Search for electromagnetic transitions between molecular states: results from the radiative capture channel

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Abstract. This paper discusses the characterization of the cluster nature of resonances in $^{12}$C+$^{12}$C and $^{12}$C+$^{16}$O by measuring their $\gamma$ decay. Results from resonant radiative capture measurements in these systems are presented. Spin attributions as well as specificities of the decay pattern are described. For the $^{12}$C+$^{12}$C system, identification of $\gamma$ transitions within the molecular band are discussed as well as a new method to measure the eventual persistence of the resonant behaviour down to astrophysical energies.

1. Introduction
Resonances are well established phenomena in light heavy-ion collisions. They have been observed in the collisions of identical bosons like $^{12}$C+$^{12}$C, $^{14}$C+$^{14}$C, $^{16}$O+$^{16}$O, $^{24}$Mg+$^{24}$Mg and $^{28}$Si+$^{28}$Si and also in some asymmetric systems like $^{12}$C+$^{16}$O, at energies ranging from the Coulomb barrier to a few MeV per nucleon. They have been shown to be related to the number of open channels in the reaction [1] and in some cases been interpreted as the result of molecular configurations of the compound system. Despite the wealth of experimental data and theoretical descriptions, the clear origin of these resonances is still a debated question. From an experimental point of view, clustering can be related to properties of the deformed compound system or specificities of its decay and fragmentation. In this contribution, we will focus on the simple assumption that if resonances are associated with molecular, very deformed configurations, they should show hints of deformation in their electromagnetic decay. In that sense, cluster states could be grouped into bands with large moment of inertia and connected by very collective transitions. In this paper, we will focus on heavy-ion systems where the resonances are the most pronounced, i.e. $^{12}$C+$^{12}$C and, to a lesser extent $^{12}$C+$^{16}$O, and discuss the experimental study of the electromagnetic decay of resonances of possible molecular nature.

- For lower spin members of the molecular bands in these systems (0$^+$ to 6$^+$), radiative capture experiments will be described;
- For higher spin members of the molecular band (8$^+$ - 10$^+$), perspectives to measure the $\gamma$ transitions between molecular states will be presented;

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As future perspectives, projects to measure deep sub-barrier fusion cross-section in the $^{12}\text{C}+^{12}\text{C}$ system, towards astrophysical energies will be briefly discussed.

2. Clusters in $^{12}\text{C}+^{12}\text{C}$ and $^{12}\text{C}+^{16}\text{O}$: results from the radiative capture experiments

The $^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg}$ and $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$ radiative capture reactions have been performed at the Triumf laboratory (Vancouver) using the Dragon spectrometer and the associated BGO $\gamma$ array [2, 3, 4], on resonances previously observed by Sandorfi et al. in the 80’s in radiative capture experiments [5]. In these pioneering experiments, excitation functions were measured using a single large NaI $\gamma$-detector. Due to the piling-up of low energy $\gamma$-rays coming from the much more intense fusion-evaporation channels, the detection was limited to high energy $\gamma$-rays feeding low-lying states in $^{24}\text{Mg}$ and $^{28}\text{Si}$ with excitation energies less than $\sim 4.5$ MeV. The measured capture cross sections to the first members of the g.s. bands show a series of resonances in both cases. After this radiative capture campaign, Sandorfi et al. improved their experimental set-up by using a Wien filter at $\sim 3^\circ$ for the $^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}$ reaction to select the compound nucleus. They could thus measure the feeding of states up to $\sim 9.5$ MeV and found, in particular a first indication of the feeding of intermediate states at $\sim 7$ MeV in $^{28}\text{Si}$ from a direct $\gamma$ transition from the resonance.

![Radiative capture spectra](Image)

**Figure 1.** Radiative capture spectra of the highest energy gamma-ray detected together with numerical simulations for different resonances characteristics.
Our experimental campaigns at Triumf have been performed at energies around and below the Coulomb barrier for both $^{12}$C+$^{12}$C and $^{12}$C+$^{16}$O systems, where resonances have been found to be narrow ($\Gamma \sim 200 \text{ KeV}$) and where the number of open channels is rather small.

The Dragon spectrometer was used to select the compound nuclei at $0^\circ$ with an incident beam rejection factor as good as $10^{12}$. This type of heavy-ion radiative capture experiments is a real tour de force since the process is dominated by fusion-evaporation which is 5 orders of magnitude more important than the radiative capture channel. The coincident $\gamma$-rays were detected in an array of 30 BGO scintillators arranged in a compact configuration. This has allowed to measure the complete $\gamma$ decay scheme from the resonances and the relative decay strengths of all branches in both cases. Surprisingly enough, for both systems, the feeding of intermediate doorway states has been identified around $E_{\gamma} = 10$ and $11$ MeV for $^{12}$C+$^{12}$C and $^{12}$C+$^{16}$O respectively. Monte Carlo GEANT calculations have been performed to simulate the response function of the experimental setup to different entrance channel conditions, i.e. energy and spin of the resonance. Details of these simulations can be found in [3, 4] and we will recall the main steps here. The acceptance of the spectrometer and its transmission is indeed depending on the $\gamma$ decay path. The complete detection setup has been described in a GEANT code. Properties of the recoiling nuclei have been taken into account such as their mass, recoiling energy and known level scheme, i.e. the full decay path and angular distribution of $E_0$. The complete geometry of the DRAGON spectrometer as well as its optical elements and the BGO detectors have been taken into account in the calculated spectra. Total number of counts in the simulated $\gamma$ spectra have been normalized to the total number of counts in the experimental spectra. Our experimental spectra were subsequently compared with simulated ones with different entrance-channel conditions (spins) to infer on the spin of the resonance and the feeding of specific states of the compound nucleus.

- For the $^{12}$C+$^{12}$C experiment, five energies have been used: four on resonance at $E_{c.m.}=6.0$, 6.8, 7.5 and 8 MeV, and one off resonance at 6.4 MeV. For the first time in the study of the capture process, the relative strength of all the decay branches could be extracted. We found an important new decay branch to $^{24}$Mg states just above the $\alpha$-threshold (9.3 MeV) which represents $\sim 50\%$ of the total $\gamma$ decay width. We were able to assign spin $0^+$ and $2^+$ for the resonances at 6.0 and 6.8 MeV and spin $4^+$ or $2^+$ would be compatible with our data for the resonances at 7.5 and at 8 MeV (see Figure 1). Enhanced feeding of deformed prolate states in $^{24}$Mg directly from the resonance was found for the three highest explored energy. At $E_{c.m.}=6.0$ MeV, namely at the Coulomb barrier, surprisingly enhanced feeding of $1^+ \ T=1$ state around 11 MeV directly from the entrance resonant state was identified. Our results are summarized in Table 1.

| Energy (MeV) | 8.0 | 7.5 | 6.8 | 6 |
|-------------|-----|-----|-----|---|
| Spin/parity | 4$^+$.2$^+$ | 4$^+$.2$^+$ | 0$^+$.2$^+$ | 2$^+$ |
| Observations | Feeding of deformed states | Enhanced feeding of 1$^+$ T = 1 |

- For the $^{12}$C+$^{16}$O experiments, five energies have been used: four on resonance at $E_{c.m.}=6.6$, 7.2, 8.5 and 9 MeV and one off resonance at 8.8 MeV. Experimental procedure and analysis is similar as for the $^{12}$C+$^{12}$C system. Our spin attributions are the following : above the
**Figure 2.** Reaction \( ^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si}, E_{\text{c.m.}} = 6.6 \text{ MeV} \): highest energy \( \gamma \)-ray spectrum compared with numerical simulations for a \( 2^+ \) entrance resonance and enhanced feeding of \( J^\pi = 1^+, T = 1 \) states around 11 MeV in \( ^{28}\text{Si} \) (dashed blue). In the region below 8 MeV, some of the lines may come from the fusion-evaporation reaction leading to \( ^{28}\text{Si} \) and produced from a possible \( ^{13}\text{C} \) contamination of the target.

Coulomb barrier (\( E_{\text{c.m.}} = 7.2, 8.5 \) and 9 MeV), spins \( 6^+ \) and \( 5^- \) are found, in agreement with previous fusion data [6] and below the barrier, a spin \( 2^+ \) is found for the resonance. Enhanced feeding of deformed states such at the \( 3^- \) state at at 6.88 MeV, from the resonance. This state is the bandhead of the \( K^\pi = 3^- \) \( ^{28}\text{Si} \) octupole band which mainly decays to the g.s. with a strong E3 transition. At the lowest explored energy, we have also observed the enhanced feeding of \( 1^+ T = 1 \). The B(M1) values extracted from our experimental data for the transition from the resonance to the \( T = 1 \) states are around 1.25 W.u., among the strongest measured in this mass region [7]. Fig. 2 shows the highest energy \( \gamma \)-ray spectrum compared with numerical simulations for a \( 2^+ \) entrance resonance and enhanced feeding of \( J^\pi = 1^+, T = 1 \) states. Experimental results are summarized in Table 2.

**Table 2.** Radiative capture experimental campaign. Summary of the results for \( ^{12}\text{C}+^{16}\text{O} \).

| Energy (MeV) | 9.0 | 8.8 | 8.5 | 6.6 |
|-------------|-----|-----|-----|-----|
| Spin/parity | \( 6^+ \) | \( 5^- \) | \( 5^-6^+ \) | \( 2^+ \) |
| Observations | Feeding of deformed states | Enhanced feeding of \( 1^+ T = 1 \) | Agreement with fusion data | B(M1) \( \sim \) 1.25 W.u. |

The \( ^{12}\text{C}(^{16}\text{O},\gamma)^{28}\text{Si} \) reaction has been performed in the past at higher energies, to study the isospin mixing in the \( ^{28}\text{Si} \) excitation energy region around 35 MeV. The reaction mechanism
was discussed in terms of populating the giant dipole resonance (GDR) built on excited states [11]. It might be that in our studies, the giant quadrupole resonance (GQR) is excited, built on the $^{24}$Mg prolate ground state for $^{12}$C+$^{12}$C [12] and on the prolate excited band in the case of $^{12}$C+$^{16}$O.

Both experimental campaigns described in this paper used the Triumf BGO array for the measurement of the resonance decay. This allowed high efficiency measurements. The radiative capture studies in these two systems would greatly benefit from better resolution experiments to unambiguously identify the resonance decay scenarios, i.e. the specific states fed and single spins of the resonances. This could be achieved with the use of new generation γ detector arrays based on scintillators such as LaBr$_3$. Such a project, called PARIS [13] has started some years ago and we plan to study radiative capture in the $^{12}$C+$^{12}$C and $^{12}$C+$^{16}$O systems using this array in the coming years.

3. Clusters in $^{12}$C+$^{12}$C : transitions between molecular resonances and future investigations at very low energies

The "smoking gun" in favour of the existence of $^{12}$C-$^{12}$C cluster configurations in $^{24}$Mg would certainly be the measurement of electromagnetic transitions between the resonances. This has recently been reported by Datar et al. for a transition from $4^+$ to $2^+$ resonances in the light $^8$Be cluster nucleus in the radiative capture experiment $^4$He+$^4$He [14]. This kind of signature is essentially missing for heavier clusters like $^{12}$C-$^{12}$C. To our knowledge, there is only one pioneering study which was reported by F. Haas et al. for $^{12}$C+$^{12}$C. They reported the measurement of a handful of events for the gamma transition between the $10^+$ and $8^+$ resonant cluster state in $^{24}$Mg using the Château de Cristal scintillator array for γ detection and two position sensitive detectors for fragment detection installed at the Orsay Tandem (France) [15]. Advances in detector technologies for particle and fragment detection as well as for γ detection with significantly better resolution and efficiency at high energy, will allow to study the γ emission between cluster resonances and should provide unique experimental validations of the cluster models. In that sense, the PARIS calorimeter [13] could be used for γ detection and could be associated to a good coverage fragment detection system.

The $^{12}$C+$^{12}$C reaction is known to be of major importance in the C burning during late stages of the evolution of massive stars. Low energy resonances in the $^{12}$C+$^{12}$C system have thus received large experimental attention. Methods used to measure the low energy $^{12}$C+$^{12}$C fusion cross sections were based on the detection of α or protons from the $^{20}$Ne+$\alpha$ and $^{23}$Na+p exit channels [16, 17, 18] or the detection of γ-rays of the residues [19, 20]. More recently a rather strong resonance was reported at $E_{c.m.} = 2.14$ MeV by T. Spillane et al. [21] close to the upper border of the Gamow window ($E_{\text{Gamow}} = 1.5$ MeV at $T = 10^7$ K). All these low energy fusion experiments suffer from large backgrounds from hydrogen or deuterium contaminations of the target, proton and deuteron recoil particles. This can lead to deviations among the different experimental results. Recently, a new method was proposed by C. L. Jiang et al. to use a particle-γ coincidence technique to reduce the background. First promising results have been obtained using the Gammasphere array at Argonne for γ detection and 3 double sided silicon strip detectors covering $\sim 20\%$ of $4\pi$ [22]. This new technique is certainly very interesting to future determine if the cluster resonances persist in the astrophysical energy region, which could have important consequences on the carbon burning in stars.
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