Nuclear alpha-clustering, superdeformation, and quasimolecular resonances
C. Beck

Institut de Recherches Subatomiques, UMR7500, IN2P3-CNRS/Université Louis Pasteur, B.P. 28, F-67037 Strasbourg Cedex 2, France

Nuclear alpha-clustering has been the subject of intense study since the advent of heavy-ion accelerators. Looking back for more than 40 years we are able today to see the connection between quasimolecular resonances in heavy-ion collisions and extremely deformed states in light nuclei. For example superdeformed bands have been recently discovered in light $N=Z$ nuclei such as $^{36}$Ar, $^{40}$Ca, $^{48}$Cr, and $^{56}$Ni by γ-ray spectroscopy. The search for strongly deformed shapes in $N=Z$ nuclei is also the domain of charged-particle spectroscopy, and our experimental group at IReS Strasbourg has studied a number of these nuclei with the charged particle multidetector array ICARE at the VIVITRON Tandem facility in a systematical manner. Recently the search for γ-decays in $^{24}$Mg has been undertaken in a range of excitation energies where previously nuclear molecular resonances were found in $^{12}$C+$^{12}$C collisions. The breakup reaction $^{24}$Mg+$^{12}$C has been investigated at $E_{\text{lab}}(^{24}\text{Mg}) = 130$ MeV, an energy which corresponds to the appropriate excitation energy in $^{24}$Mg for which the $^{12}$C+$^{12}$C resonance could be related to the breakup resonance. Very exclusive data were collected with the Binary Reaction Spectrometer in coincidence with EUROBALL IV installed at the VIVITRON. Preliminary results on the population of specific structures of large deformation in binary reactions will be presented and their γ-decay determined.

1. Introduction

The region of the nuclear chart between the Mg and Ni isotopes is important for the next generation of radioactive beam experiments and for several astrophysical applications. The interest in the theoretical calculations for sd-shell nuclei around $^{40}$Ca [1, 2, 3, 4, 5, 6, 7] has increased recently with the discovery of highly deformed shapes and superdeformed (SD) rotational bands in the $N=Z$ nuclei $^{36}$Ar [8, 9], $^{40}$Ca [10, 11], $^{42}$Ca [12], $^{48}$Cr [13, 14] and $^{56}$Ni [15]. Therefore the $A_{CN} \approx 30-60$ mass region becomes of particular interest since quasimolecular resonances have also been observed for these α-like nuclei, in particular, in the $^{28}$Si+$^{28}$Si reaction [16, 17]. Although there is no experimental evidence to link the SD bands with the higher lying rotational bands formed by known quasimolecular resonances [18], 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
Figure 1. Exclusive energy spectra of α particles measured in the 28Si+28Si reaction at $E_{\text{lab}} = 180$ MeV. Solid and dashed lines are CACARIZO statistical-model calculations with and without deformations effects, respectively.

have been interpreted in terms of nuclear molecules [18]. However, in many cases these structures have been connected to strongly deformed shapes and to the alpha-clustering phenomena, predicted from the α-cluster model [19], Hartree-Fock calculations [20], the Nilsson-Strutinsky approach [21], and from a generalized liquid drop model [22,23,24]. In this paper we will show that the search for strongly deformed shapes in N=Z nuclei is also the domain of charged-particle spectroscopy. In particular the study of a number of α-cluster nuclei with the charged particle multidetector array ICARE at the VIVITRON facility is presented in Sec. 2. In Sec. 3, the search for a $^{12}$C+$^{12}$C molecule in $^{24}$Mg* is discussed with a description of a recent particle-γ experiment using EUROBALL IV. Finally, a summary and discussion of our results is added in Sec. 4 for both topics.

2. Search for extremely extended shapes and cluster emission using charged-particle spectroscopy

Since the light charged particle (LCP) detection is relatively simple, the analysis of their spectral shapes (see Fig. 1) can be also considered to be a good tool for exploring nuclear deformation and other properties of hot rotating nuclei at high angular momenta [25,26] which are primarily investigated by γ-ray spectroscopy [27]. The LCP's emitted during the CN decay processes carry information on the underlying nuclear shapes and level densities. New information on nuclear structure far above the yrast line can be obtained from their study by a comparison with statistical-model calculations. An experimental programme
is undertaken at the VIVITRON Tandem facility of the IReS Strasbourg laboratory in the ICARE scattering chamber. Both the heavy fragments \((A \geq 10)\) and their associated LCP’s (protons, deuterons, tritons, \(^3\)He, and \(\alpha\) particles) were detected in coincidence using the ICARE charged-particle multidetector array \[25,26\] which consists of nearly 50 telescopes. The properties of the LCP’s emitted in the \(^{28}\)Si+\(^{28}\)Si reaction at the bombarding energy \(E_{\text{lab}} = 112\) MeV, which corresponds to the \(^{56}\)Ni excitation energy of the conjectured \(J^\pi = 38^+\) quasimolecular resonance \[16,17\], were first investigated \[25\]. The magnitude of the adjustments in the yrast line position suggests deformation effects at high spin for the \(^{56}\)Ni composite system in agreement with very recent \(\gamma\)-ray spectroscopy data obtained at much lower spins \[15\]. This is also consistent with the generalized liquid drop model developed by G. Royer and coworkers \[24\]. The extent to which the resonant behaviour is responsible to the observed nuclear deformation is still an open question. To resolve this issue, we have performed a subsequent \(^{28}\)Si+\(^{28}\)Si experiment at \(E_{\text{lab}} = 180\) MeV outside the “molecular window” where quasimolecular resonances are known to disappear \[28\]. The strong cluster emission of \(^8\)Be which was observed by the \(^{28}\)Si+\(^{12}\)C reaction \[26\] has motivated the search for similar effects in the \(^{27}\)Al+\(^{12}\)C \[31\], \(^{31}\)P+\(^{12}\)C \[31\], \(^{32}\)S+\(^{12}\)C \[29\], and \(^{16}\)O+\(^{28}\)Si \[30\] reactions. Deformation effects have also been investigated in great detail in \(^{28}\)Si+\(^{12}\)C \[26\], in \(^{32}\)S+\(^{12}\)C \[29\], and in \(^{16}\)O+\(^{28}\)Si \[30\].

Exclusive energy spectra measured for \(\alpha\) particles are displayed in Fig. 1 for \(^{28}\)Si+\(^{28}\)Si. The analysis of the data has been performed using CACARIZO \[25\], the Monte Carlo version of the statistical-model code CASCADE. The parameters needed for the statistical description, i.e. the nuclear level densities and the barrier transmission probabilities, are usually obtained from the study of LCP evaporation spectra. The change in the emission barriers and, correspondingly, the transmission probabilities affects the lower energy part of the calculated evaporation spectra. On the other hand the high-energy part of the \(\alpha\)-particle spectra depends critically on the available phase space obtained from the level densities at high spin. This is clearly shown by the solid and dashed lines of Fig. 1 for \(^{28}\)Si+\(^{28}\)Si at \(E_{\text{lab}} = 180\) MeV. The level density, \(\rho(E, J)\), for a given angular momentum \(J\) and energy \(E\) is given by the well known Fermi gas expression:

\[
\rho(E, J) = \frac{(2J+1)A^{1/2}}{12} \cdot \frac{h^2}{2J_{\text{eff}}} \cdot \frac{3/2}{(E - \Delta - T - E_J)^2} \cdot \exp(2[a(E - \Delta - T - E_J)]^{1/2})
\]

where \(a\) is the level density parameter set equal to \(a = A/8\) MeV\(^{-1}\) (\(A\) is the mass number), \(T\) is the “nuclear” temperature, and \(\Delta\) is the pairing correction, \(E_J = \frac{h^2}{2J_{\text{eff}}} J(J+1)\) is the rotational energy, \(J_{\text{eff}} = J_{\text{sphere}} \times (1 + \delta_1 J^2 + \delta_2 J^4)\) is the effective moment of inertia, \(J_{\text{sphere}} = \frac{2}{5}AR^2 = \frac{2}{5}A^{5/3}r_0^2\) is the rigid body moment of inertia of a spherical nucleus with radius parameter \(r_0\), and \(\delta_1\) and \(\delta_2\) are the deformability parameters. The solid lines in Fig. 1 show the predictions using the same parameter set with deformation effects that has been used at \(E_{\text{lab}} = 180\) MeV \[25\]. Predictions with the parameters of the finite-range liquid drop model \[32\] are unable to reproduce the data (dashed lines). Since the highest incident energy is outside of the “molecular window” \[28\], we conclude that the highly deformed shapes (with \(\beta \approx 0.5\)) observed for both energies are not related to the \(^{28}\)Si+\(^{28}\)Si quasimolecular resonances \[16,17,28\]. However they may still be linked to shape isomericism of rotating \(^{56}\)Ni as suggested very recently by G. Royer et al. \[24\]. Similarly, the extremely extended shapes that are needed to explain the \(\alpha\)-particle spectra measured in the \(^{28}\)Si+\(^{12}\)C \[26\], \(^{32}\)S+\(^{12}\)C \[29\], and \(^{28}\)Si+\(^{16}\)O \[30\] reactions should correspond to shape
Figure 2. Energy-correlation plots between α particles and ER’s for the $^{28}\text{Si}+^{12}\text{C}$, $^{27}\text{Al}+^{12}\text{C}$, $^{32}\text{S}+^{12}\text{C}$, and $^{16}\text{O}+^{28}\text{Si}$ reactions at the indicated angle settings.
isomerism of rotating $^{40}$Ca \cite{22} and $^{44}$Ti \cite{23,24}.

Superimposed on the Maxwellian shapes typical of their evaporative origin, nonstatistical $\alpha$-particles components were found in the energy spectra measured in coincidence with S residues in the $^{28}$Si+$^{12}$C reaction \cite{26} and Ar residues for the $^{32}$S+$^{12}$C reaction \cite{29}, respectively. In both reactions, these additional components attributed to the decay of unbound $^8$Be nuclei are more easily observed in the corresponding energy correlation plot displayed in Fig. 3 (left side of the upper panel). They appear as well defined peaks lying outside the “statistical evaporation region” which is consistent with CACARIZO calculations (see Fig. 10 of Ref. \cite{26}). Their “folding angles” are compatible with the two-body kinematics required for the $^{32}$S+$^8$Be binary exit-channel. To clearly establish the mechanism resulting in these yields subsequent experiments have been undertaken with other reaction with a $^{12}$C target \cite{31} such as $^{27}$Al(150 MeV)+$^{12}$C and $^{31}$P(112 MeV)+$^{12}$C. Fig. 2 also displays the energy-correlation plots between $\alpha$ particles and ER’s for three of these reactions \cite{31} and for the $^{16}$O+$^{28}$Si reaction at $E_{lab}(^{16}$O) = 112 MeV \cite{30}. The fact that the two-body components do not show-up for this last reaction \cite{30} indicates the binary nature of the $\alpha$-particle peaks present in the reactions involving a $^{12}$C target. This hypothesis is consistent with the cluster-transfer picture proposed by Morgenstern et al. \cite{33} for incomplete fusion mechanisms.

To summarize this topic, we have confirmed that the charged-particle spectroscopy appears to be a very efficient technique to search for superdeformed and hyperdeformed shapes in light ions, as well as to identify $^8$Be and $^{12}$C $\alpha$-cluster emissions with excellent selectivity at high excitation energy.

3. Search for the $^{12}$C+$^{12}$C molecule in the $^{24}$Mg+$^{12}$C breakup reaction

In the presentation of the second topic of this paper we investigate 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. Various decay branches from the highly excited $^{24}$Mg$^*$ nucleus, including the emission of $\alpha$ particles or heavier fragments such as $^8$Be and $^{12}$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 \cite{35,36,37}, which have searched for these very small branches expected in the range of $10^{-4} - 10^{-5}$ fractions of the total width \cite{38,39}. 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 $^{24}$Mg$^*$ as populated by a breakup process (via resonances) as shown in previous works \cite{40,41,42}. The $^{24}$Mg+$^{12}$C reaction has been extensively investigated by several measurements of the $^{12}$C($^{24}$Mg,$^{12}$C$^{12}$C) $^{12}$C breakup channel \cite{40,41,42}. 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 $^{12}\text{C}+^{12}\text{C}$ quasi-molecular configuration. Several attempts \cite{11} were made to link the $^{12}\text{C}+^{12}\text{C}$ barrier resonances \cite{13} with the breakup states. The underlying reaction mechanism is now fairly well established \cite{12} 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 \cite{21}.

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 $E_{\text{lab}}(^{24}\text{Mg}) = 130 \text{ MeV}$ with the Binary Reaction Spectrometer \cite{14} (BRS) in coincidence with EUROBALL IV installed at the Vivitron \cite{39}. The choice of the $^{12}\text{C}(^{24}\text{Mg},^{12}\text{C})^{24}\text{Mg}^*$ reaction implies that for an incident energy of $E_{\text{lab}} = 130 \text{ MeV}$ an excitation energy range up to $E^* = 30 \text{ MeV}$ in $^{24}\text{Mg}$ is covered \cite{11}. The BRS gives access to a novel approach to the study of nuclei at large deformations \cite{39}. 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 kinematical 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. Fig. 3 displays a typical example of a two-dimensional Bragg-Peak versus energy spectrum obtained for the $^{24}\text{Mg}+^{12}\text{C}$ reaction. This coincident spectrum shows the excellent charge discrimination achieved with the Bragg-curve ionization chambers. The $Z=12$ gate, which is shown in Fig. 3, will be used in the following for the processing of the $\gamma$-ray spectra of the $^{24}\text{Mg}$ nucleus of interest.

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 angular range is optimum for $\theta_{\text{lab}} = 12^\circ\text{-}40^\circ$ in the lab-system (with $\theta_{\text{lab}} = 12^\circ\text{-}25^\circ$ for the recoils) 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. 4 displays a Doppler-corrected $\gamma$-ray spectrum for $^{24}\text{Mg}$ events in coincidence with the $Z=12$ gate defined in the Bragg-Peak vs energy spectrum of Fig. 3. All known transitions of $^{24}\text{Mg}$ \cite{16,43} 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 $K=2$ rotational band, appears to be selectively enhanced. The strong population of the $K=2$ band has also been observed in the $^{12}\text{C}(^{12}\text{C},\gamma)$ radiative capture reaction \cite{14}. 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. [43]. It has been checked in the $\gamma$-$\gamma$ coincidences that most of the states of Fig. 4 belong to cascades which contain the characteristic 1368 keV $\gamma$-ray and pass through the lowest $2^+$ state in $^{24}\text{Mg}$. Still a number of transitions in the high-energy part of the spectrum (6000 keV - 8000 keV) have not been clearly identified. The reason why the search for a $\gamma$-decay in $^{12}\text{C}+^{12}\text{C}$ has not been conclusive so far [35,36,37] is due to the excitation energy in $^{24}\text{Mg}$ as well as the spin region ($8\hbar$-$12\hbar$) 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.

4. Summary and conclusions

The occurrence of highly deformed configurations in light $N=Z$ nuclei and their possible link with alpha-clustering have been investigated at the Vivitron Tandem facility of the IReS Strasbourg by using two complementary experimental techniques: either the ICARE charged-particle multidetector array or the BRS/Euroball IV detection system. In the first case, the properties of the emitted LCP’s in several reactions have been analysed with the CACARIZO statistical-model code that was adapted to calculate evaporation spectra and angular distributions for deformed nuclei. The measured observables such as energy spectra in-plane and out-of-plane angular correlations are well described by Hauser-Feshbach calculations which include spin-dependent level densities. The magnitude of the adjustments in the yrast line suggests deformations at high spins that are far in excess of those predicted by the finite-range liquid drop model [32]. The deformation parameters deduced for the $^{28}\text{Si}+^{12}\text{C}$ [26], $^{32}\text{S}+^{12}\text{C}$ [29], $^{16}\text{O}+^{28}\text{Si}$ [30], and $^{28}\text{Si}+^{28}\text{Si}$ [25] reactions are comparable to recent $\gamma$-ray spectroscopy data for the $^{40}\text{Ca}$ nucleus [10] and
for the $^{56}$Ni nucleus \cite{15} at much lower spins. The use of large $\gamma$-ray multidetector arrays will be helpful to extend the existing level scheme of the $^{44}$Ti nucleus \cite{34} for the search for weakly populated SD rotational bands (predicted by the theory \cite{45}) equivalent to those discovered in $^{40}$Ca \cite{10}. For the both the $^{28}$Si+$^{12}$C and $^{32}$Si+$^{12}$C reactions the components which are found in the $\alpha$-particle energy spectra measured in coincidence with S and Ar residues are attributed to the cluster decay of unbound $^{8}$Be nuclei \cite{26,29}. The hypothesis of the binary nature of the $^{8}$Be cluster emission is consistent with the preliminary results found for the two other reactions involving a $^{12}$C target \cite{31}: $^{27}$Al+$^{12}$C at $E_{\text{lab}} = 150$ MeV, $^{31}$P+$^{12}$C at $E_{\text{lab}} = 112$ MeV and 220 MeV. In the second topic of the paper the link of alpha-clustering and quasimolecular resonances has been discussed with the search for the $^{12}$C+$^{12}$C molecule populated by the $^{24}$Mg+$^{12}$C breakup reaction. The most intriguing result is the strong population of the K=2 band of the $^{24}$Mg nucleus that has also been observed in an exploratory investigation of the $^{12}$C($^{12}$C,$\gamma$) radiative capture reaction \cite{44}. New experiments are planned in the near future with highly efficient spectrometers (the Dragon separator at Triumf and the Fma at Argonne) to study this possible overlap of the $^{24}$Mg states observed in the present work with radiative capture states more in detail. As far as the $\gamma$-ray spectroscopy is concerned, the coexistence of $\alpha$-cluster states and superdeformed states predicted in $^{32}$S by antisymmetrized molecular dynamics (AMD) studies \cite{45} is still an experimental challenge.

Acknowledgments: I would like to acknowledge the physicists of Icare and BRS/Euroball IV collaborations, with special thanks to M. Rousseau, P. Papka, A. Sánchez i Zafra, C. Bhat-tacharya, and S. Thummerer. We thank the staff of the Vivitron for providing us with good stable beams, M.A. Saettel for preparing targets, and J. Devin and C. Fuchs for their excellent support during the experiments. This work was supported by the french IN2P3/CNRS and the EC Euroviv contract HPRI-CT-1999-00078.

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