Molecular resonance phenomena and alpha-clustering: recent progress and perspectives

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The connection between molecular resonance phenomena in light heavy-ion collisions, alpha-clustering and extremely deformed states in light α-like nuclei is discussed. For example, the superdeformed bands recently discovered in light N−Z nuclei such as $^{36}$Ar, $^{40}$Ca, $^{48}$Cr, and $^{56}$Ni by γ-ray spectroscopy may have a special link with resonant states in collisions with α-like nuclei. The resonant reactions involving identical bosons such as $^{12}$C+$^{12}$C, $^{16}$O+$^{16}$O $^{24}$Mg+$^{24}$Mg and $^{28}$Si+$^{28}$Si are of interest. For instance, a butterfly mode of vibration of the $J^\pi = 38^+$ resonance of $^{28}$Si+$^{28}$Si has been discovered in recent particle γ-ray angular correlations measurements. The search for signatures of strongly deformed shapes and clustering in light N−Z nuclei is also the domain of charged particle spectroscopy. The investigation of γ-decays in $^{24}$Mg has been undertaken for excitation energies where previously nuclear molecular resonances were found in $^{12}$C+$^{12}$C collisions. In this case the $^{12}$C−$^{12}$C scattering states can be related to the breakup resonance and, tentatively, to the resonant radiative capture $^{12}$C+$^{12}$C reaction.

1. Introduction

The recent discovery of highly deformed shapes and superdeformed (SD) rotational bands in the N−Z nuclei $^{36}$Ar [1], $^{40}$Ca [2], $^{48}$Cr [3,4] and $^{56}$Ni [5] has renewed the interest in theoretical calculations for sd-shell nuclei around $^{40}$Ca [6,7,8]. Therefore the $A_{CN} \approx 30$-60 mass region becomes of particular interest [9] since quasimolecular resonances have also been observed for these α-like nuclei, in particular, in the $^{28}$Si+$^{28}$Si reaction [10,11,12]. Although there is no experimental evidence to link the SD bands with the higher lying rotational bands formed by known quasimolecular resonances [13], both phenomena are believed to originate from highly deformed configurations of these systems. The interpretation of resonant structures observed in the excitation functions in various combinations of light α-cluster nuclei in the energy regime from the barrier up to regions with excitation energies of 30-50 MeV remains a subject of contemporary debate. In particular, in collisions between two $^{12}$C nuclei, these resonances have been interpreted in terms of nuclear molecules [13]. However, in many cases these structures have been connected to strongly deformed shapes and to the alpha-clustering phenomena [14,15,16]. There has been a continuing discussion as to whether these molecular resonances represent true cluster states in the $^{24}$Mg compound system, or whether they simply reflect scattering states in the ion-ion potential. In this paper, a few examples will be given showing the close connection between molecular resonance phenomena, alpha-clustering, and nuclear
2. Molecular resonances in $^{28}\text{Si} + ^{28}\text{Si}$

The molecule-like sequences of resonances observed in $^{28}\text{Si} + ^{28}\text{Si}$ with measured angular momenta up to $L = 42\hbar$ represented some nuclear excitations with the highest spins ever observed [10]. In the number of open channels model [17-18], highly successful in selecting the systems showing resonance behavior, the main condition for observing a resonance behavior is associated with surface transparency. The $^{28}\text{Si} + ^{28}\text{Si}$ reaction is a particularly favorable case [18], where the corresponding optical model (OM) potentials have small imaginary components at distances corresponding to peripheral collisions. Therefore, the well established $J^\pi = 38^+$ molecular resonance observed in $^{28}\text{Si} + ^{28}\text{Si}$ data at $E_{lab} = 112$ MeV has been studied at the VIVITRON Tandem facility of the IReS by both fragment-fragment and fragment-fragment-$\gamma$ coincidence measurements [11-12]. A subsequent experiment [19] using charged particle spectroscopy techniques with the ICARE multidetector array [20] has indicated the occurrence of strongly deformed shapes at high spin (with axis ratios consistent with SD bands) for the $^{56}\text{Ni}$ composite system at the resonant energy in agreement with very recent $\gamma$-ray spectroscopy data obtained at much lower spins [5]. From the analysis of the particle angular distributions of the mass-symmetric $^{28}\text{Si} + ^{28}\text{Si}$ exit-channel [12], it could be concluded that, at the resonance energy, the spin vectors of the $^{28}\text{Si}$ fragments do not couple with the orbital angular momentum, leading to $m = 0$. The fragment-fragment-$\gamma$ coincidence data [11] demonstrate that for the $^{28}\text{Si}$ fragments, the mutually excited states are the most strongly populated. The resonance behavior appears to involve preferentially the low-lying states of the mass-symmetric channel.

In Fig. 1 the results of the $\gamma$-ray angular correlations for the mutual excitation exit-channel ($2^+_1, 2^+_1, 2^+_1$) are shown. The distributions are presented in terms of the polar angles with respect to the three different quantization axes defined as: (a) the beam axis, (b) the
axis normal to the scattering plane, and (c) the axis perpendicular to both axes defined in (a) and (b). The (c) axis corresponds approximately to the molecular axis of the outgoing binary fragments. The strong minimum in Fig. 1(b) at 90° implies that the magnetic substate \( m \) is equal to zero \( (m = 0) \), and, thus, that the intrinsic spin vectors of the \( 2^+ \) states are oriented in the reaction plane perpendicularly to the orbital angular momentum. The value of the total angular momentum, therefore, remains close to \( L = 38 \hbar \), in good agreement with the angular distributions results [12]. These observations do favor the calculations of the molecular model of Uegaki and Abe [21], which predict a vanishing spin alignment for \( ^{28}\text{Si} + ^{28}\text{Si} \) arising from a butterfly mode of vibration of the di-nuclear system at the resonance energy.

3. Spin-alignment measurements of molecular states

The present \( ^{28}\text{Si} + ^{28}\text{Si} \) data show, for the first time in a heavy-ion collision, a vanishing spin alignment. Therefore, the comparison between the three symmetric systems \( ^{12}\text{C} + ^{12}\text{C} \), \( ^{24}\text{Mg} + ^{24}\text{Mg} \) and \( ^{28}\text{Si} + ^{28}\text{Si} \) in Fig. 2 shows an interesting contrast in the spin orientation at resonance energies.

The results indicate that the \( ^{28}\text{Si} + ^{28}\text{Si} \) oblate-oblate system, illustrated by Fig. 2(b), is characterised by spin disalignment in contrast to the spin alignment observed for both the \( ^{12}\text{C} + ^{12}\text{C} \) system [22,23] of Fig. 2(c) (oblate-oblate) and the \( ^{24}\text{Mg} + ^{24}\text{Mg} \) system [24] of Fig. 2(a) (prolate-prolate). Molecular-model calculations [24] are capable to explain the vanishing spin alignment in the oblate-oblate \( ^{28}\text{Si} + ^{28}\text{Si} \) system [12], where both nuclear spin vectors are perpendicular to the orbital angular momentum lying in the reaction plane.

A new butterfly mode of vibration for the \( ^{28}\text{Si} + ^{28}\text{Si} \) triaxial molecule can then be speculated. However, the question of why the spin orientations in the two oblate-oblate systems \( ^{28}\text{Si} + ^{28}\text{Si} \) and \( ^{12}\text{C} + ^{12}\text{C} \) are so different is still unclear. Differences in the interactions between the constituent nuclei may play a key role. For example, there is a remarkable difference in the available molecular configurations in the excitation spectra of the \( ^{12}\text{C} + ^{28}\text{Si} \) nuclei. In \( ^{12}\text{C} + ^{12}\text{C} \) there are few molecular configurations, located at the energies associated with the observed resonances, while in \( ^{28}\text{Si} + ^{28}\text{Si} \) there are many more.

![Figure 2: Equilibrium configurations of three different dinuclear systems: a) for \( ^{24}\text{Mg} + ^{24}\text{Mg} \), b) for \( ^{28}\text{Si} + ^{28}\text{Si} \), and c) for \( ^{12}\text{C} + ^{12}\text{C} \).](image-url)
+^{28}\text{Si} there are many more configurations. It is possible that the large number of available configurations [15] allows for the formation of coherent or collective states. This explains the sharp resonances which decay into many inelastic channels. In the $^{12}\text{C} + ^{12}\text{C}$ system, such coherent effects may not be allowed to develop. In this case the individual configurations may be observed. Overall, the results of these experiments provide further support for recent theoretical investigations that view the resonances in terms of shape-isomeric states stabilized in hyperdeformed secondary minima [14,15,16]. However, a more global understanding will surely require a more fundamental synthesis of the theories which describe reaction mechanisms with those describing nuclear structure at high excitation energy and angular momentum.

4. $^{24}\text{Mg}$ breakup states and the $^{12}\text{C} + ^{12}\text{C}$ molecule

In the framework of the search for nuclear molecules the most spectacular results have often been obtained for the $^{12}\text{C} + ^{12}\text{C}$ reaction [17]. However, the question whether $^{12}\text{C} + ^{12}\text{C}$ molecular resonances represent true cluster states in the $^{24}\text{Mg}$ compound system, or whether they simply reflect scattering states in the ion-ion potential is still unresolved [13]. In many cases these structures have been connected to strongly deformed shapes and to the alpha-clustering phenomena, predicted from the $\alpha$-cluster model [14], Hartree-Fock calculations [15], the Nilsson-Strutinsky approach [16]. Various decay branches from the highly excited $^{24}\text{Mg}^*$ nucleus, including the emission of $\alpha$ particles or heavier fragments such as $^8\text{Be}$ and $^{12}\text{C}$, are possibly available. However, $\gamma$-decays have not been observed so far. Actually the $\gamma$-ray branches are predicted to be rather small at these excitation energies, although some experiments have been reported [25,26,27], which have searched for these very small branches expected in the range of $10^{-4}$-$10^{-5}$ fractions of the total width [9,28]. The rotational bands built on the knowledge of the measured spins and excitation energies can be extended to rather small angular momenta, where finally the $\gamma$-decay becomes a larger part of the total width. The population of such states in $\alpha$-cluster nuclei, which are lying below the threshold for fission decays and for other particle decays, is favored in binary reactions, where at a fixed incident energy the composite nucleus is formed with an excitation energy range governed by the two-body reaction kinematics. These states may be coupled to intrinsic states of $^{24}\text{Mg}^*$ as populated by a breakup process (via resonances) as shown in previous works [29,30,31]. The $^{24}\text{Mg} + ^{12}\text{C}$ reaction has been extensively investigated by several measurements of the $^{12}\text{C}(^{24}\text{Mg},^{12}\text{C})^{12}\text{C}$ breakup channel [29,30,31]. Sequential breakups are found to occur from specific states in $^{24}\text{Mg}$ at excitation energies ranging from 20 to 35 MeV, which are linked to the ground state and also have an appreciable overlap with the $^{12}\text{C} + ^{12}\text{C}$ quasi-molecular configuration. Several attempts [30] were made to link the $^{12}\text{C} + ^{12}\text{C}$ barrier resonances [13] with the breakup states. The underlying reaction mechanism is now fairly well established [31] and many of the barrier resonances appear to be correlated indicating that a common structure may exist in both instances. This is another indication of the possible link between barrier resonances and secondary minima in the compound nucleus. The study of particle-$\gamma$ coincidences in binary reactions in reverse kinematics is probably a unique tool for the search for extreme shapes related to clustering. In this way the
$^{24}\text{Mg} + ^{12}\text{C}$ reaction has been investigated with high selectivity at $E_{\text{lab}}(^{24}\text{Mg}) = 130$ MeV with the Binary Reaction Spectrometer (BRS) in coincidence with EUROBALL IV installed at the VIVITRON [9] [28]. The choice of the $^{12}\text{C}(^{24}\text{Mg}, ^{12}\text{C})^{24}\text{Mg}^*$ reaction implies that for an incident energy of $E_{\text{lab}} = 130$ MeV an excitation energy range up to $E^* = 30$ MeV in $^{24}\text{Mg}$ is covered [30]. The BRS gives access to a novel approach to the study of nuclei at large deformations [9] [28]. The excellent channel selection capability of binary and/or ternary fragments gives a powerful identification among the reaction channels, implying that EUROBALL IV is used mostly with one or two-fold multiplicities, for which the total $\gamma$-ray efficiency is very high. The BRS trigger consists of a kinematic coincidence set-up combining two large-area heavy-ion telescopes. Both detector telescopes comprise each a two-dimensional position sensitive low-pressure multiwire chamber in conjunction with a Bragg-curve ionization chamber. All detection planes are four-fold subdivided in order to improve the resolution and to increase the counting rate capability (100 k-events/s). The two-body Q-value has been reconstructed using events for which both fragments are in well selected states chosen for spectroscopy purposes as well as to determine the reaction mechanism responsible for the population of these peculiar states. The inverse kinematics of the $^{24}\text{Mg} + ^{12}\text{C}$ reaction and the negative Q-values give ideal conditions for the trigger on the BRS, because the chosen angular range is optimum and because the solid angle transformation gives a factor 10 for the detection of the heavy fragments. Thus we have been able to cover a large part of the angular distribution of the binary process with high efficiency, and a selection of events in particular angular ranges has been achieved. In binary exit-channels the exclusive detection of both ejectiles allows precise Q-value determination, Z-resolution and simultaneously optimal Doppler-shift correction.

Fig. 3 displays a Doppler-corrected $\gamma$-ray spectrum in coincidence with $^{24}\text{Mg}$ events identified in the Bragg-Peak vs energy spectra of the BRS. All known transitions of $^{24}\text{Mg}$ [1] [32] can be identified in the energy range depicted. As expected we see decays feeding the yrast line of $^{24}\text{Mg}$ up to the $8^+_2$ level. The population of some of the observed
states, in particular, the $2^+$, $3^+$ and $4^+$ members of the $K^\pi = 2^+$ rotational band, appears to be selectively enhanced. The strong population of the $K^\pi = 2^+$ band and his $4^+$ member at $E_x = 6.01$ MeV has also been observed in the $^{12}\text{C}(^{12}\text{C}, \gamma)$ radiative capture reaction \cite{33}. Furthermore, there is an indication of a $\gamma$-ray around 5.95 MeV which may be identified with the $10^+_1 \rightarrow 8^+_2$ transition as proposed in Ref. \cite{32}. It has been checked in the $\gamma\gamma$ coincidences that most of the states of Fig. 3 belong to cascades which contain the characteristic 1368 keV $\gamma$-ray and pass through the lowest $2^+$ state in $^{21}\text{Mg}$. Still a number of transitions in the high-energy part of the spectrum (6-8 MeV) have not been clearly identified. Even at higher energies, $^{24}\text{Mg}$ states appear to show up around 10 MeV (not shown) with very poor statistics and of unknown structure. Similar states were also observed in the radiative capture reaction \cite{33}. Their occurrence may be in qualitative agreement with a decay scenario of radiative capture states proposed by Baye and Descouvemont \cite{34, 35} in the framework of a microscopic study of the $^{12}\text{C}+^{12}\text{C}$ system with the Coordinate Generator Method. The reason why the search for a $\gamma$-decay in $^{12}\text{C}+^{12}\text{C}$ has not been conclusive so far \cite{25, 26, 27} is due to the excitation energy in $^{24}\text{Mg}$ as well as the spin region ($8h-12h$) which were chosen too high. The next step of the analysis will be the use of the BRS trigger in order to select the excitation energy range by the two-body Q-value (in the $^{12}\text{C}+^{24}\text{Mg}$ channel), and thus we will be able to study the region around the decay barriers, where $\gamma$-decay becomes observable. According to recent predictions $\gamma$-rays from $6^+ \rightarrow 4^+$ should have measurable branching ratios. Work is currently in progress to analyse the $\gamma$ rays from the $^{12}\text{C}(^{24}\text{Mg}, ^{12}\text{C}^{12}\text{C})^{12}\text{C}$ ternary breakup reaction.

5. Summary and conclusions

We have discussed the possible link between resonant states in collisions with identical bosons such as $^{12}\text{C}+^{12}\text{C}$, $^{24}\text{Mg}+^{24}\text{Mg}$ and $^{28}\text{Si}+^{28}\text{Si}$ and the SD bands recently discovered in light $N=Z$ nuclei such as $^{36}\text{Ar}$, $^{40}\text{Ca}$, $^{48}\text{Cr}$, and $^{50}\text{Ni}$. A new butterfly mode of vibration of the well established $J^\pi = 38^+$ resonance of the $^{28}\text{Si}^{28}\text{Si}$ triaxial molecule has been discovered experimentally. The connection of alpha-clustering and quasimolecular resonances has been discussed with the search for the $^{12}\text{C}+^{12}\text{C}$ molecule populated by the $^{24}\text{Mg}+^{12}\text{C}$ breakup reaction. The most spectacular result is the strong population of the $K^\pi = 2^+$ band of the $^{24}\text{Mg}$ nucleus that has also been observed in an exploratory investigation of the $^{12}\text{C}(^{12}\text{C}, \gamma)$ radiative capture reaction \cite{33}. Subsequent radiative capture experiments are planned in the near future with highly efficient spectrometers (the DRAGON separator at TRIUMF and the FMA at Argonne) to investigate the overlap of $^{24}\text{Mg}$ states observed in the present work with radiative capture states. As far as the $\gamma$-ray spectroscopy is concerned, the coexistence of $\alpha$-cluster states and SD states predicted in $^{32}\text{S}$ by recent antisymmetrized molecular dynamics (AMD) calculations \cite{36} is still an experimental challenge. This kind of experiments designed to measure very small $\Gamma_\gamma/\Gamma_{\text{total}}$ branching ratios is extremely difficult since it requires not only high-efficient fragment detection in conjunction with a high-resolution Ge multidetector such as the GAMMASPHERE and EUROBALL $4\pi \gamma$ arrays but also a large amount of beam time.
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