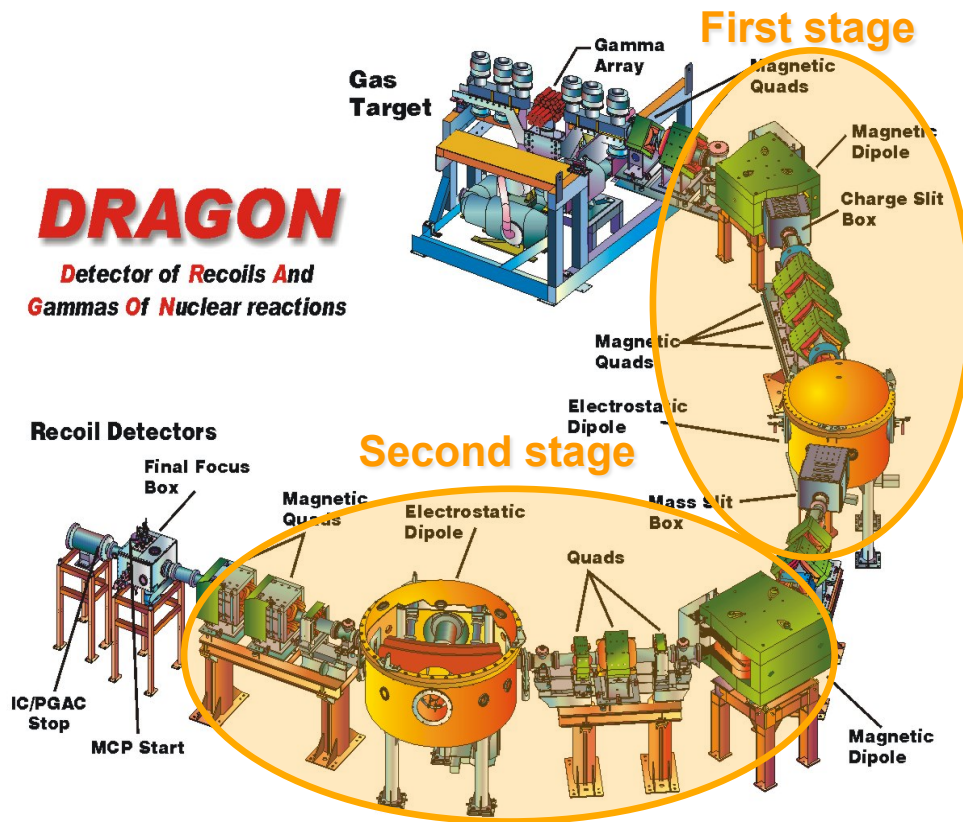


- 20 years later
- The Gammasphere and FMA experiments
Doorways states as a principal decay pathway in $^{12}\text{C}(^{12}\text{C},\gamma)$
radiative capture.
D.G. Jenkins et al., PRC71 (2005) 042301R

The Triumph Experiment

D.A. Hutcheon et al., NIMA 498, 190 (2003).

DRAGON Detector of Recoils And Gammas Of Nuclear reactions

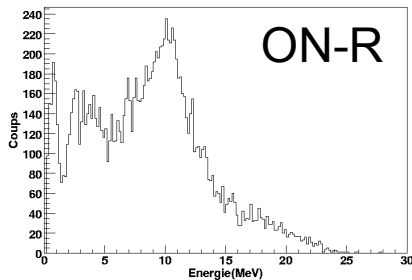


- ISAC I : RNBS / Stable (OLIS)
- 0° spectrometer
- ToF : 17 m
- Beam rejection: 10^{13}
- Acceptance : cone $\frac{1}{2}$ angle 20 mrad
- gaz/solid target
- focal plane (DSSSD, ...)
- BGO ($\epsilon = 50\%$ @ 5 MeV)

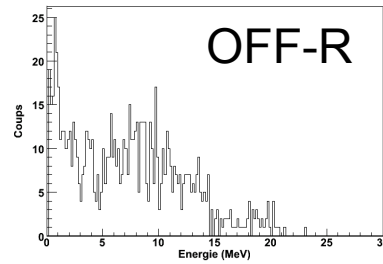
□ The $^{12}\text{C}+^{12}\text{C}$ experiment at Triumf (Vancouver)

□ ON and OFF resonance measurements

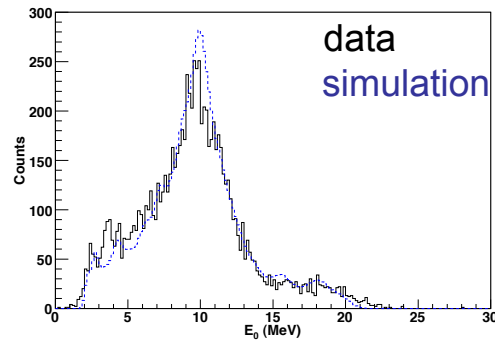
$E_{\text{CM}} = 6,7 \text{ MeV}$



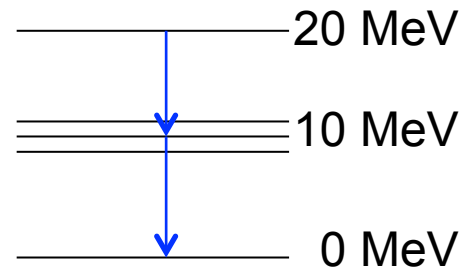
$E_{\text{CM}} = 6,4 \text{ MeV}$



resonance 2^+



The main decay mode

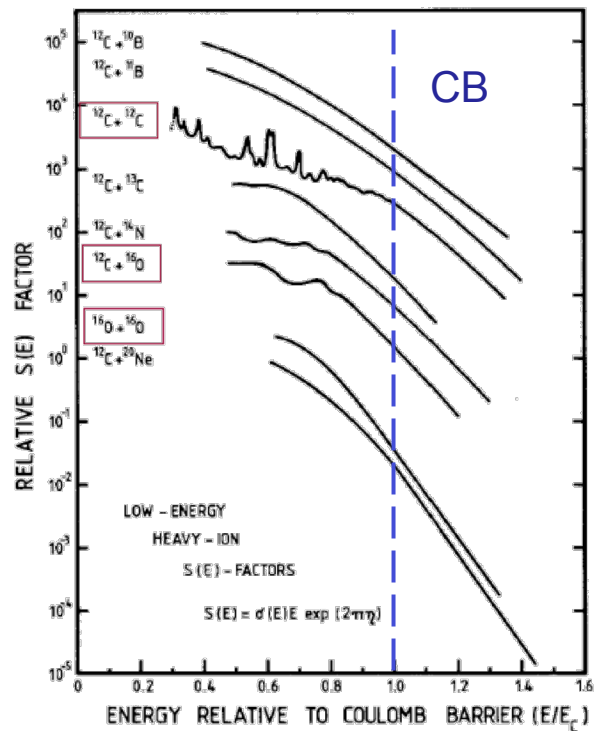


□ The conditions of the simulation

→ Identify the ^{24}Mg states which contribute to the large γ structure around $\sim 10 \text{ MeV}$. A better γ resolution experiment is needed → The “PARIS” gamma detector

$^{12}\text{C} + ^{12}\text{C}$: Down to very low energies

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

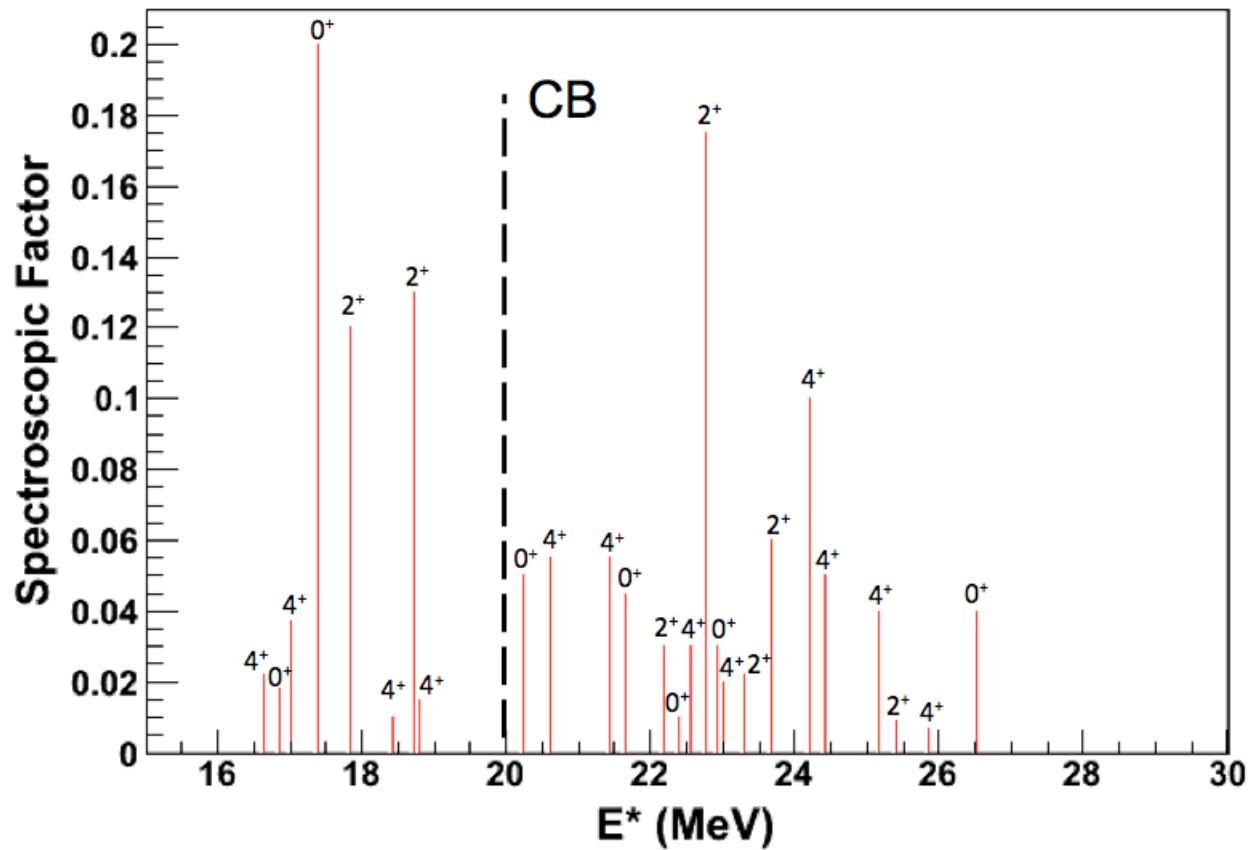


H.W. Becker *et al.*, *Z. Phys.* **A305** (1982).

| System | Number of open channels at CB |
|-------------------------------|-------------------------------|
| $^{12}\text{C}+^{12}\text{C}$ | 9 |
| $^{12}\text{C}+^{16}\text{O}$ | 350 |
| $^{16}\text{O}+^{16}\text{O}$ | 600 |

F. Haas and Y. Abe, Phys. Rev. Lett. **46** (1981) 1667

Down to very low energies



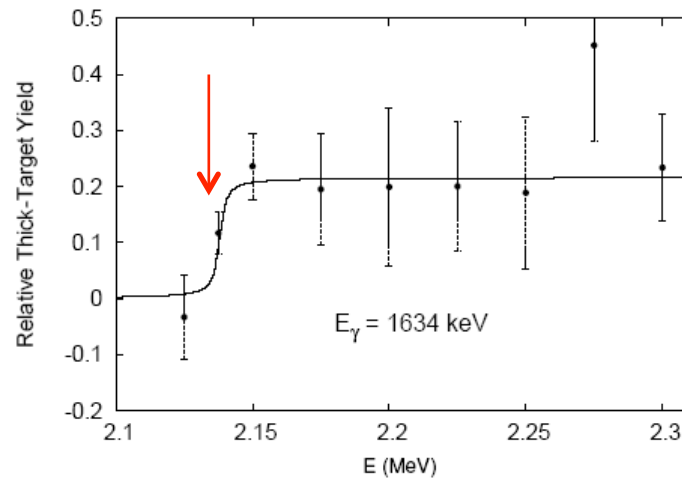
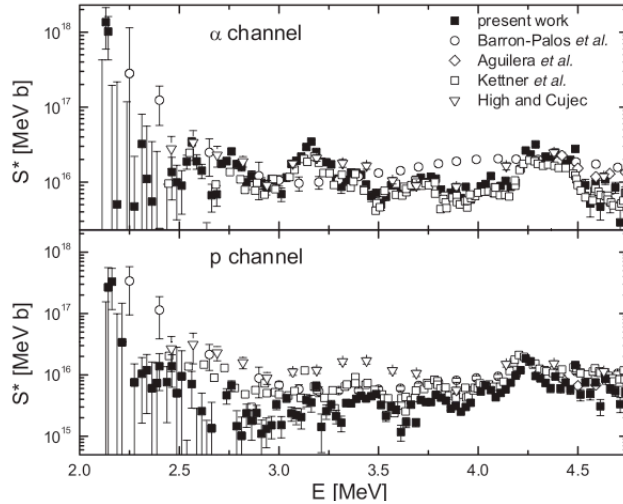
Y. Suzuki and K.T. Hecht, *Nucl. Phys. A* **388**, 102 (1982).

Sub-Coulomb $^{12}\text{C} + ^{12}\text{C}$ resonances in a microscopic $^{12}\text{C} + ^{12}\text{C}, \alpha + ^{20}\text{Ne}, ^8\text{Be} + ^{16}\text{O}$ cluster basis

Down to astrophysical energies

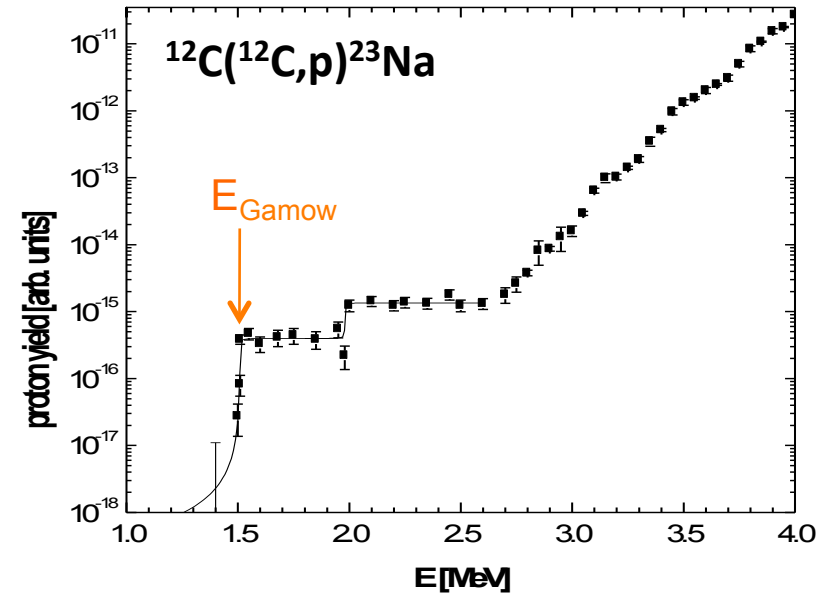
Resonances @ very low energies in the $^{12}\text{C}+^{12}\text{C}$ system

DTL Bochum data



T. Spillane *et al.*, Phys. Rev. Lett. **98**,122501 (2007).

CIRCE Caserta, Naples data



Energy region

F. Strieder, *priv. comm.*

$$E_{\text{Gamow}} = 1.5 (0.3) \text{ MeV @ } T = 5 \cdot 10^8 \text{ K}$$

My main “ $^{12}\text{C}+^{12}\text{C}$ ” collaborators over the years

R.M. Freeman (Strasbourg), J.J. Kolata (Notre Dame)

Y. Abe (Kyoto)

A. Morsad (Casablanca)

A. Elanique (Agadir)

S. Szilner, Z. Basrak (Zagreb)

D. Jenkins (York)

S. Courtin, D. Lebhertz (Strasbourg)