Role of deformation in the decay of $^{56}$Ni and $^{40}$Ca di-nuclei

C. Bhattacharya*, M. Rousseau, C. Beck, V. Rauch, R. Nouicer, R.M. Freeman, O. Stezowski, D. Mahboub

IRES, UMR7500, CNRS-IN2P3 et Université Louis Pasteur, F-67037 Strasbourg, France

S. Belhabib, A. Hachem, E. Martin

Université de Nice-Sophia-Antipolis, Nice, France

A. Dummer, S.J. Sanders

University of Kansas, Lawrence, Kansas 66045, USA

A. Szanto de Toledo

Instituto de Fisica da Universidade de São Paulo, São Paulo, Brazil

*Permanent address : Variable Energy Cyclotron Centre, 1/A F Bidhan Nagar, Calcutta, India
ABSTRACT

Inclusive as well as exclusive energy spectra of the light charged particles emitted in the $^{28}\text{Si}(E_{\text{lab}} = 112.6\ \text{MeV}) + ^{28}\text{Si}, ^{12}\text{C}$ reactions have been measured at the Strasbourg VIVITRON facility in a wide angular range $15^0$ - $150^0$, using the ICARE multidetector array. The observed $\alpha$-particle energy spectra are generally well reproduced by the statistical model using a spin-dependent level density parameterisation. The results suggest significant deformation effects at high spin.
I. INTRODUCTION

In recent years, a number of experimental and theoretical studies have been made to understand the decay of light di-nuclear systems ($A \leq 60$) formed through low-energy ($E_{lab} \leq 10$ MeV/nucleon), heavy-ion reactions. In most of the reactions studied, the properties of the observed, fully energy damped yields have been successfully explained in terms of either a fusion-fission (FF) mechanism or a heavy-ion resonance behavior [1].

The strong resonance-like structures observed in elastic and inelastic excitation functions of $^{24}$Mg+$^{24}$Mg [2] and $^{28}$Si+$^{28}$Si [3] have indicated the presence of shell stabilized, highly deformed configurations in the $^{48}$Cr and $^{56}$Ni compound systems, respectively. In a recent experiment using EUROGAM, the present collaboration studied the possibility of preferential population of highly deformed bands in the symmetric fission channel of the $^{56}$Ni compound nucleus as produced through the $^{28}$Si+$^{28}$Si [4] reaction at $E_{lab} = 111.6$ MeV.

The present work aims to investigate the possible occurrence of highly deformed configurations of the $^{50}$Ni and $^{40}$Ca di-nuclei produced in the $^{28}$Si+$^{28}$Si and $^{28}$Si+$^{12}$C reactions through the study of light charged particle (LCP) emission. In-plane coincidences of the LCP’s with both evaporation residues (ER) and FF fragments have been measured. The LCP’s emitted from FF fragments may provide informations on the deformation properties of these fragments. Moreover, the in-plane angular correlations data will be used to extract the temperatures of the emitters. In this paper we will concentrate on the ER results.
II. EXPERIMENTAL DETAILS

The experiments were performed at the IReS Strasbourg VIVITRON tandem facility using 112.6 MeV $^{28}\text{Si}$ beams on $^{28}\text{Si}$ (180 $\mu$g/cm$^2$) and $^{12}\text{C}$ (160 $\mu$g/cm$^2$) targets. Both the heavy ions and their associated LCP’s were detected using the ICARE charged particle multidetector array. The heavy fragments (ER, quasi-elastic, deep-inelastic and FF fragments) were detected in eight telescopes, each consisting of an ionization chamber (IC) followed by a 500 $\mu$m Si detector. The in-plane detection of coincident LCP’s was done using four triple telescopes (Si 40 $\mu$m, Si 300 $\mu$m, 2 cm CsI(Tl)) placed at forward angles, 16 two-element telescopes (Si 40 $\mu$m, 2 cm CsI(Tl)) placed at forward and backward angles and two telescopes consisting of IC’s followed by 500 $\mu$m Si detectors placed at the most backward angles. The IC’s were filled with isobutane and the pressures were kept at 30 torr and at 60 torr for detecting heavy fragments and light fragments, respectively. Typical inclusive and exclusive (coincidence with all ER’s detected at 15°) energy spectra of $\alpha$ particles at 40° for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction are shown by solid histograms in Fig. 1(a) and 1(b), respectively. Exclusive $^{28}\text{Si} + ^{12}\text{C}$ $\alpha$ spectra measured at 40° in coincidence with S and P ER’s at 15° are also displayed in Fig. 2.
III. EXPERIMENTAL RESULTS AND STATISTICAL-MODEL CALCULATIONS

The data analysis was performed using CACARIZO, the Monte Carlo version of the statistical-model code CASCADE [6]. The angular momenta distributions, needed as the principal input to constrain the calculations were taken from compiled $^{28}$Si+$^{28}$Si [4] and $^{28}$Si+$^{12}$C [3,4] complete fusion data. The other ingredients for the realistic statistical-model calculations such as the nuclear level densities and the barrier transmission coefficients, are usually deduced from the study of the evaporated light particle spectra. In recent years, it has been observed in many cases that the standard statistical model cannot predict the shape of the evaporated $\alpha$-particle energy spectra satisfactorily [3,10,11], with the measured average energies of the $\alpha$ particles generally much lower than the corresponding theoretical predictions. Several attempts have been made to explain this anomaly either by changing the emission barrier or by using a spin-dependent level density. The change in the emission barriers and consequently the transmission probabilities affects the lower energy part of the calculated evaporation spectra. On the other hand, the high-energy part of the spectra depends critically on the available phase space obtained from the level densities at high spin as well as the corresponding transmission coefficients. In hot rotating nuclei formed in heavy-ion reactions, the level density at higher angular momentum should be spin dependent. The level density, $\rho(E, J)$, for a given angular momentum $J$ and energy $E$ is given by the well known Fermi gas expression:

$$\rho(E, J) = \frac{(2J + 1)}{12} a^{1/2} \frac{\hbar^2}{2J_{eff}} \left( \frac{1}{(E - \Delta - E_J)^2} \right) exp(2[a(E - \Delta - E_J)]^{1/2}),$$

where $a$ is the level density parameter, $\Delta$ is the pairing correction and $E_J = \frac{\hbar^2}{2J_{eff}} J(J+1)$ is the rotational energy, $J_{eff} = J_0 \times (1 + \delta_1 J^2 + \delta_2 J^4)$ is the effective moment of inertia, $J_0$ is the rigid body moment of inertia and $\delta_1, \delta_2$ are the deformation parameters [3,4].

By changing the deformation parameters one can simulate the deformation effects on
the level densities. The CACARIZO calculations have been performed using two sets
of input parameters: one with a standard set and another with non-zero values for the
deformation parameters.

The solid lines in Fig. 1 show the predictions of CACARIZO using the standard
parameter set with the usual liquid drop model deformation. It is clear that the aver-
age energies of the measured α spectra are lower than those predicted by the standard
statistical-model calculations. The dashed lines show the predictions of CACARIZO using
$\delta_1 = 3.2 \times 10^{-4}$ and $\delta_2 = 2.2 \times 10^{-7}$. The shapes of the inclusive as well as the exclusive
α energy spectra are well reproduced after including the deformation effects.

In the case of $^{28}\text{Si} + ^{12}\text{C}$ an interesting result is observed. In order to explain the
inclusive energy spectra of α-particles it has been necessary to use the similar deformation
parameters as for $^{28}\text{Si} + ^{28}\text{Si}$ system. However, it was not possible to explain the exclusive
energy spectra of α particles obtained in coincidence with all of the ER’s using this set.
Therefore, α energy spectra have been generated in coincidence with individual S and P
ER’s as shown in Fig. 2. The shape of the α spectrum (solid histograms) obtained in
coincidence with S is completely different from the spectrum obtained in coincidence with
P.

The dashed lines in Fig. 2 are the predictions of CACARIZO using non-zero values
of $\delta_1$ and $\delta_2$. The shape of the α spectrum measured in coincidence with P is reasonably
well reproduced by the theoretical curve. However, the model could not predict the shape
of the α spectrum obtained in coincidence with S. This is due to the fact that in this
case, there may be additional contributions to the α-particle spectra from the decay of
unbound $^8\text{Be}$, produced through a binary decay such as asymmetric FF and/or an orbiting
mechanism with $^{40}\text{Ca} \rightarrow ^{32}\text{S} + ^8\text{Be}$. This confirms the double-humped structure found in
the inclusive $^{32}\text{S}$ velocity spectra measured by Harmon et al. [8]. The question of the real
nature (FF or orbiting) of this decay process remains open.
IV. SUMMARY

Inclusive as well as exclusive energy spectra of $\alpha$-particles have been measured for the reaction $^{28}\text{Si} + ^{28}\text{Si}$ and $^{28}\text{Si} + ^{12}\text{C}$, respectively. The observed energy spectra of $\alpha$ particles are not well reproduced by the standard statistical-model calculations with the usual liquid drop model deformation. However, a satisfactory description of the measured energy spectra has been achieved by invoking the changes in the level density and barrier due to the onset of large deformation effects at high spins. The $\alpha$ spectra obtained in coincidence with $S$ for the reaction $^{28}\text{Si} + ^{12}\text{C}$ have an additional component which may come from the decay of $^8\text{Be}$, which is unbound and produced through the binary decay of $^{40}\text{Ca} \rightarrow ^{32}\text{S} + ^8\text{Be}$. Work is in progress to analyse the proton energy spectra as well as the angular correlations of both the proton and $\alpha$ in-plane angular correlations.
V. REFERENCES

[1] K. Farrar et al., Phys. Rev. C 54, 1249 (1996) and references therein.

[2] R.W. Zurmühle et al., Phys. Lett. 129B, 384 (1983).

[3] R.R. Betts et al., Phys. Rev. Lett. 47, 23 (1981).

[4] R. Nouicer, Ph.D. Thesis, Strasbourg University, Report IReS 97-35.

[5] T. Bellot, Ph. D. Thesis, Strasbourg University, Report IReS 97-34.

[6] G. Viesti et al., Phys. Rev. C 38, 2640 (1988) and references therein.

[7] M.F. Vineyard et al., Phys. Rev. C 41, 1005 (1990).

[8] B.A. Harmon et al., Phys. Rev. C 34, 552 (1986).

[9] M.F. Vineyard et al., Phys. Rev. C 47, 2374 (1993).

[10] G. La Rana et al., Phys. Rev. C 37, 1920 (1988); ibidem C 40, 2425 (1989).

[11] I.M. Govil et al., Phys. Rev. C 57, 1269 (1998); ibidem Phys. Lett. B307, 283 (1993).
VI. FIGURE CAPTIONS

FIG. 1. $\alpha$-particle energy spectra obtained at $40^0$ for the $^{28}\text{Si}+^{28}\text{Si}$ reaction.

FIG. 2. Exclusive $\alpha$-particle energy spectra obtained at $40^0$ for the $^{28}\text{Si}+^{12}\text{C}$ reaction.
(a) Inclusive

\[ \frac{d^2\sigma}{dE \, d\Omega} \text{ (a.u)} \]

(b) Exclusive

\[ E_{\text{lab}} \text{(MeV)} \]
(a) in coin. with S

(b) in coin. with P

\( d^2\sigma / dE d\Omega \) (a.u.)

E_{lab} (MeV)