Decay Modes of Narrow Molecular Resonances

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1. Resonances in light heavy-ion collisions

2. Resonant Radiactive Capture
Reactions for $^{12}\text{C}^{+^{12}\text{C}}$ and $^{12}\text{C}^{+^{16}\text{O}}$

3. Results
Resonances in light heavy-ions

Known for more than 30 years

Resonances? molecular states?
narrow resonances

Decay modes

$^{24}\text{Mg}^{+^{24}}\text{Mg}, \Gamma \sim 150 \text{ keV}, E_B = 2 \times CB$, high spin (36$^+$)

$^{12}\text{C}^{+^{12}}\text{C}, \Gamma = 150 \text{ keV}, E_B \sim CB$, low spin (0-4)
$^{12}\text{C}^{+^{16}}\text{O}, \Gamma = 150 \text{ keV}, E_B \sim CB$, low spin (0-4)

Fragment and particle decay
$\gamma$ decay
Radiative Capture and Heavy-Ions

Nuclear Astrophysics, light particles
Inverse kinematics

Heavy Ions, a few systems only ...

- Pioneering study at GSI (J.G. Keller, K.H. Schmidt et al. PRC 29, 1569 (1984))
  $^{90}\text{Zr}(358 \text{ MeV})+^{90}\text{Zr} \rightarrow ^{180}\text{Hg} + x\gamma$ \( \sigma = 40 \text{ pb} \)
- Recently at Argonne (F. Camera et al., PLB 560, 155 (2003))
  $^{89}\text{Y}(352 \text{ MeV})+^{90}\text{Zr} \rightarrow ^{179}\text{Au} + x\gamma$

- Light heavy-ions : $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{24}\text{Mg} + \gamma$
  Sandorfi et al. (Brookhaven) : NaI (~ 1980)
  Resonances
  $E\gamma > 18 \text{ MeV}$, deexcitation to the low-lying states of $^{24}\text{Mg}$
  \textbf{Similar results for} $^{12}\text{C} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + \gamma (1981)$
Radiative Capture and light Heavy-Ions / Decay Studies

\(^{12}\text{C}+^{12}\text{C}\) and \(^{12}\text{C}+^{16}\text{O}\)

\textbf{Jenkins et al.} \(^{12}\text{C}^{(12}\text{C};\gamma)^{24}\text{Mg}\), more recently:

- Gammasphere (Berkeley) as a calorimeter:
  - Decay of resonances not statistical, feeding of \(K^\pi = 2^+\) band
  - Feeding of states ~ 10 MeV \((^{24}\text{Mg} \text{ shape isomers with }^{12}\text{C}-^{12}\text{C} \text{ structure ?})\)

- FMA (Argonne) no \(\gamma\) detection:
  - Due to new decay channels: larger radiative capture cross-sections

\textit{D.G. Jenkins et al., PRC 71, 041301(R)(2005)}

\textbf{What is the structure of those states?}

- Model predictions of \(^{16}\text{O}+^{12}\text{C}\) cluster bands in \(^{28}\text{Si}\) from

- Predictions for \(^{12}\text{C}+^{12}\text{C}\)
  \textit{P. Descouvemont and D. Baye, Phys.Lett. 169 B (1986) 143}

\textbf{Links between low-lying members of these cluster bands?}
$^{12}\text{C} + ^{12}\text{C}$ and $^{12}\text{C} + ^{16}\text{O}$ experimental studies

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

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

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

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

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

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

20-25 MeV

GDR

Super deformed $^{24}\text{Mg},^{28}\text{Si}$

Hyper deformed $^{24}\text{Mg},^{28}\text{Si}$

Competition between

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

- ISAC I: RNBs / Stable (OLIS)
- $0^\circ$ spectrometer
- Tof on 17 m
- Beam rejection $10^{13}$
- Acceptance: cone $\frac{1}{2}$ angle 20 mrad
- gas/solid target system
- recoil detectors (DSSSD, ...)
- BGO array ($\varepsilon = 50\%$ @ 5 MeV)

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

$^{12}\text{C} + ^{16}\text{O}$
- Recoil spectrum ($^{28}\text{Si}$)
- Highest energy $\gamma$-ray
- $\sim 13$ MeV
- $26$ MeV
- $\sim 13$ MeV
- $0$ MeV
- $^{28}\text{Si}$
- $20$ MeV
- $\sim 10$ MeV
- $0$ MeV

$^{12}\text{C} + ^{12}\text{C}$
- $2^{+} \sim 0^{+}$
- $4^{+} \sim 2^{+}$
- $3^{+}, 0^{+}, 3$
- $\sim 13$ MeV

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Monte-Carlo simulations, $^{12}\text{C} + ^{12}\text{C}$

GEANT 3 simulations of the $^{12}\text{C} + ^{12}\text{C}$ reaction as a first step

Branching ratio ?

GEANT 3 results: Angular distributions

- Branching ratio
- $^{24}\text{Mg}$: 0 MeV, $^0\text{Mg}$
- $^{24}\text{Mg}$: 10 MeV, $^2\text{Mg}$
- $^{24}\text{Mg}$: 20 MeV, $^2\text{Mg}$

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Conclusions, future plans

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

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

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

It would be nice to have a new spectrometer with a higher acceptance than Dragon and a $\gamma$-array with high efficiency and a resolution of $\sim 1-2$ % (array of LaBr$_3$(Ce))

We are on the way to clearly identify EM transitions between cluster states!
Thanks!

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