Gamma Decay of Molecular Resonances

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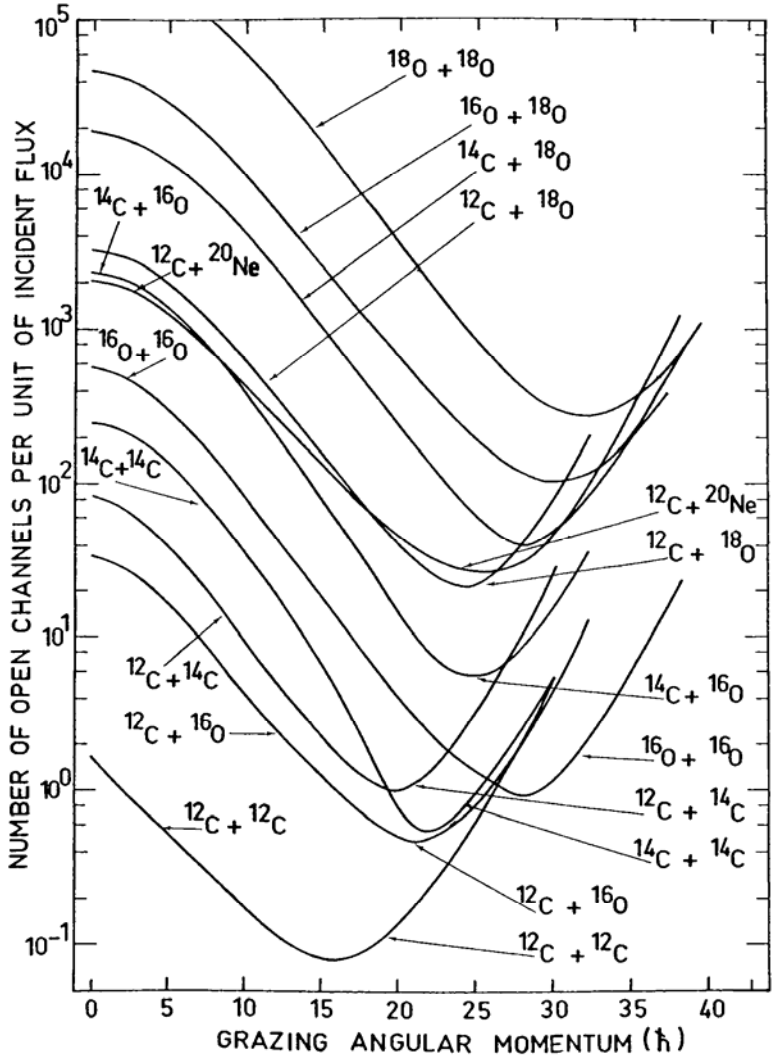
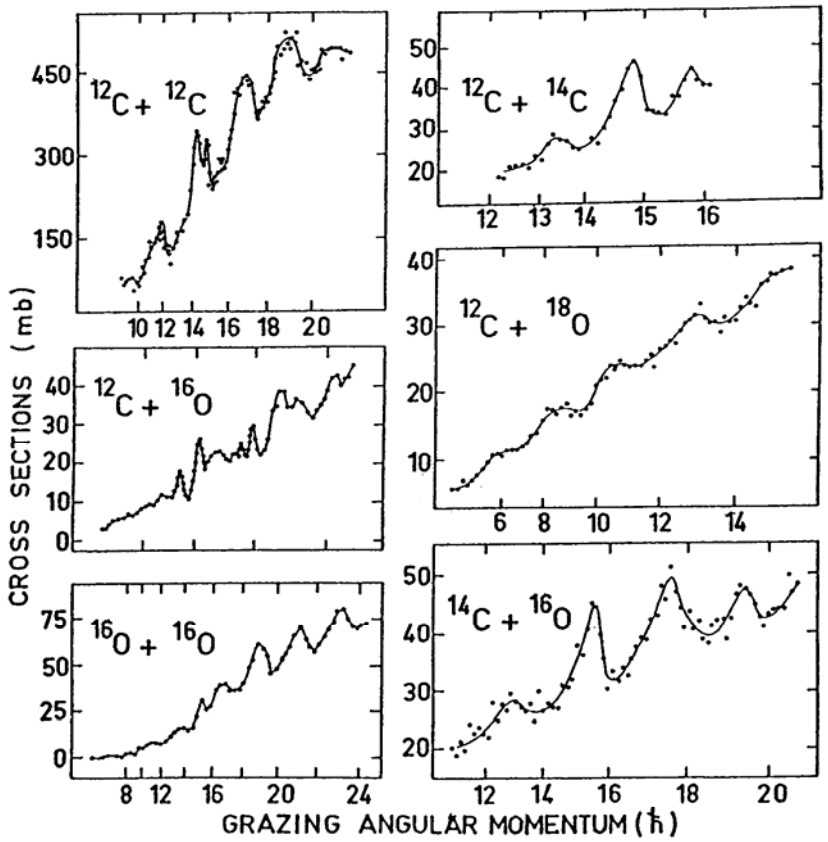
- Resonances in ‘Light’ Heavy-Ion Reactions

- Resonance phenomena at energies from the CB to ~ 5 MeV per nucleon
  Examples in the case of identical boson collisions:
  $^{12}C+^{12}C$, $^{14}C+^{14}C$, $^{16}O+^{16}O$, $^{24}Mg+^{24}Mg$, $^{28}Si+^{28}Si$

- Observation in these systems is understood:
  small number of open channels → Weak Absorption


NUMBER OF OPEN CHANNELS PER UNIT OF INCIDENT FLUX
GRAZING ANGULAR MOMENTUM (ħ)
18O + 18O
16O + 18O
14C + 18O
12C + 18O
14C + 16O
12C + 20Ne
16O + 16O
14C + 14C
12C + 20Ne
12C + 18O
14C + 16O
16O + 16O
12C + 14C
14C + 14C
12C + 14C
12C + 16O
12C + 12C
12C + 16O
12C + 12C


CROSS SECTIONS (mb)
GRAZING ANGULAR MOMENTUM (ħ)
12C + 12C
12C + 14C
12C + 16O
12C + 18O
16O + 16O
14C + 16O

Resonant Structures ↔ Molecular States

- Experimental and complementary signatures in the DECAY

- ❑ Main fragment channels, width, spins
- ❑ Molecular states and deformed states
- Search for the gamma decay of resonant structures
- But Γ_γ / Γ is (very) weak: 10^{-4} – 10^{-6}

- α clustering in light nuclei

- α cluster band
  → $^{16}O(^{12}C+\alpha)$, $^{18}O(^{14}C+\alpha)$, $^{20}Ne(^{16}O+\alpha)$, $^{44}Ti(^{40}Ca+\alpha)$
  →Be and C neutron rich isotopes with 2αxn and 3αxn configurations
  W. Von Oertzen and the HMI group (dimers and polymers)
  M. Freer and the Charissa group

- Our best examples of α clustering:
  → $^{8}Be(0^+)$ at E_x = 0.0 MeV
  → $^{9}Be(3/2^-, 5/2^-)$ at E_x = 0.0, 2.43 MeV
  $E2(5/2^- \rightarrow 3/2^-)$: 24 W.u.
  → $^{10}Be(0^+)$ at E_x = 6.18 MeV
  → $^{12}C(0^+)$ at E_x = 7.65 MeV
  $E2(0^+ \rightarrow 2^+)$: 8 W.u.
  → $^{16}O(0^+, 2^+, 4^+)$ at E_x = 6.05, 6.92, 10.36 MeV
  $E2(2^+ \rightarrow 0^+)$: 27 W.u., $E2(4^+ \rightarrow 2^+)$: 65 W.u.

- Clustering in heavier systems

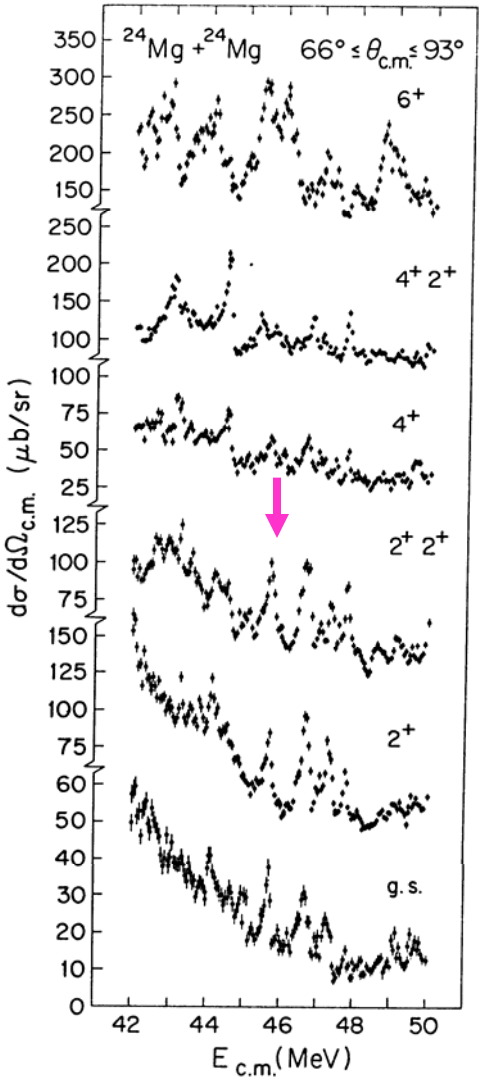
- CN at high excitation energies but narrow resonance (spreading) width of Γ = 100-200 keV observed in the two most remarkable examples: $^{12}C+^{12}C$ and $^{24}Mg+^{24}Mg$

- $^{12}C+^{12}C$: at the CB, low spin (0^+-4^+), at $E_x(^{24}Mg) \sim 20$ MeV
  $^{24}Mg+^{24}Mg$: at 2xCB, high spin (36^+-38^+), at $E_x(^{48}Cr) \sim 60$ MeV

- $^{12}C+^{12}C \rightarrow {}^{24}Mg$ case :
  Radiative capture reaction $^{12}C(^{12}C,\gamma)^{24}Mg$, gamma decay through doorway states …

- $^{24}Mg+^{24}Mg \rightarrow {}^{48}Cr$ case :
  Resonances at high excitation energy in the CN, study of the fragment and particle decay channels

The $^{24}Mg+^{24}Mg$ reaction



- Excitation functions → resonant phenomena in collisions
- Origin of the resonances
- Resonances ↔ molecular state in the composite system
- Focus on the $^{24}Mg+^{24}Mg$ resonance

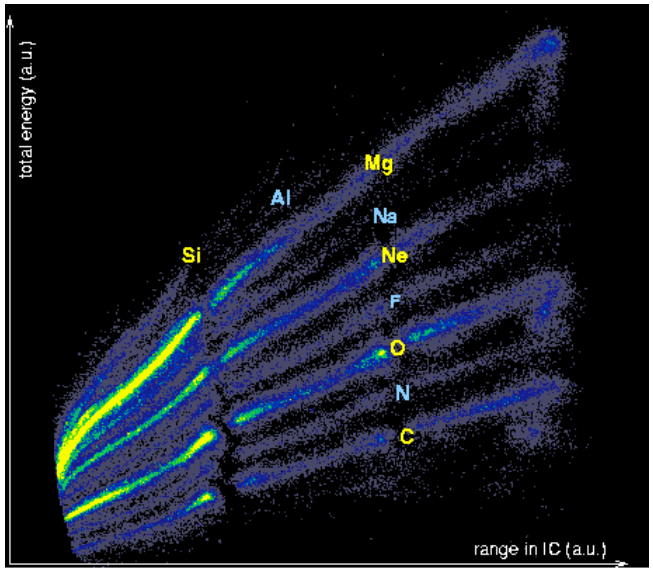
$J^{\pi} = 36^{+}$
E_{CM} = 45,7 MeV
Γ = 170 keV

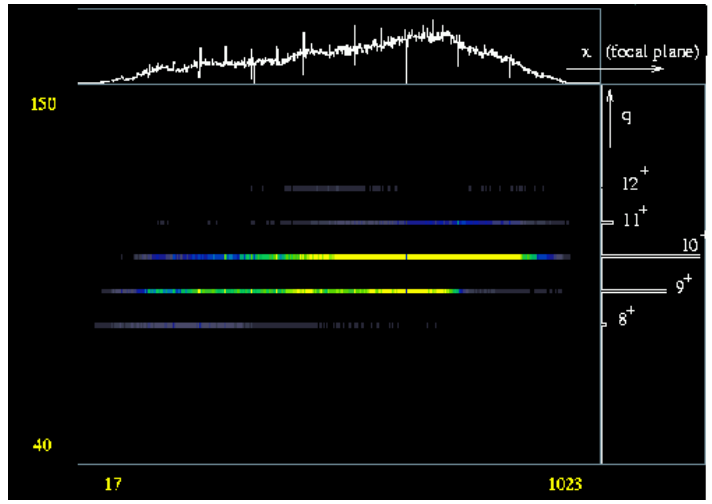
$^{24}Mg+^{24}Mg$ ON and OFF resonance measurements to study the decay into inelastic channels

Reaction $^{24}Mg + ^{24}Mg$

- **Target** : ^{24}Mg – 40 µg.cm^{-2}
- **Beam** : ^{24}Mg at E_L = 91.72 MeV (**ON**) and E_L = 92.62 MeV (**OFF**)
- Inelastic channels
- ^{24}Mg fragments in **PRISMA** ($\theta = 43^\circ \pm 5^\circ$)
- Gamma rays in coincidence in **CLARA**

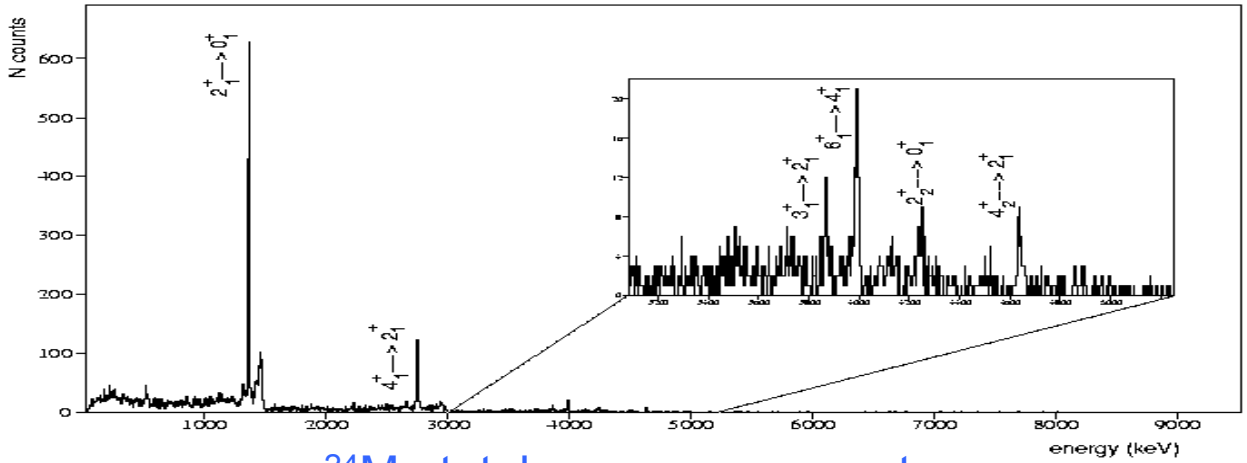
Analysis of the experiment





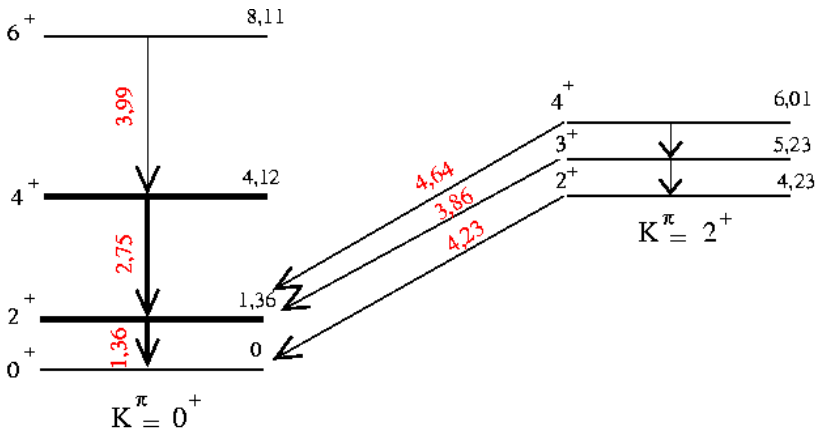
Z selection

q^+ versus X (focal plane)→q^+ selection

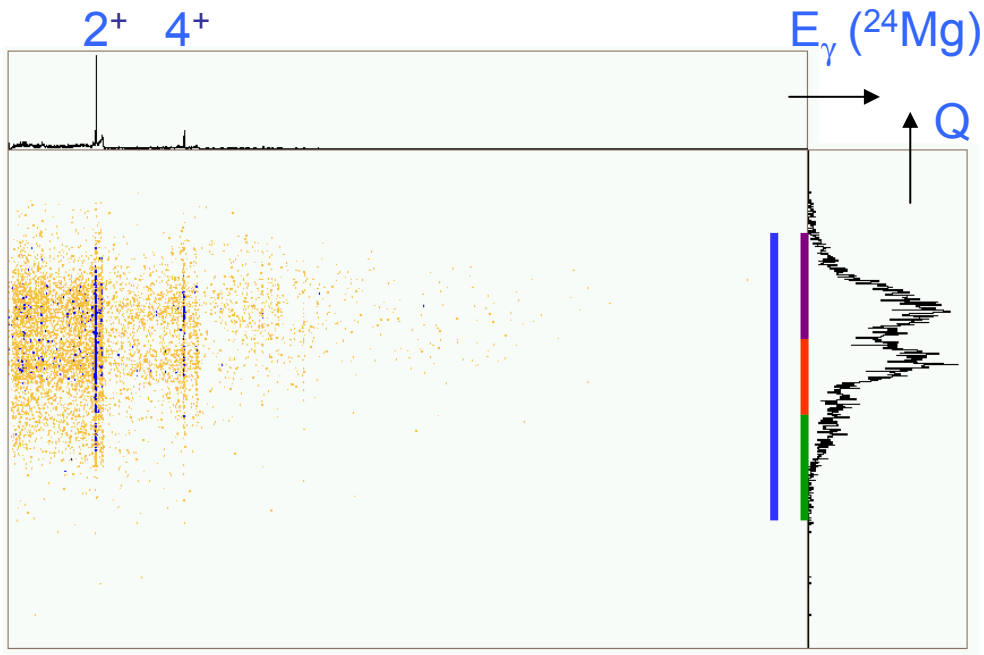


^{24}Mg total gamma ray spectrum

Gamma transitions observed in ^{24}Mg



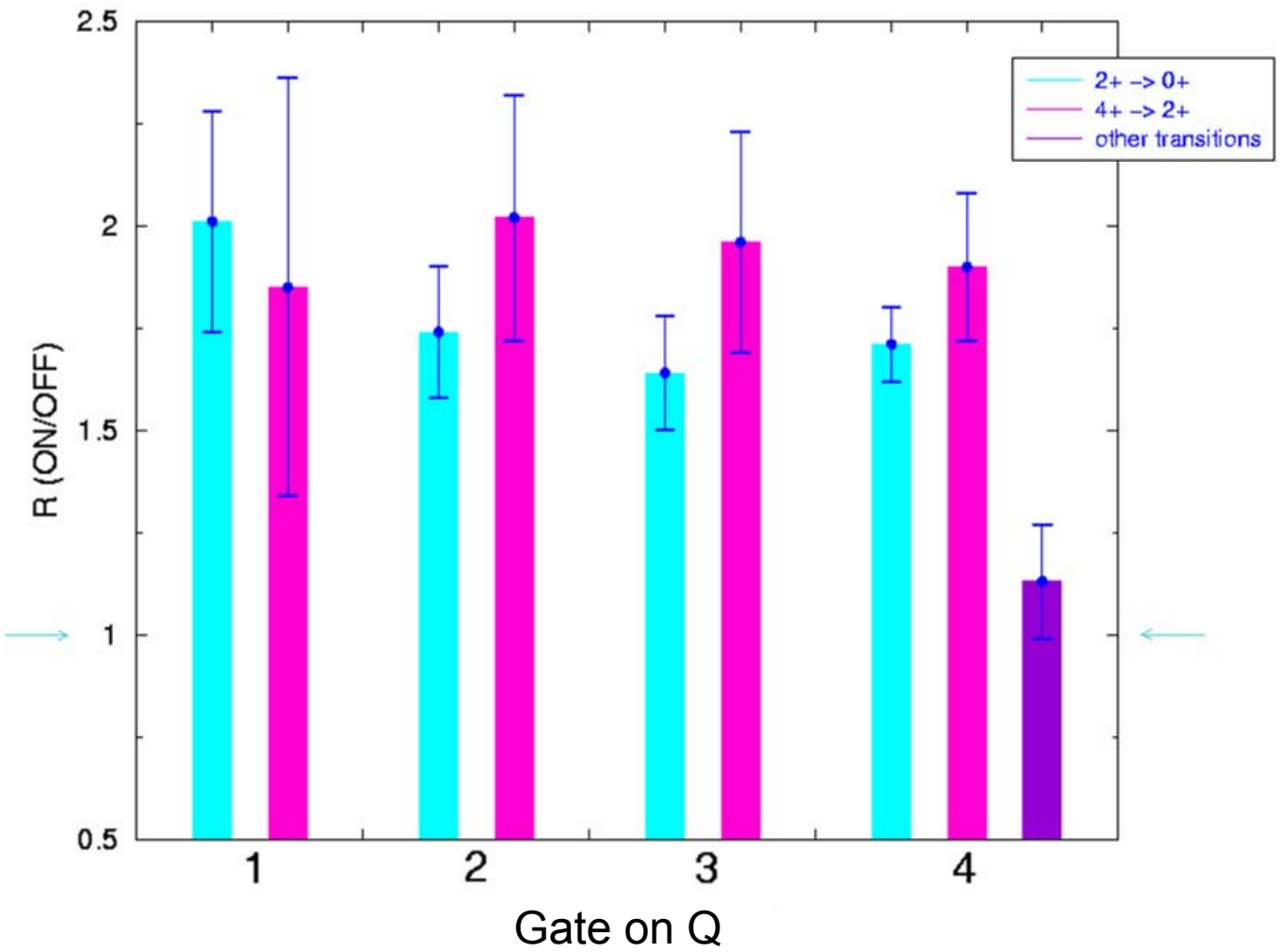
Transitions observed in ^{24}Mg



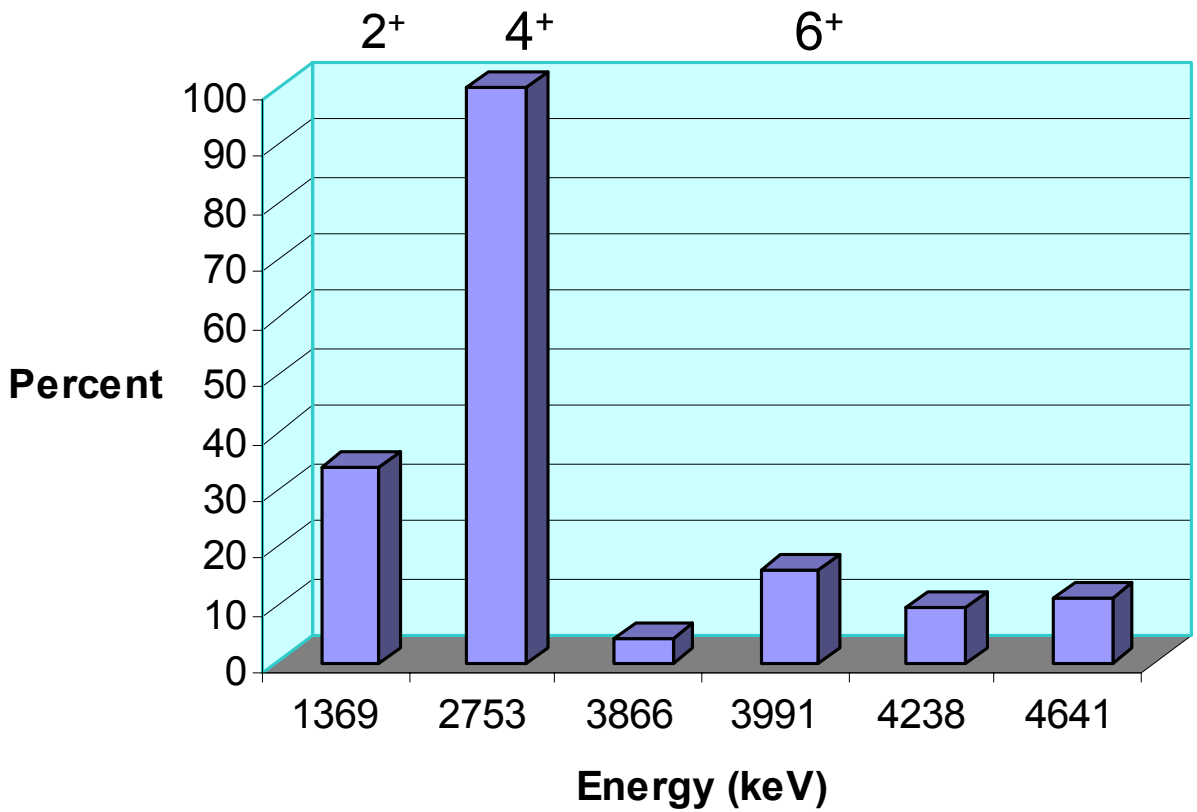
E_γ versus Q

Gate 1	E_{ex} = 1 – 4.6 MeV
Gate 2	E_{ex} = 4.7 – 7.3 MeV
Gate 3	E_{ex} = 7.3 – 11 MeV
Gate 4	E_{ex} = 1 – 11 MeV

Inelastic channel contributions to the resonance



Direct feeding of the ^{24}Mg states

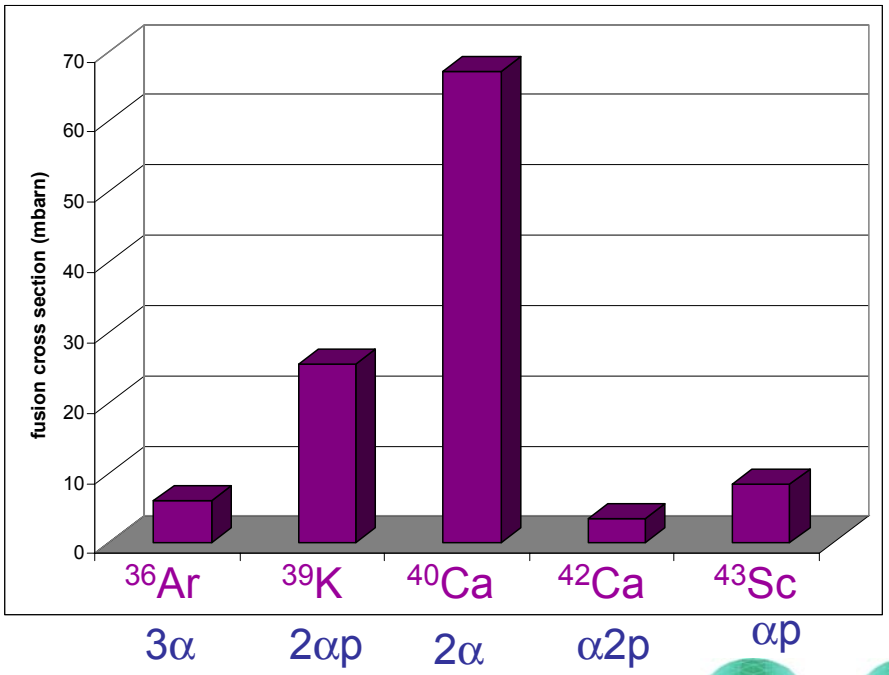


- Resonance is seen in the 2^+, 4^+ g.s band members and also in the 0^+ g.s (from other measurements) .

In the inelastic channels, the ^{24}Mg + ^{24}Mg resonance flux is essentially observed in the 2^+ and 4^+ of the ^{24}Mg g.s band.

- This is in agreement with the molecular model proposed by Abe and Uegaki *(Phys. Lett.231B (1989) 28)* to describe the ^{24}Mg + ^{24}Mg high spin resonances.

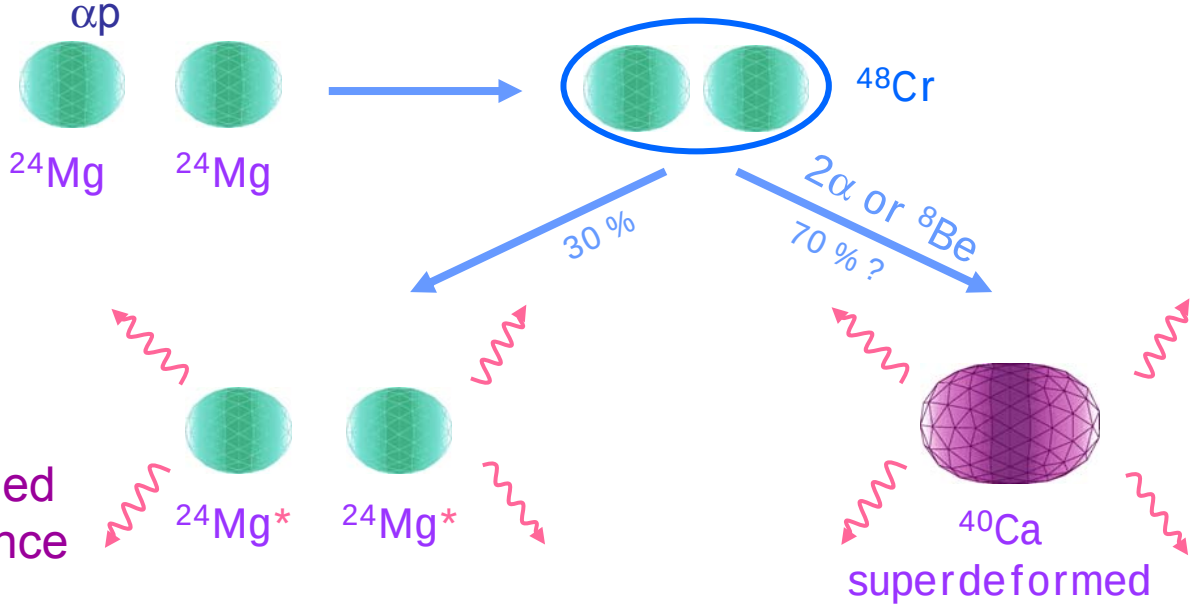
Where is the missing flux ?



→ Cacarizo calculations for J=36

→ The 2α fusion channel is strong

- New experiment: $^{24}Mg(^{24}Mg,2\alpha)^{40}Ca$
  ON and OFF resonant measurements

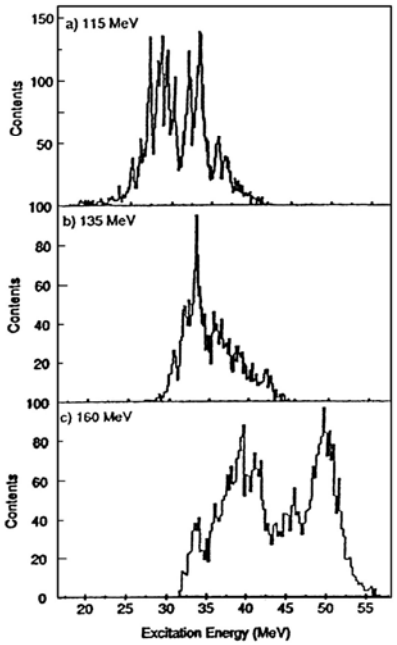


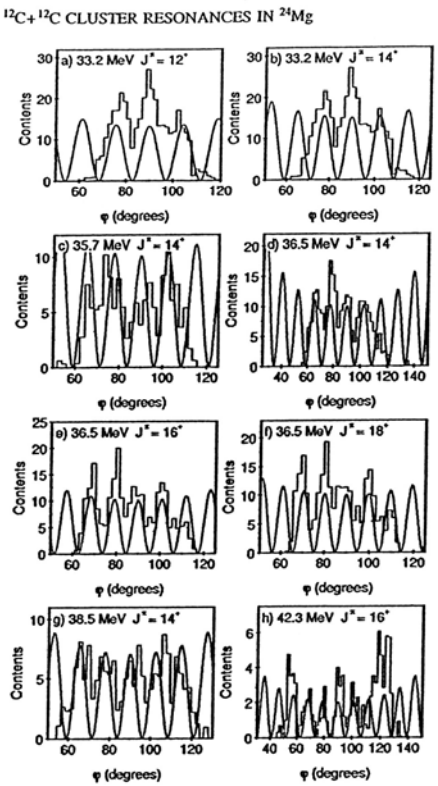
- Link between ^{48}Cr and ^{40}Ca superdeformed states

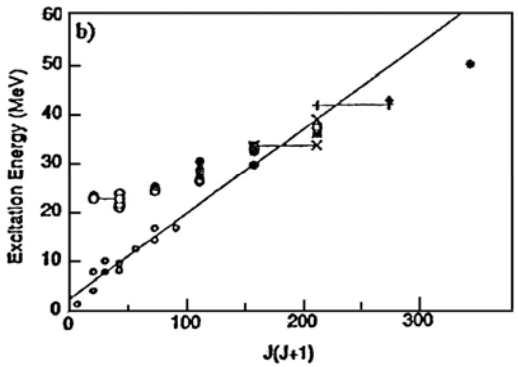
- Molecular state in ^{48}Cr is formed through the $^{24}Mg+^{24}Mg$ resonance

1st experiment : Prisma/Clara

2nd experiment : Gasp/Euclides







- **$^{12}C+^{12}C$ cluster resonances in ^{24}Mg up to E_x = 50 MeV**
  C.J. Metelko et al., Phys.Rev. C68 (2003) 0544321
- **Reaction $^{12}C(^{16}O,^{12}C^{12}C)\alpha$**
- **Dedicated equipment : Position Sensitive Double-Sided Silicon Strip detectors for multiparticle coincidence detection**

The Resonant Radiative Capture Reactions

Radiative capture in light heavy-ion induced reactions:
detailed study for only the $^{12}C+^{12}C$ and $^{12}C+^{16}O$ reactions

The $^{12}C(^{12}C,\gamma)^{24}Mg$ reaction

- Sandorfi et al.: NaI (~ 1980)
  Resonances
  $E\gamma > 18$ MeV

- Jenkins et al., (2000 - 2004)
  Gammasphere (Berkeley) :
  Decay of resonance not statistical
  Feeding of $K^{\pi} = 2^{+}$ band
  Feeding of states 10 MeV (^{24}Mg shape isomers with ^{12}C-^{12}C structure ?)

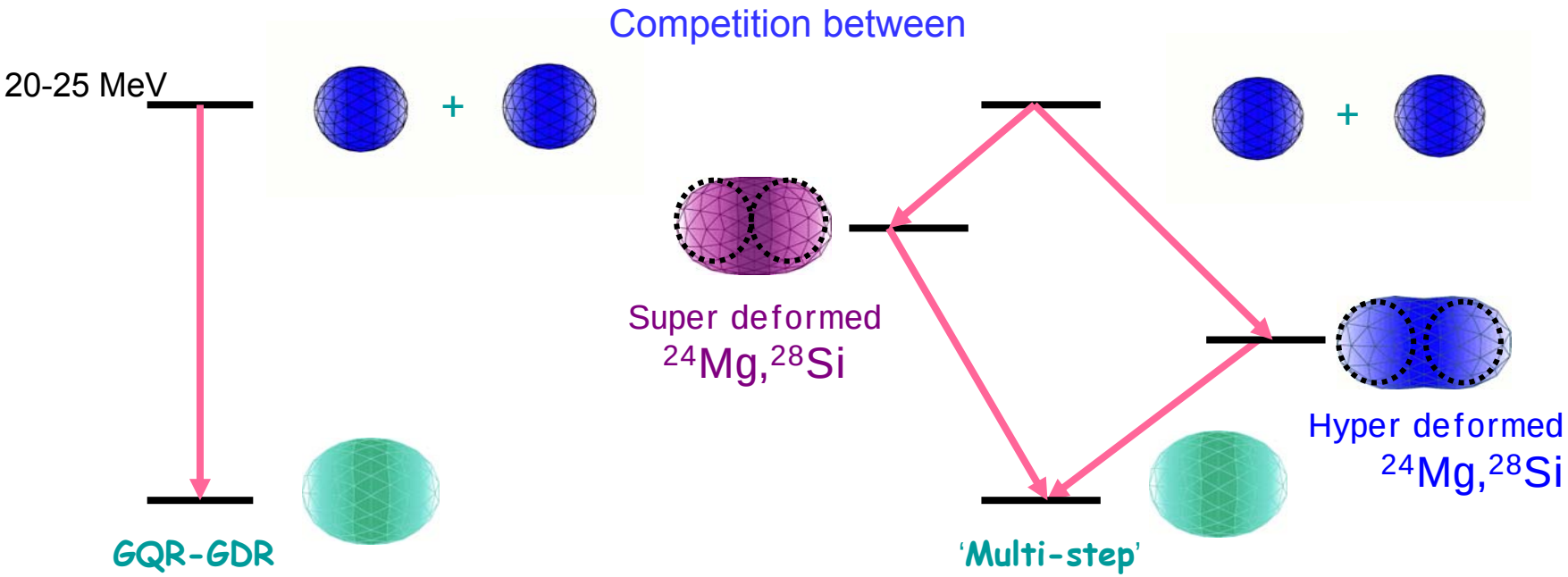
  FMA (Argonne) :
  Due to new decay channels : larger radiative capture cross-sections

a breakthrough !

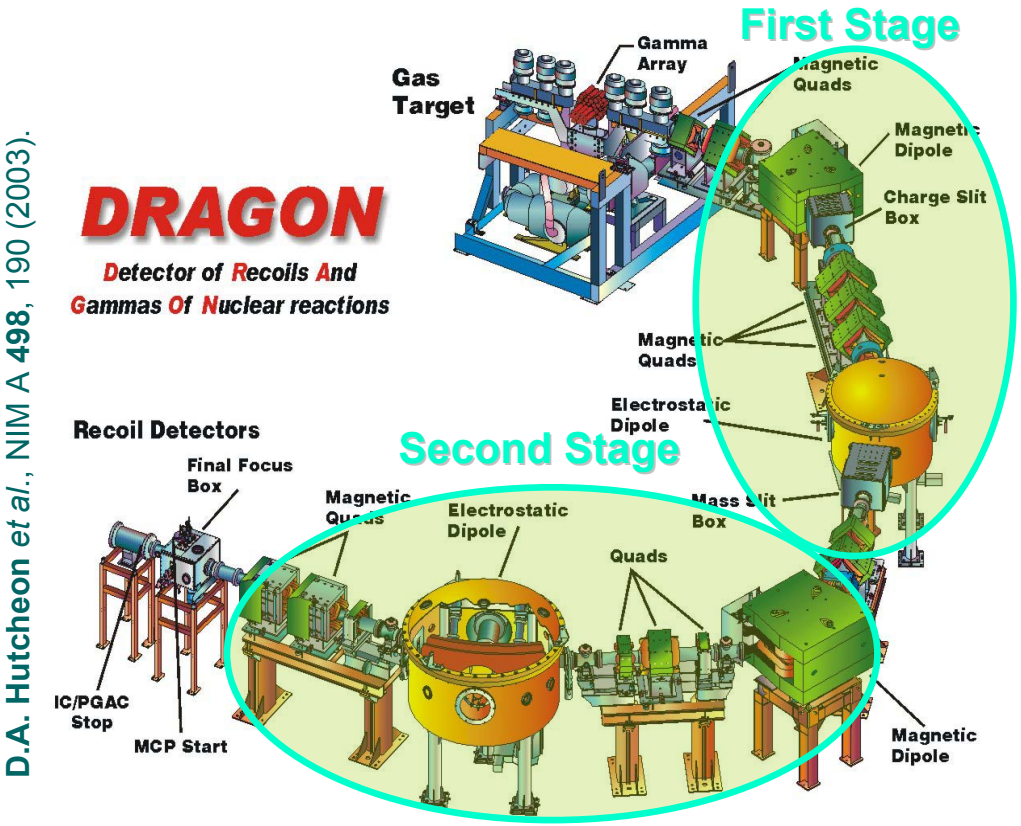
$^{12}C+^{12}C$ and $^{12}C+^{16}O$ experimental studies

$^{12}C+^{12}C$(12.0, 13.4, 16.0 MeV ON-resonance) at DRAGON (Triumf, D.G. Jenkins et al., March 2004)
$^{12}C+^{16}O$(20.7 MeV ON-resonance) at DRAGON (Triumf, S. Courtin et al., August 2005)

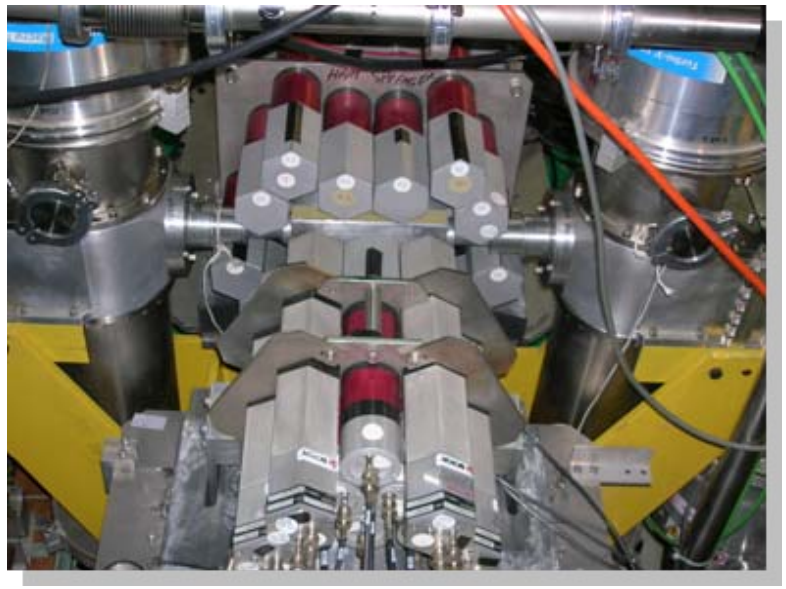
Solid enriched ^{12}C targets (40 μg/cm^2)
Energies ON/OFF resonance
DRAGON + BGO array
What is the decay of the resonances ?
Is there a multistep decay feeding doorway cluster ^{24}Mg,^{28}Si states ?



$^{12}C+^{12}C$ and $^{12}C+^{16}O$ experimental studies



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

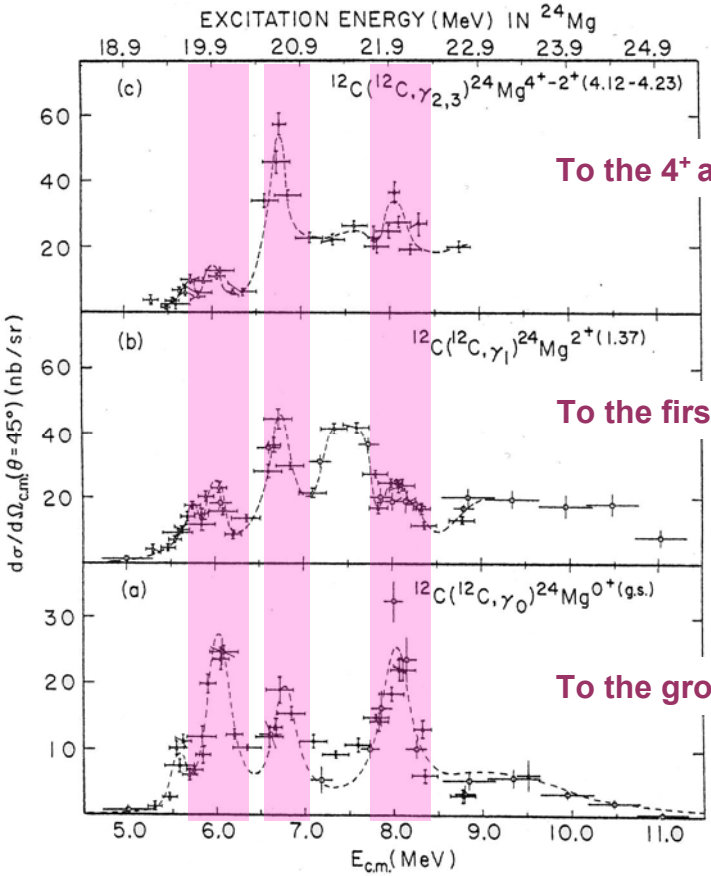


- ISAC I : RNBs / Stable (OLIS)
- 0° spectrometer
- Tof on 17 m
- Beam rejection 10^{13}
- Acceptance : cone ½ angle 20 mrad

- gas/solid target system
- recoil detectors (DSSSD, …)
- BGO array (ε = 50 % @ 5 MeV)

$^{12}C+^{12}C$ and $^{12}C+^{16}O$ experimental studies

$^{12}C(^{12}C,\gamma)^{24}Mg$

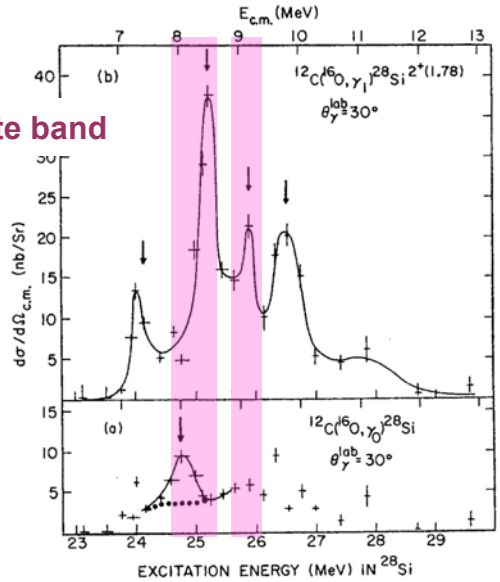


To the 4$^+$ and 2nd 2$^+$

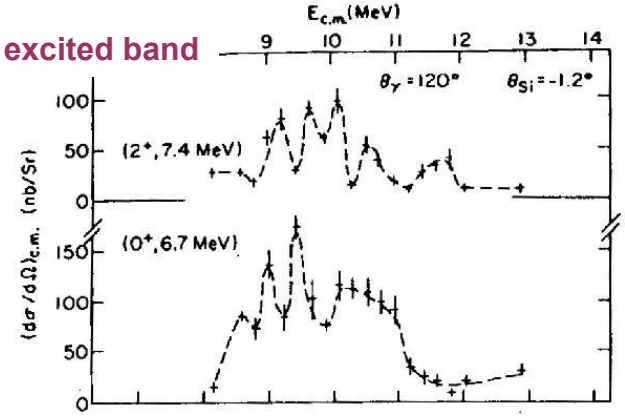
To the first 2$^+$

To the ground state

$^{12}C(^{16}O,\gamma)^{28}Si$



To the ground state band

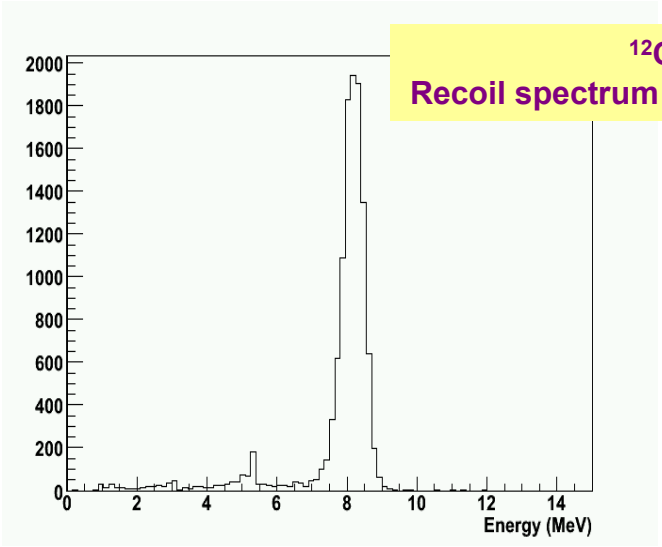


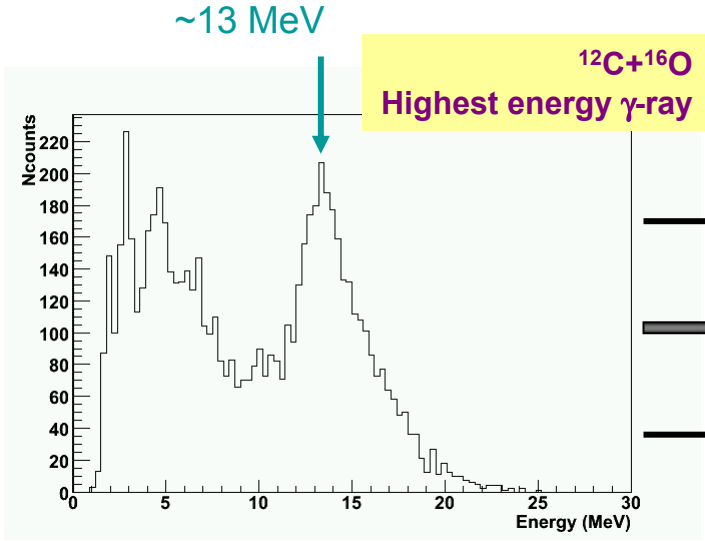
To the prolate excited band

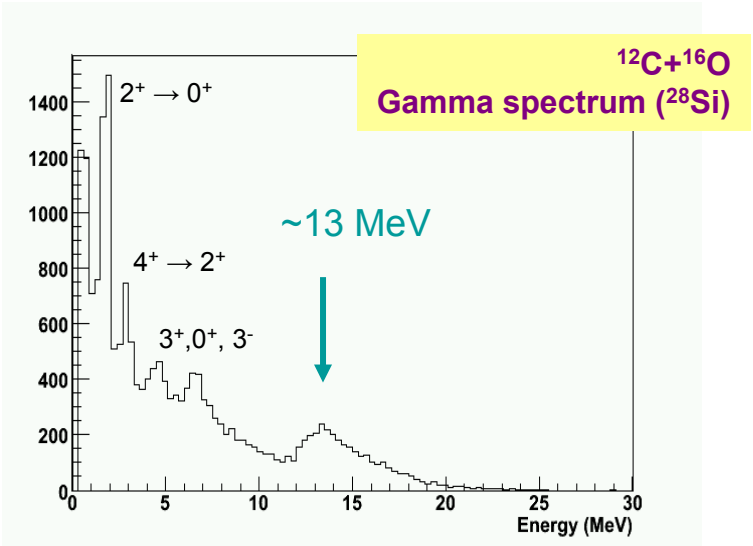
A.M. Sandorfi, in Treatise on Heavy-Ion Science, D.A. Bromley, Vol II, sec. 3.

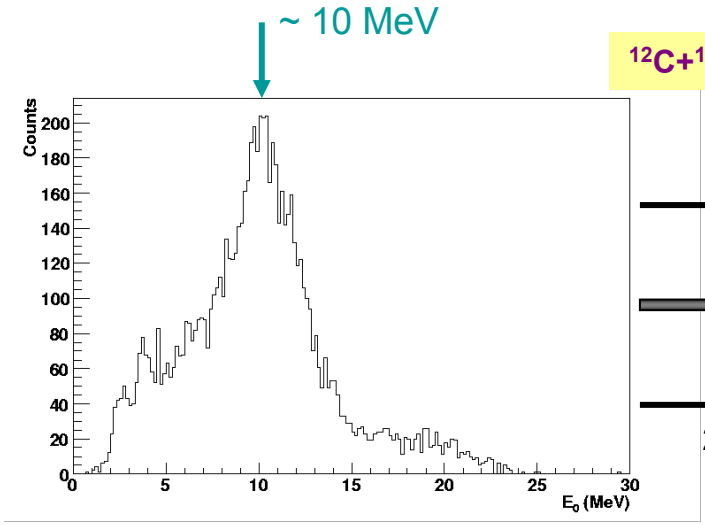
M.T. Collins, A.M. Sandorfi and D.H. Hoffmann, Phys.Rev. Lett. 49 (1982), 1553 / A.M. Nathan, A.M. Sandorfi and T.J. Bowles, Phys.Rev. C24 (1981) 931.

$^{12}C+^{16}O$ and $^{12}C+^{12}C$, results of the Dragon experiment









Conclusions, future plans

Multistep decay of resonances dominant for both systems
^{24}Mg(^{12}C-^{12}C), states around 10 MeV, (α+^{20}Ne threshold = 9.32 MeV)
^{28}Si(^{12}C-^{16}O), states around 13 MeV, (α+^{24}Mg threshold = 9.99 MeV)

What are those states ? There are candidates in the litterature, i.e. **unbound low spin states with $\Gamma_\gamma/\Gamma \sim 1$**
Simulations of different scenarii under progress

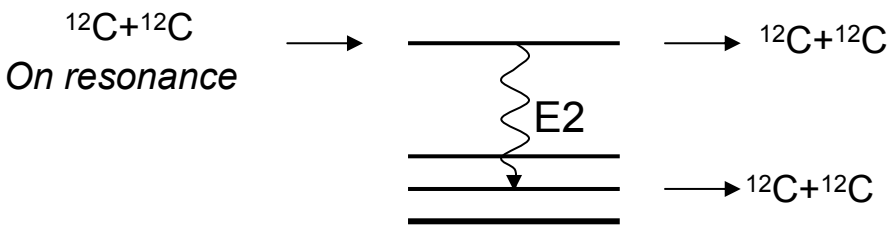
A definitive answer concerning the identification of the doorway states
An experiment accepted at ANL (FMA + Gammasphere)
1 system (^{12}C+^{12}C) at 1 energy (6 MeV resonance)

It would be nice to have a new spectrometer with a higher acceptance than Dragon and a γ-array with high efficiency and a resolution of ~1-2 % (array of $LaBr_3$(Ce))

We are on the way to clearly identify EM transitions between molecular resonance states and cluster states !

What about γ–rays between cluster states ?

- Resonant Structures ↔ Molecular States



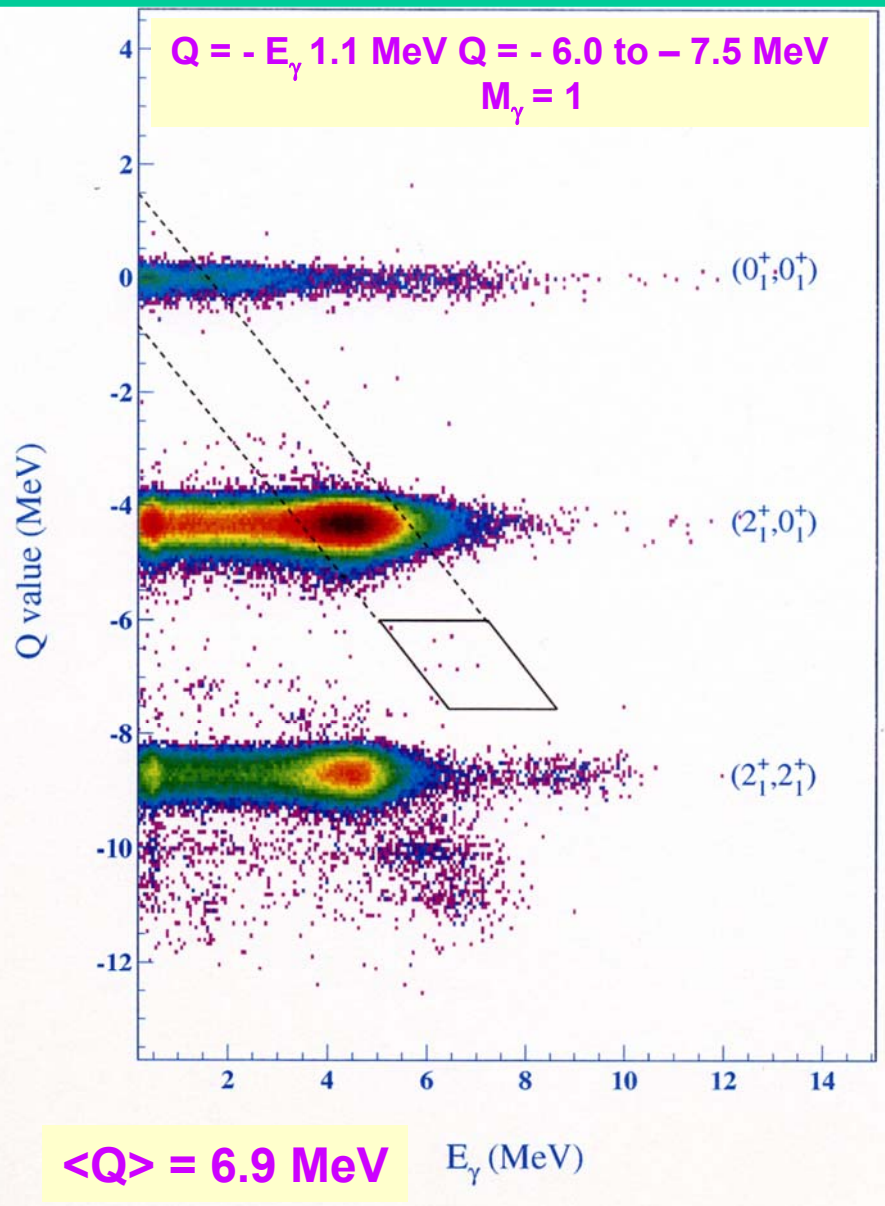
- Strasbourg-York (Haas et al.) Orsay Tandem
  E_{CM} = 16.45 MeV, 10^+ resonance,
  $E_X(^{24}Mg)$ = 30.5 MeV

Château de Cristal + PSSD

γ-rays from 10^+ to 8^+ resonant states

$\Gamma_\gamma / \Gamma = (1.2 \pm 0.4)\times10^{-5}$

What about $^{24}Mg+^{24}Mg$, $^{28}Si+^{28}Si$?



<Q> = 6.9 MeV

Thanks !

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