Abstract

Charged particle and $\gamma$-decays in light $\alpha$-like nuclei are investigated for $^{24}\text{Mg}+^{12}\text{C}$. Various theoretical predictions for the occurrence of superdeformed and hyperdeformed bands associated with resonance structures with low spin are presented. The inverse kinematics reaction $^{24}\text{Mg}+^{12}\text{C}$ is studied at $E_{\text{lab}}(^{24}\text{Mg}) = 130$ MeV. Exclusive data were collected with the Binary Reaction Spectrometer in coincidence with EUROBALL IV installed at the VIVITRON Tandem facility at Strasbourg. Specific structures with large deformation were selectively populated in binary reactions and their associated $\gamma$-decays studied. Coincident events from $\alpha$-transfer channels were selected by choosing the excitation energy or the entry point via the two-body $Q$-values. The analysis of the binary reaction channels is presented with a particular emphasis on $^{20}\text{Ne}-\gamma$ and $^{16}\text{O}-\gamma$ coincidences.

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I. INTRODUCTION

The observation of resonant structures in the excitation functions for various combinations of light $\alpha$-cluster (N = Z) nuclei in the energy regime from the barrier up to regions with excitation energies of $E_X = 20-50$ MeV remains a subject of contemporary debate [1, 2]. These resonances have been interpreted in terms of nuclear molecules [1]. The question whether quasimolecular resonances represent true cluster states in the compound systems, or whether they simply reflect scattering states in the ion-ion potential is still unresolved [1, 2]. In many cases, these resonant structures have been associated with strongly-deformed shapes and with clustering phenomena, predicted from the cranked $\alpha$-cluster model [3], Hartree-Fock calculations [4] and the Nilsson-Strutinsky approach [5]. Of particular interest is the relationship between superdeformation (SD) and nuclear molecules, since nuclear shapes with major-to-minor axis ratios of 2:1 have the typical ellipsoidal elongation for light nuclei [6]. Furthermore, the structure of possible octupole-unstable 3:1 nuclear shapes - hyperdeformation (HD) - for actinide nuclei has also been widely discussed [6, 7] in terms of clustering phenomena.

Large (quadrupole) deformations and $\alpha$-clustering in light N = Z nuclei are known to be general phenomena at low excitation energy. For high angular momenta and higher excitation energies, very elongated shapes are expected to occur in $\alpha$-like nuclei for $A_{CN} = 20-60$. These predictions come from the generalized liquid-drop model, taking into account the proximity energy and quasi-molecular shapes [8]. In fact, highly deformed shapes and SD rotational bands have been recently discovered in several such N = Z nuclei, in particular, $^{36}$Ar and $^{40}$Ca using $\gamma$-ray spectroscopy techniques [9, 10]. HD bands in $^{36}$Ar and its related ternary clusterizations are predicted theoretically [11]. With the exception of the cluster decay of $^{56}$Ni recently studied using charged particle spectroscopy [12], no evidence for ternary breakup has yet been reported [13] in light nuclei; the particle decay of $^{36}$Ar SD bands (and other highly excited bands) is still unexplored. The main binary reaction channels of the $^{24}$Mg+$^{12}$C reaction, for which both resonant effects and orbiting phenomena [13] have been observed, is investigated in this work by using charged particle-$\gamma$-ray coincidence techniques.
II. EXPERIMENTAL RESULTS.

FIG. 1: Schematic drawing of the scattering chamber showing the BRS arrangement for fragment detection and the $\gamma$-ray detectors of EB. At forward angles the two BRS gas detector telescopes are depicted, as well as two rings of Clover-Ge-detectors at angles around $\theta = 90^\circ$ and Cluster-Ge-detectors at backward angles, respectively.

The study of charged particle-$\gamma$-ray coincidences in binary reactions in inverse kinematics is a unique tool in the search for extreme shapes related to clustering phenomena. In this paper, we investigate the $^{24}\text{Mg} + ^{12}\text{C}$ reaction with high selectivity at a bombarding energy $E_{\text{lab}}(^{24}\text{Mg}) = 130$ MeV by using the Binary Reaction trigger Spectrometer (BRS) \cite{10, 12} in coincidence with the EUROBALL IV (EB) $\gamma$-ray spectrometer \cite{10} installed at the VIVITRON Tandem facility of Strasbourg. The $^{24}\text{Mg}$ beam was produced and accelerated by the VIVITRON, negative MgH$^-$ ions were extracted from the ion source and then the MgH molecules were cracked at the stripping foils of the terminal accelerator. The beam intensity was kept constant at approximately 5 pnA. The targets consisted of 200 $\mu$g/cm$^2$ thick foils of natural C. The choice of the $^{12}\text{C}(^{24}\text{Mg},^{12}\text{C})^{24}\text{Mg}^*$ reaction implies that for an incident beam energy of $E_{\text{lab}} = 130$ MeV an excitation energy range up to $E^* = 30$ MeV in $^{24}\text{Mg}$ is covered. The BRS, in conjunction with EB, gives access to a novel approach for the study of nuclei at large deformations as described below.
FIG. 2: Two-dimensional angle versus energy spectrum, using fragment-fragment coincidences, measured for the $^{16}\text{O}+^{20}\text{Ne}$ exit-channel. The relative intensity is shown on the side bar. The dashed line corresponds to the high-energy cutoff due to the geometrical bias of the kinematical coincidences. The regions labelled I to VI are defined in the text.

The BRS associated with EB combines as essential elements two large-area (with a solid angle of 187 msr each) heavy-ion gas-detector telescopes in a kinematical coincidence setup at forward angles. A schematic lay-out of the actual experimental set-up of the BRS with EB is shown in Fig. 1. The two telescope arms are mounted symmetrically on either side of the beam axis, each covering the forward scattering angle range $12.5^\circ-45.5^\circ$, i.e. $\theta = 29^\circ \pm 16.5^\circ$. For this reason the 30 tapered Ge detectors of EB [10] were removed.

Fig. 2 illustrates a typical example of a two-dimensional angle versus energy spectrum for the $^{16}\text{O}+^{20}\text{Ne}$ exit-channel. The six regions labelled I to VI have been defined as a function of the inelasticity of the reaction channel from the ground-state Q-value $E^* = 0$ (quasi-elastic) to full damping with $E^*$ larger than 12 MeV (orbiting deep-inelastic). The properties of this $\alpha$-transfer channel will be further discussed thereafter.
FIG. 3: Gated γ-ray spectra, using fragment-fragment-γ-ray coincidences, measured for the $^{16}$O+$^{20}$Ne exit-channel. The six excitation energy gates labelled I to VI in Fig. 2 and defined in the text have been used as triggers to the six γ-ray spectra. The main γ-ray transitions in $^{20}$Ne are labelled.

Figs. 3 and 4 display the Doppler-shift corrected γ-ray spectra for events in coincidence with Z=8 and Z=10 gates defined in the BP vs E spectra as well as gates on Fig. 2. Most of the known transitions of both $^{16}$O and $^{20}$Ne can be identified in the energy range depicted. The six different excitation energy gates displayed in Fig. 2 are used to generate the γ-ray spectra shown in Fig. 3 (low-energy transitions). The γ-ray spectrum of Fig. 4 was triggered with the use of the gate labelled IV.

Identifications of the most intense γ rays in $^{20}$Ne is straightforward and their labelling are given in Fig. 3. As expected, we observe decays feeding the yrast line of the $^{20}$Ne nucleus.
Two previously unobserved transitions in $^{16}$O from the decay of the $3^+$ state at 11.09 MeV are clearly visible in the $\gamma$-ray spectrum of Fig. 4, have been identified for the first time in Fig. 4 (inset) for new the partial level scheme. We note that, thanks to the excellent resolving power of the EB+BRS set-up, the respective first escape peak positions of the 6.13 MeV, 6.92 MeV and 7.12 MeV $\gamma$-ray transitions in $^{16}$O are also apparent in this spectrum.

With appropriate Doppler-shift corrections applied to oxygen fragments identified in the BRS, it has been possible to extend the knowledge of the level scheme of $^{16}$O at high energies [14, 15, 16], well above the $^{12}$C+$\alpha$ threshold, 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 11.085 MeV ± 3 keV (which does not $\alpha$-decay because of non-natural parity [16], in contrast to the two neighbouring $4^+$ states at 10.36 MeV and 11.10 MeV, respectively) to the $2^+$ state at 6.92 MeV (54.6 ± 2 %) and a value for the decay width $\Gamma_\gamma$ fifty times lower than the one given in the literature [14, 15], it means $\Gamma_{3^+} < 0.23$ eV. This result is important as it is the highest known $\gamma$-decaying level for the well studied $^{16}$O nucleus [14, 15].

The connection of $\alpha$-clustering, quasimolecular resonances, orbiting phenomena and extreme deformations (SD, HD, ...) can be discussed in terms of the aspects of $\gamma$-ray spectroscopy of binary fragments from either inelastic excitations and direct transfers (with small energy damping and spin transfer) or from orbiting (fully damped) processes [13]. Exclusive data were collected with the Binary Reaction Spetrometer (BRS) in coincidence with EUROBALL IV installed at the VIVITRON Tandem facility of Strasbourg. New $\gamma$-ray spectroscopy results on $^{16}$O from the direct alpha transfer reactions has been presented in this work. The search for extremely elongated configurations (HD) in rapidly rotating medium-mass nuclei, which has been pursued exclusively using $\gamma$-spectroscopy, will have to be performed in conjunction with charged particle spectroscopy in the near future.
FIG. 4: $^{16}$O high-energy excited states populated in the $^{16}$O+$^{20}$Ne exit-channel with the gate IV of Fig. 2 as defined in the text. Doppler-shift corrections have been applied for O fragments detected in the BRS. The three blue arrows show the respective first escape peak positions of the 6.13 MeV, 6.92 MeV and 7.12 MeV $\gamma$-ray transitions in $^{16}$O. The new partial level scheme of $^{16}$O is plotted in the inset.

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