Experimental Study of Nuclear Molecular States

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Abstract. Resonance phenomena in light heavy-ion collisions are experimentally well established and their observation can be understood in terms of the number of open reaction channels. In the cases of $^{12}C+^{12}C \rightarrow ^{24}Mg$, $^{12}C+^{16}O \rightarrow ^{28}Si$ and $^{24}Mg+^{24}Mg \rightarrow ^{48}Cr$, similar and strikingly narrow resonances have been observed. New results or proposed experiments on the γ, fragment and particle decays of these resonances are presented.

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RESONANCES IN LIGHT HEAVY-ION COLLISIONS

The observation of resonances in light heavy-ion collisions is a well established experimental fact. Such phenomena have been seen for composite systems with masses less than 60 and, in the case of identical boson systems for example, in the reactions $^{12}C+^{12}C$, $^{14}C+^{14}C$, $^{16}O+^{16}O$, $^{24}Mg+^{24}Mg$ and $^{28}Si+^{28}Si$. The selective occurrence of resonances can be explained by phase space arguments. This is shown on Fig.1a. [1] where for a variety of light heavy-ion collisions, the number of open channels (NOC) is represented as a function of the grazing angular momentum (L_g). Strong resonance effects have been observed in systems where NOC is small, such systems involve the α-like nuclei ^{12}C and ^{16}O but also the non α-like nucleus ^{14}C which has a closed neutron shell, a semi-closed proton shell, a first excited state above 6 MeV and behaves, what NOC is concerned, almost like ^{16}O. Another remarkable feature seen in Fig.1 is the very small value of NOC for $^{12}C+^{12}C$ over a large range of L_g, i.e., a large range of bombarding energies. This explains why the resonance phenomena have always been strongest in $^{12}C+^{12}C$. In Fig.1b. are also shown a few examples of resonant excitation functions [1] measured for certain integrated direct reaction channels of the indicated systems. The structures are more or less pronounced depending on the system and in particular on NOC.

In the case of $^{12}C+^{12}C$, $^{12}C+^{16}O$ and $^{16}O+^{16}O$ where strong resonance structures have been seen from the Coulomb Barrier (CB) to ~ 5 MeV par nucleon, experiments have been performed at higher energies to study the evolution of these structures. For the $^{12}C+^{12}C$ reaction, the results are reported in Fig.2a. In the case of the 90° elastic scattering [2] it is seen that above 5-6 MeV per nucleon, the narrow structures become large structures which in other words means that the resonant effects become refractive effects. The deep minimum observed at E_{lab} = 102.1 MeV corresponds to the second Airy minimum while the first is predicted by the optical model calculations to occur at E_{lab} = 132 MeV. The near-side, far-side decompositions of the elastic scattering angular distributions (Fig.2.b.) at the two Airy minima energies show clearly the importance of the refractive far-side amplitudes [3-6]. If confirmed by future experiments, a first Airy minimum at 132 MeV means that the energy region above ~ 150 MeV corresponds to the dark side of the nuclear rainbow and also signifies the end of the famous series of 'Airy' elephants … (Fig.2.c.). It is quite remarkable to note that strong refractive effects are only seen in systems showing strong resonance effects. This is because both effects require weak absorption. In the case of observable refractive effects [3-6], deep nucleus-nucleus potentials have been deduced which not only describe nuclear scattering but also nuclear molecular structure as for example in the case of $^{12}C+^{16}O$ [7].

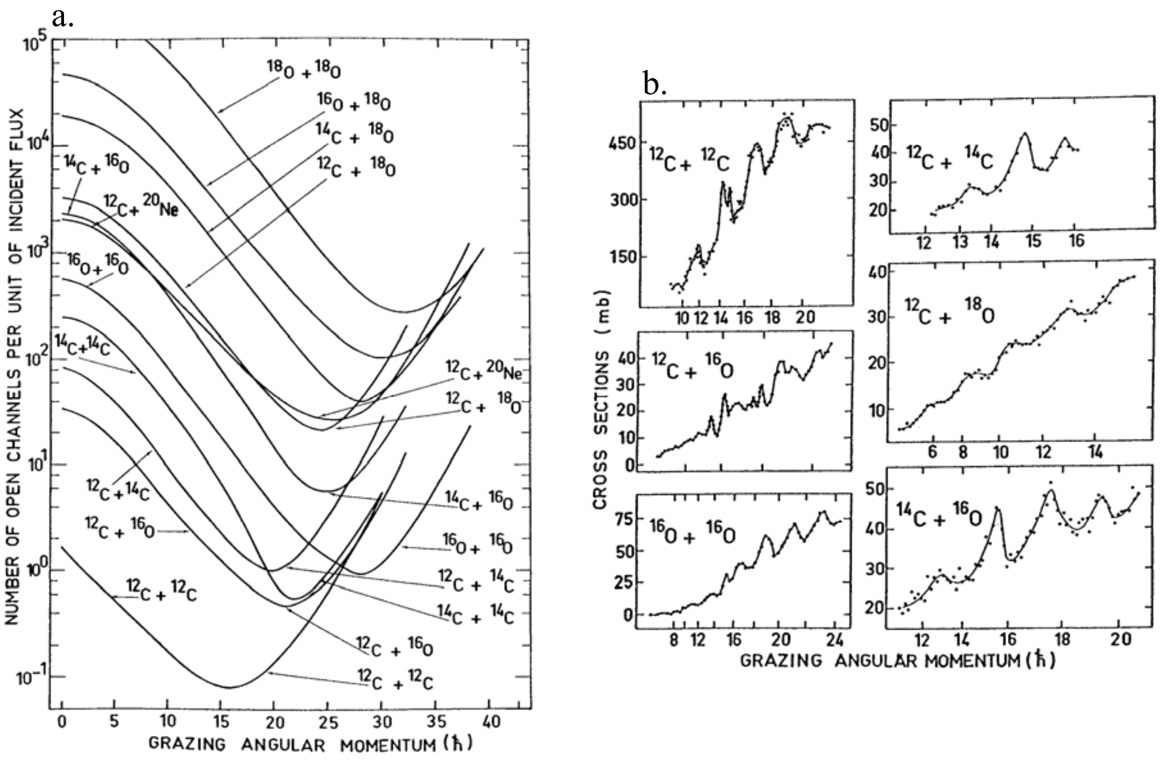

FIGURE 1. a. Number of open channels as a function of grazing angular momentum for C+C, C+O, O+O collisions [1]; b. Excitation functions of angular integrated direct reaction channels for the collisions indicated [1].

RESONANCES VERSUS MOLECULAR STATES

It has been shown in the previous section that the existence of resonances in light heavy-ion collisions is experimentally well established. However, their relation to large molecular states in the composite systems is still a debated question. Such a

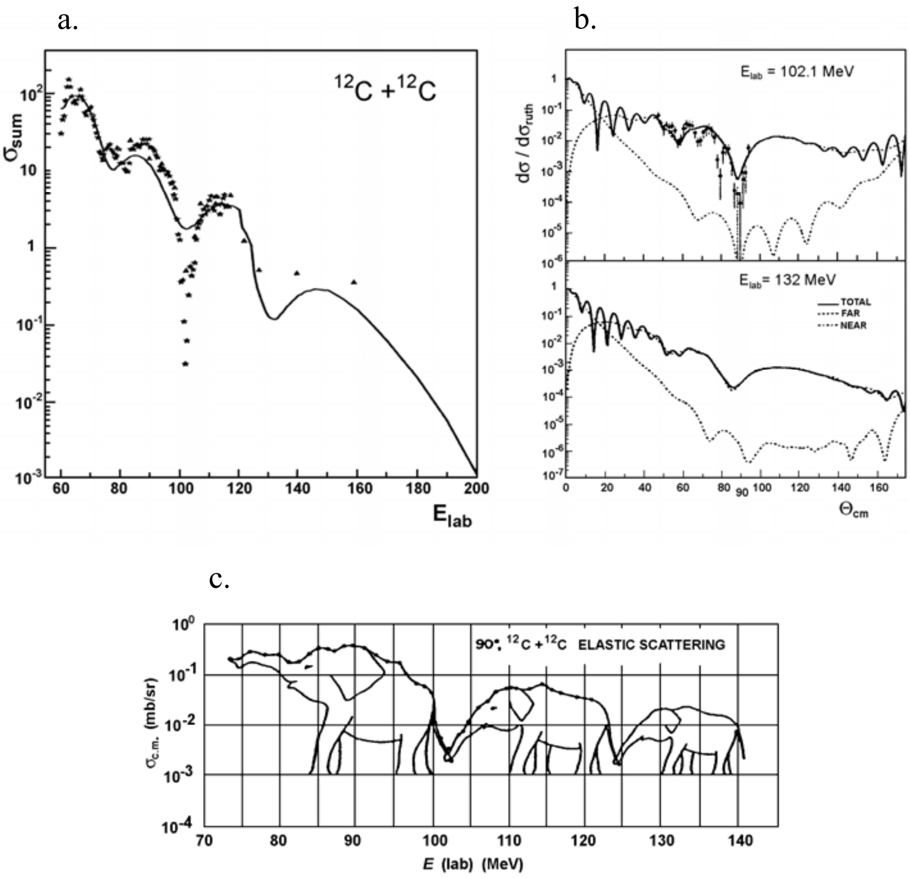

FIGURE 2. a. 90° elastic scattering excitation function for $^{12}C+^{12}C$ [2], the full line is an optical model calculation; b. Near-side/Far-side decompositions of the angular distributions at the two first Airy minima at E_{lab} = 102.1 and 132 MeV; c. The gross structures in the excitation function represented as a series of so-called 'Airy' elephants.

connection can only be more firmly established through measurements of their spins and parities, fragment and γ decay widths.

Alpha clustering is well known in light nuclei where α cluster bands exist for example in ^{16}O, ^{18}O, ^{20}Ne and ^{44}Ti. Recent and important work on neutron-rich Be and C isotopes [8,9] has established and characterized states in these nuclei with $2\alpha xn$ and $3\alpha xn$ configurations.

Cluster or molecular states are deformed states for which the γ decay should contain specific signatures. In the case of the ^{16}O α cluster band (4p-4h configuration) with states at Ex = 6.05 (0^+), 6.92 (2^+) and 10.36 (4^+) MeV, this is indeed the case because strongly accelerated E2 transitions of 65 and 27 W.u. have been measured for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions, respectively.

What heavier clusters and particularly molecular states are concerned, it is expected that they can be reached through heavy-ion resonances which populate the composite systems at high excitation energies where the density of states is large. The best cases to study are those for which the resonance width and thus also the spreading width are small. The ^{12}C+^{12}C and ^{24}Mg+^{24}Mg reactions are two striking examples where similar narrow width resonances (Γ = 100-200 keV) have been observed under rather different conditions: around the Coulomb Barrier for ^{12}C+^{12}C with low spins and composite ^{24}Mg excitation energies of ~ 20 MeV; at twice the CB for ^{24}Mg+^{24}Mg with high spins and composite ^{48}Cr excitation energies of ~ 60 MeV. Our experimental research programme in Strasbourg has been focused on these two cases and in particular on the γ and fragment decay modes of the narrow resonances.

THE RESONANT RADIATIVE CAPTURE REACTIONS

Resonances were observed by Sandorfi [10] 25 years ago in the radiative capture reaction ^{12}C(^{12}C,γ)^{24}Mg. In this pioneering work, only the γ decay to low-lying states in ^{24}Mg could be observed. Recently this capture reaction was studied again with improved experimental techniques [11] and it was demonstrated that there was strong competition between different modes of decay (see Fig.3.). It was in particular shown [11] that there was strong feeding of the ^{24}Mg $K^\pi = 2^+$ band and also of ^{24}Mg states around 10 MeV which could be the predicted shape isomers with ^{12}C-^{12}C structure. It was also demonstrated that due to these additional decay channels the radiative capture cross-section is 4 ot 5 times stronger than reported previously [10].

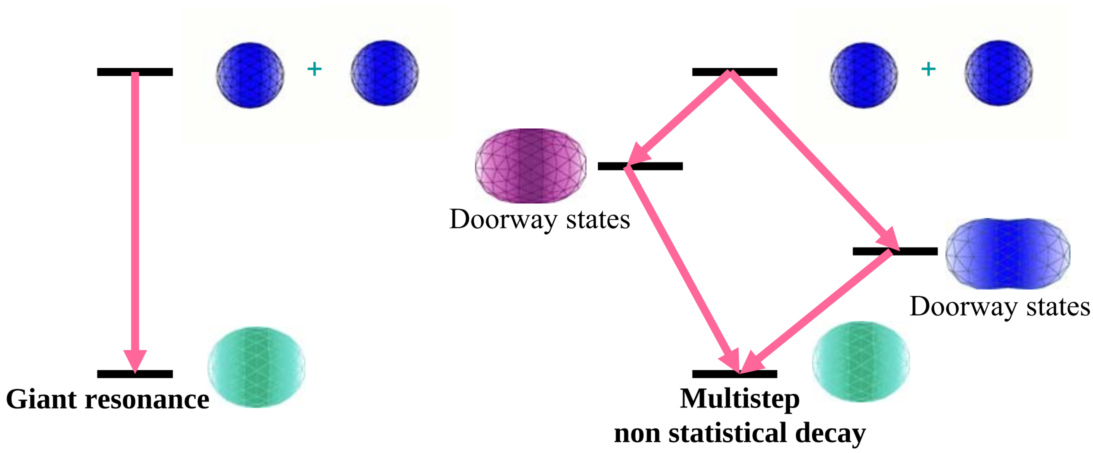

FIGURE 3. Competition between different γ decay modes in resonant radiative capture reactions like ^{12}C(^{12}C,γ)^{24}Mg or ^{12}C(^{16}O,γ)^{28}Si.

A similar study is going to be performed in a near future by our group on the resonant radiative capture reaction $^{12}C(^{16}O,\gamma)^{28}Si$ [10] using the 0° spectrometer Dragon at Triumf (Vancouver) and its associated BGO γ-array with the aim to look for ^{12}C-^{16}O doorway cluster states in ^{28}Si predicted to lie at $E_x \sim 15$ MeV [7].

THE RESONANT $^{24}Mg+^{24}Mg$ REACTION

Our research programme on this system is performed at the Legnaro Tandem and is focused on the decay of the narrow resonance $J^\pi = 36^+$ at $E_{cm} = 45.7$ MeV [12]. In an experiment using the fragment spectrometer Prisma and its associated γ-array Clara, the feeding on and off resonance of the inelastic channels was studied (see Fig.4). Resonance strength is observed essentially in inelastic channels involving the 0^+, 2^+ and 4^+ members of the ^{24}Mg ground state band. A full account of this experiment is given in another contribution to ENS'05 [13]. For the resonance under study, only 30% of the flux has been observed up to now in the inelastic and transfer channels. We propose to search for the missing flux in the 2α (or ^8Be) fusion channel feeding the known ^{40}Ca deformed or superdeformed states (see Fig.4). The aim of the study is of course to establish an eventual link between the ^{48}Cr molecular states fed through the $^{24}Mg+^{24}Mg$ resonances and the ^{40}Ca superdeformed states.

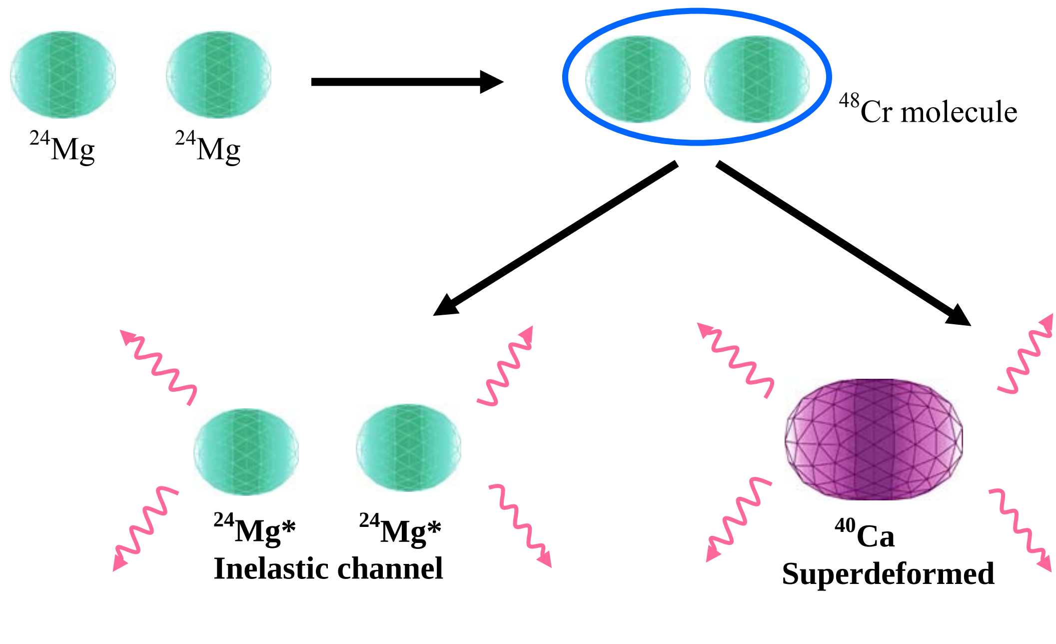

FIGURE 4. Competition between different fragment and particle decay modes of a $^{24}Mg+^{24}Mg$ resonance forming a ^{48}Cr nuclear molecule.

CONCLUSIONS

To establish more firmly the connection between heavy-ion resonances and nuclear molecules, new experiments on the resonance decay modes are called for. For the lighter $^{12}C+^{12}C \rightarrow ^{24}Mg$ or $^{12}C + ^{16}O \rightarrow ^{28}Si$ cases, the most promising research programme actually underway is the study of the resonant radiative capture reactions and the search for enhanced γ-decay through specific cluster doorway states. For the heavier $^{24}Mg+^{24}Mg \rightarrow ^{48}Cr$ case, the narrow resonances correspond to much higher excitation energies in the composite systems and the proposed studies are more devoted to the study of the fragment and particle decay channels with the aim to establish a link between molecular states and low lying superdeformed states.

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