Study of binary reaction channels in the ^{24}Mg+^{12}C collision

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The study of γ-decays in ^{24}Mg* is presented for excitation energies between the α+^{20}Ne (9.3 MeV) and ^{12}C+^{12}C (13.9 MeV) thresholds, where molecular resonances have been observed in ^{12}C+^{12}C collisions. Various theoretical predictions exist for the occurence of superdeformed and hyperdeformed bands which can partially be identified with known resonance structures correlated in several reaction channels, and for which low spin members are predicted within the measured ^{24}Mg* excitation energy region. The inverse kinematics reaction ^{24}Mg+^{12}C has been investigated at E$_{lab}$(^{24}Mg) = 130 MeV, an energy which enable the population of ^{24}Mg states decaying into ^{12}C+^{12}C resonant breakup states. Exclusive data were collected with the Binary Reaction Spetrometer (BRS) in coincidence with EUROBALL installed at the VIVITRON Tandem facility of the IReS at Strasbourg. Specific structures with large deformation were selectively populated in binary reactions and their γ-decays determined by using the BRS as a master trigger. Coincident events with inelastic as well as with binary α-transfer channels have been selected by choosing the excitation energy or the entry point via the two-body Q-values. The analysis of the binary and quasi-binary reaction channels is presented with a particular emphasis on the ^{24}Mg-γ and ^{20}Ne-γ coincidences as well as the ^{12}C-^{12}C coincidences.

1. Introduction

In the search for nuclear molecules the most spectacular results have often been obtained for the ^{12}C+^{12}C reaction [1] which is the most favorable one for the observation of molecular resonances [2–4]. However, the question whether ^{12}C+^{12}C molecular resonances represent true cluster states in the ^{24}Mg compound system, or whether they simply reflect scattering states in the ion-ion potential is still unresolved [5,6]. In many cases these structures have been connected to strongly deformed shapes and to the alpha-clustering

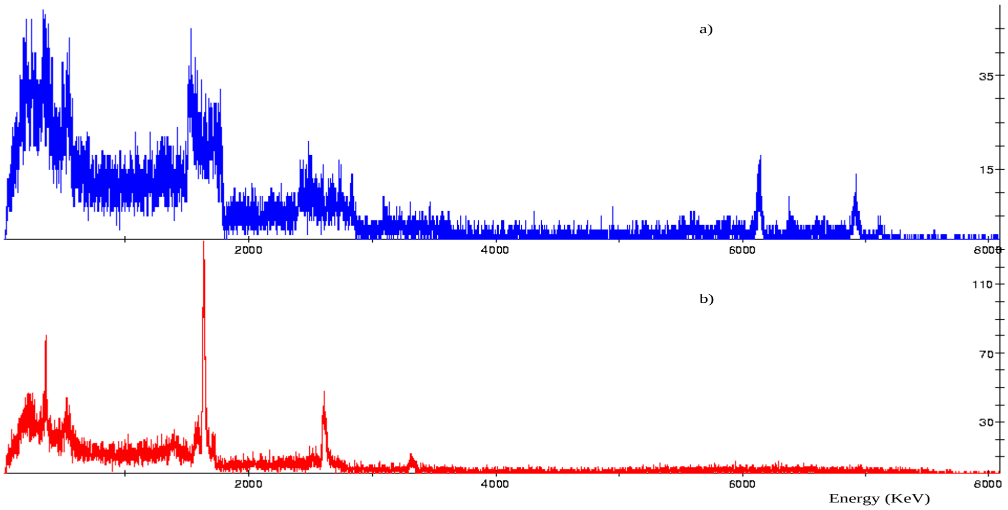

Figure 1. *Experimental γ-ray spectra, using particle-particle-γ coincidences, measured in the ^{24}Mg(130 MeV)+^{12}C with EUROBALL IV. The upper (lower) spectrum labelled a (b) has been obtained with Doppler-shift corrections assuming O (Ne) fragments detected in one of the BRS telescopes.*

phenomena, predicted from the α-cluster model [7], Hartree-Fock calculations [8], and the Nilsson-Strutinsky approach [9]. Various decay branches from the highly excited ^{24}Mg* nucleus, including the emission of α particles or heavier fragments such as ^{8}Be and ^{12}C, are possibly available [2,3]. However, γ-decays have not been observed so far. Actually the γ-ray branches are predicted to be rather small at these exitation energies, although some experiments have been reported [10–12] to search for these very small branchs expected in the range of $10^{-4} - 10^{-5}$ fractions of the total width [5,6,13]. 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 γ-decay becomes a larger part of the total width. The population of such states in α-cluster nuclei, which are lying below the threshold for fission decay and for other particle decays, is favored in binary reaction. These states may be coupled to intrinsic states of ^{24}Mg* as populated by a breakup process (via resonances) as shown in Refs. [14–16]. The ^{24}Mg+^{12}C reaction has been exensively investigated by several measurements of the ^{12}C(^{24}Mg^{12}C^{12}C)^{12}C breakup channel [14–16]. Sequential breakups are found to occur from specific states in ^{24}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}C+^{12}C quasi-molecular configuration. Several attempts [15] were made to link the ^{12}C+^{12}C barrier resonances [1] with the breakup states. The underlying reaction mechanism is now fairly well established [16] 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 [1,3] and secondary minima in the compound nucleus [7–9].

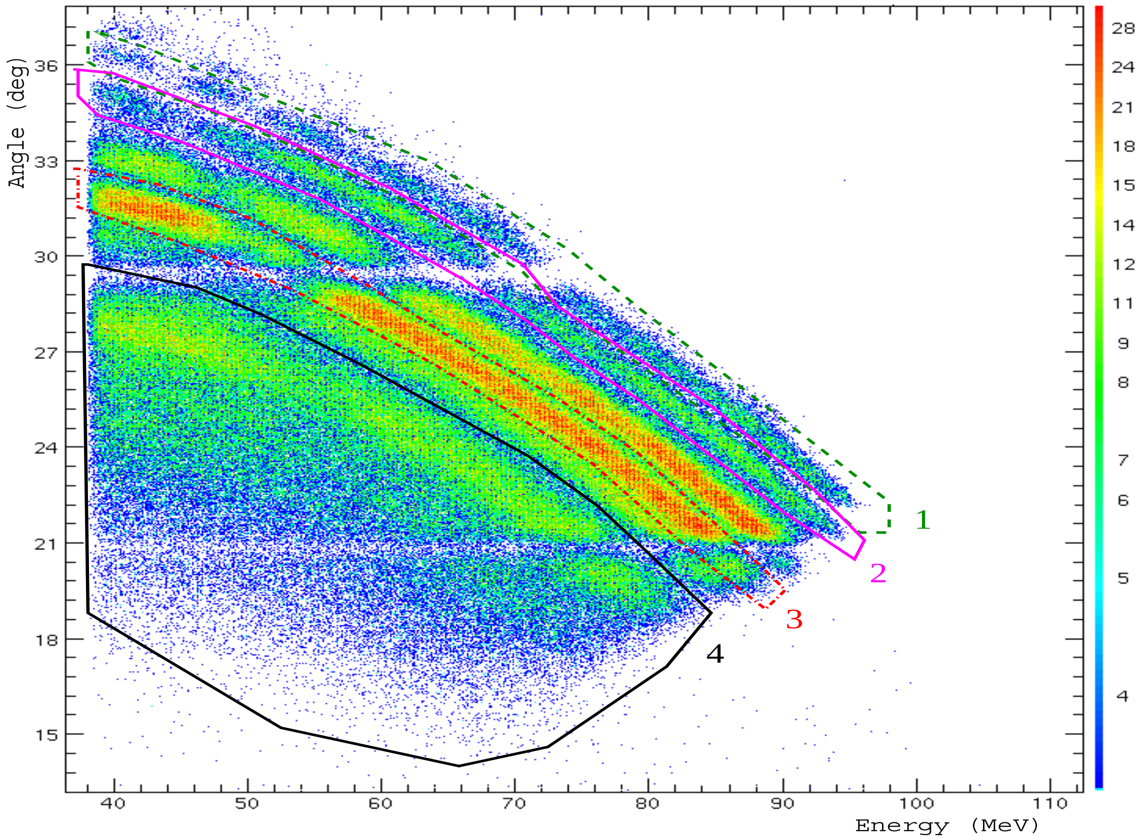

Figure 2. *Two-dimensional angle versus energy spectrum, using particle-particle coincidences, measured for the* ^{16}O+^{20}Ne *exit channel in* ^{24}Mg*(130 MeV)+*^{12}C *reaction. The gates labelled 1 to 4 are defined in the text.*

2. Experimental methods

Particle-γ measurements in inverse kinematics binary reactions constitute most likely one of the most powerful tool for the study of large deformations related to clustering. In this paper we investigate the ^{24}Mg+^{12}C reaction with high selectivity at $E_{lab}(^{24}\mathrm{Mg})$ = 130 MeV with the Binary Reaction Spectrometer [17,18] (BRS) in coincidence with EUROBALL IV [19] (EB) installed at the VIVITRON Tandem facility of the IReS (Strasbourg). The choice of the ^{12}C(^{24}Mg,^{12} C)^{24}Mg* reaction implies that for an incident energy of 130 MeV an excitation energy range up to E* = 30 MeV in ^{24}Mg is covered [15]. The BRS gives access to a novel approach to the study of nuclei at large deformations. The excellent channel selection capability of binary and/or ternary fragments gives a precise identification among reaction channels, implying that EB is used mostly with one or two-fold multiplicities, for which the total γ-ray efficiency is very high.

A schematic lay-out of the actual experimental set-up of the BRS with EB is shown in Fig. 3 of Ref. [17]. The BRS trigger consists of a kinematical coincidence set-up combining two large-ara (187 msr) heavy-ion telescopes. Both detector telescopes comprise each a

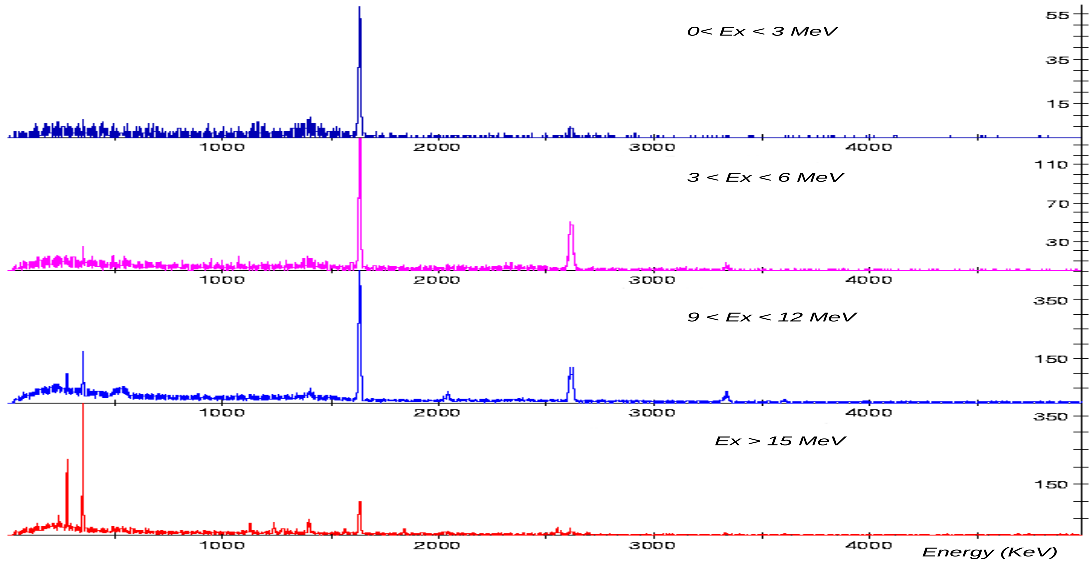

Figure 3. *Gated γ-ray spectra, using particle-particle-γ coincidences, measured for the ^{16}O+^{20}Ne exit channel in ^{24}Mg(130 MeV)+^{12}C reaction. The four excitation energy gates are displayed in Fig.2 as defined in the text.*

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 kevents/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 of the population of these particular states. A typical example of a two-dimensional Bragg-Peak versus energy spectrum obtained for the ^{24}Mg+^{12}C reaction can be found in a previous publication (see Fig. 1 of [18]) presenting a preliminary report of the present work. The Bragg-Peak versus energy spectrum shows the excellent charge discrimination achieved with the Bragg-curve ionization chambers. Well defined Z gates can be used for the processing of the γ-ray spectra of the ^{16}O, ^{20}Ne and ^{24}Mg nuclei of interest.

The inverse kinematics of the ^{24}Mg+^{12}C reaction and the negative Q-values give ideal conditions for the trigger on the BRS, because their large range is optimum for $\delta\theta$ = 12°-46° (in plane) and $\delta\phi$ = 2 X 17.4° (out of plane) in the lab-system (with the range of 12° to 25° for the recoils) and because the solid angle transformation gives a factor 10 for the detection efficiency 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 as shown in Fig. 1 for the ^{16}O+^{20}Ne α-transfer channel.

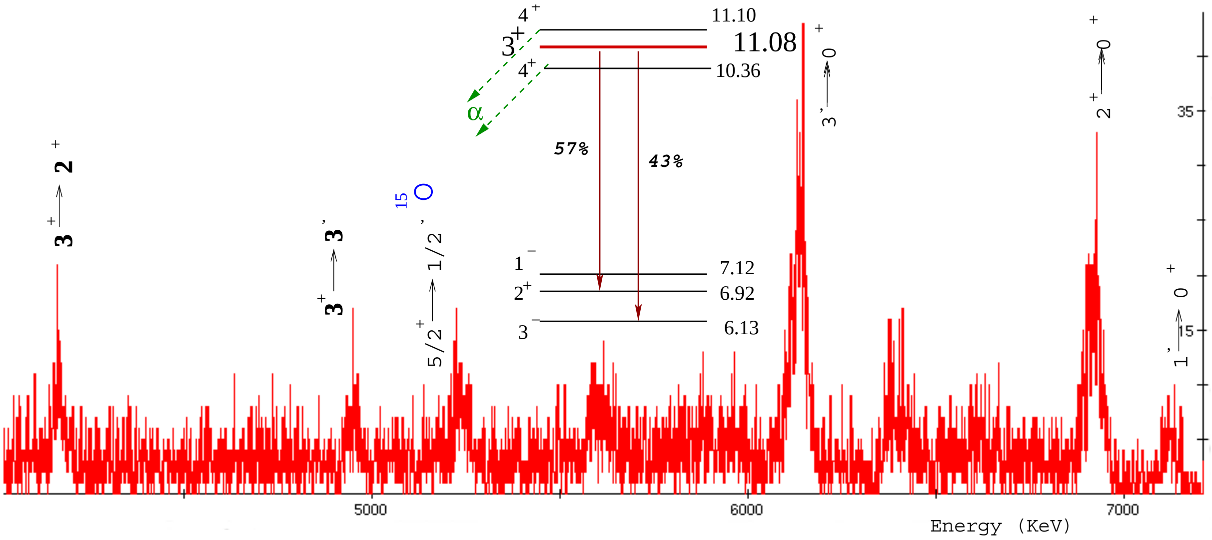

Figure 4. ^{16}O *excited states populated in the* $^{16}O+^{20}Ne$ *exit channel of the* ^{24}Mg*(130 MeV)+*^{12}C *reaction. Dopple-shift corrections have been applied for O fragments detected in the BRS. The* ^{16}O *level scheme is given for the sake of comparison.*

3. Experimental results

Fig. 1 displays two Doppler-shift corrected γ-ray spectra for ^{16}O and ^{20}Ne events in coincidence with respective Z=8 and Z=10 gates appropriately defined in the Bragg-Peak vs enery spectra. All known transitions of both ^{16}O and ^{20}Ne can be easily identified in the energy range depicted. As expected we observe decays feeding the yrast line of the ^{20}Ne nucleus.

The next step of the analysis is the use of the BRS trigger in order to select the excitation energy range by the two-body Q-value (in the ^{16}O+^{20}Ne channel), and thus allowing to study the region around the decay barriers, where γ-decay becomes observable. The two-dimensional angle versus energy spectrum, shown in Fig. 2 for the α-transfer channel, selects well defined excitation energy (Q-value) regions ranging from the (gs) elastic and inelastic (^{20}Ne,2_1^+) transfer (gate 1) up to highly excited (deep-inelastic) states (gate 4). The second (gate 2) and third E* regions include mainly the second excited state of ^{20}Ne (4_1^+,4248 keV). The following one (gate 3) with the largest intensity arise from the corresponding mutual excitations with the excitation of the (3^-, 6.129 MeV) collective state of ^{16}O. The four different excitation energy gates displayed in Fig. 2 are used to generate the γ-ray spectra shown in Fig. 3.

The first two gates in excitation energies ($0 \leq E^* \leq 3$ MeV and $3 \leq E^* \leq 6$ MeV) allow essentially the feeding of the first two excited states of the ^{20}Ne yrast g.s. band: the γ-rays from $2^+ \rightarrow 0^+$ and from $4^+ \rightarrow 2^+$ are dominant. When E* is increased by choosing the other two E* gates ($10 \leq E^* \leq 15$ MeV and $E^* \geq 15$ MeV), higher-energy states are excited in ^{20}Ne. Other γ-rays from ^{21}Ne and ^{19}Ne nuclei do show up with increasing yields. They correspond to multi-nucleon transfer channels: 2p,n and α,n. It

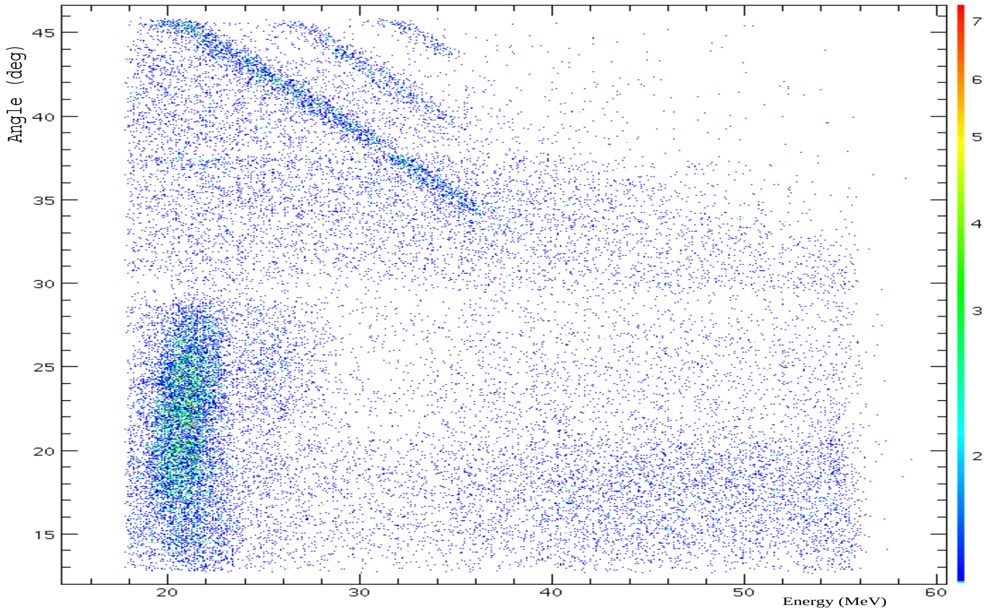

Figure 5. *Two-dimensional particle-particle (angle vs energy) coincidence spectrum, measured by the BRS for the $^{12}C+^{12}C$ exit channel in the $^{24}Mg(130\ MeV)+^{12}C$ reaction.*

is also interesting to notice that the feedings of the ^{20}Ne states appear to saturate with incerasing E* since binary decays decrease as compared to sequential three-body decay channels such as ^{16}O+^{20}Ne$^* \rightarrow$ ^{16}O+^{16}O+α. With appropriate Doppler-shift corrections applied to O fragments identified in the BRS, it has been possible to extend the knowledge of the level scheme of ^{16}O at high energies, well above the ^{12}C+α threshold (7.667 MeV), which is given in Fig. 4 for the sake of comparison. New information has been deduced on branching ratios of the decay of the 3^+ state of ^{16}O at 11.089 MeV (which does not α-decay in contrast to the two neighbouring 4^+ states at 10.356 MeV and 11.096 MeV, respectively) to the 3^+ state at 7.12 MeV (57 ± 4 and to the 3^- state at 6.129 MeV (43 $\pm$ 3 . Please note the $5/2^+ \rightarrow 1/2^-$ transition of ^{15}O corresponding to a multi-nucleon transfer of 2p and 1n.

The BRS-EB setup allows also quasi-binary reaction channels to be studied as ^{12}C-^{12}C coincidences shown in Fig. 5. Work is still currently in progress to analyse the γ rays from the ^{12}C(^{24}Mg,^{12}C ^{12}C)^{12}C ternary breakup reaction. Preliminary results can be obtained from the particle-particle coincidences plotted in Fig. 5 when Z=6 gates are set in both arms of the BRS. The left upper part of Fig. 5 shows a very nice triple structure corresponding to the 0^+-0^+, 0^+-2^+,and 2^+-2^+ states as they are well separated by an energy difference of 4.44 MeV. As a matter of fact the 4.44 MeV peak of the ^{12}C 2^+ state is clearly visible in the corresponding gated γ-ray spectrum. Although we have not been able to measure its cross section the mechanism responsible for this "exotic" triple structure can be further investigated thanks to the large solid angles of the BRS detectors. The fact that for the ^{12}C-^{12}C events the coplanarity condition is fulfilled and both detected ^{12}C fragments have similar energies implies that the third undetected ^{12}C fragment (at rest in the center-of-mass frame) is emitted in the forward direction. A corresponding measurement showing such a phenomenon of the α-particle (traveling the c.m. velocity in the beam direction) from the neck in the decay of ^{28}Si into ^{12}C+α+^{12}C has been already reported [20]. This speculated scenario might be a possible indication of the occurence of the ternary decay of a hyperdeformed ^{36}Ar nucleus proposed by several authors [21–23].

4. Conclusion

The connection of alpha-clustering and quasimolecular resonances has been discussed in this work with the search for the ^{12}C+^{12}C molecule. We have investigated the possible link between breakup states in the ^{24}Mg+^{12}C collision and ^{12}C+^{12}C resonances. Exclusive data were collected with the Binary Reaction Spetrometer (BRS) in coincidence with EUROBALL IV installed at the VIVITRON Tandem facility of the IReS at Strasbourg. New information has been deduced on branching ratios of the decay of the 3^+ state of ^{16}O at 11.089 MeV from a careful analysis of the ^{16}O+^{20}Ne α-transfer exit-channel. A possible scenario for the ^{12}C-^{12}C coincidence data implies the occurence of the ternary decay of a hyperdeformed ^{36}Ar. This work shows that the search for hyperdeformation in medium-mass nuclei, which has been pursued exclusively using γ-spectroscopy, will have to be performed in conjunction with charged particle spectroscopy in the near future.

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