PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 57, No. 1
July 2001
pp. 203–207

Deformation effects in the ^{28}Si + ^{12}C and ^{28}Si + ^{28}Si reactions

C BHATTACHARYA[a,e], M ROUSSEAU[a], C BECK[a], V RAUCH[a], R M FREEMAN[a], R NOUICER[a] F HAAS[a], O DORVAUX[a], K EDDAHBI[a], P PAPKA[a], O STEZOWSKI[a], S SZILNER[a], D MAHBOUB[a], A SZANTO DE TOLEDO[b], A HACHEM[c], E MARTIN[c] and S J SANDERS[d]

[a]Institut de Recherches Subatomiques, F-67037 Strasbourg, Cedex 2, France
[b]Instituto de Física da Universidade de São Paulo, São Paulo, Brazil
[c]Université de Nice-Sophia-Antipolis, Nice, France
[d]University of Kansas, Lawrence, KS 66045, USA
[e]Present address: Variable Energy Cyclotron Centre, Kolkata, India

Abstract. The possible occurrence of highly deformed configurations is investigated in the ^{40}Ca and ^{56}Ni di-nuclear systems as formed in the ^{28}Si + ^{12}C, ^{28}Si reactions by using the properties of emitted light charged particles. Inclusive as well as exclusive data of the heavy fragments and their associated light charged particles have been collected by using the ICARE charged particle multidetector array. The data are analysed by Monte Carlo CASCADE statistical-model calculations using a consistent set of parameters with spin-dependent level densities. Significant deformation effects at high spin are observed as well as an unexpected large ^{8}Be cluster emission of a binary nature.

Keywords. Fusion–fission; nuclear deformation; exclusive light charge particle measurements.

PACS Nos 25.70.Jj; 25.70.Gh

1. Introduction

Extensive efforts have been made in recent years, to understand the decay of *light* di-nuclear systems ($A_{\rm CN} \le 60$) formed through low-energy ($E_{\rm lab} \le 10$ MeV/nucleon) heavy-ion reactions [1]. In most of the reactions studied, the observed fully energy-damped yields of the fragments have been successfully explained in terms of a fusion–fission mechanism [1] with the noticeable exception of ^{28}Si + ^{12}C reaction for which the deep-inelastic orbiting mechanism has been found to be particularly competitive [2]. Strong resonance-like structures have been observed in elastic and inelastic excitation functions of some specific reactions (such as ^{24}Mg + ^{24}Mg or ^{28}Si + ^{28}Si) indicating the presence of shell stabilized, highly deformed configurations in the (^{48}Cr and ^{56}Ni) compound systems [3,4]. The investigation of the structure of the doubly-magic ^{56}Ni nucleus has recently become a subject of great interest [5–9]. In a recent experiment using the EUROGAM multidetector array, the present collaboration studied the possibility of preferential population of highly deformed bands in the symmetric fission channel of the ^{56}Ni compound nucleus (CN), produced through the ^{28}Si + ^{28}Si [10,11] reaction at $E_{\rm lab} = 112$ MeV, which corresponds to the energy of the conjectured $J^{\pi} = 38\hbar$ quasi-molecular resonance [4].

The study of light charged particle (LCP) emission is a good tool in exploring nuclear deformations and other properties of hot rotating nuclei at high spins and angular momenta [12–16]. The present work has been performed with the aim to investigate the possible occurrence of highly deformed configurations of the ^{40}Ca and ^{56}Ni di-nuclear systems as formed in the ^{28}Si + ^{12}C and ^{28}Si + ^{28}Si reactions, by using the properties of emitted LCP. Inclusive as well as exclusive data of the heavy fragments $(A \geq 6)$ and their associated light charged particles ($p, d, t,$ and α-particles) emitted in both reactions at $E_{\rm lab}$(^{28}Si) = 112, 180 MeV have been measured [17–20] using the *ICARE* multidetector array [21]. The LCP's emitted from FF fragments may provide the deformation properties of these fragments. Moreover, the in-plane angular correlations data will be used to extract the emitters temperatures. In this paper we will present the exclusive data of LCP's in coincidence with ER.

2. Experimental details

The two experiments were performed at the IReS Strasbourg VIVITRON Tandem facility using 112 MeV and 180 MeV ^{28}Si beams on ^{12}C (160 μg/cm^2 thick) and ^{28}Si (230 μg/cm^2 thick) targets respectively [17–20]. Both the heavy ions $(A \geq 6)$ and their associated LCP's ($p, d, t,$ and α) were detected using the *ICARE* charged particle multidetector array [21] which consists in nearly 40 telescopes in coincidence. The heavy fragments, i.e. ER, quasi-elastic (QE), DI, and FF fragments, were detected in 10 telescopes, each consisting of an ionization chamber (IC) followed by a 500 μm Si detector. The in-plane coincident LCP's were detected using either 3 three-elements telescopes (Si 40 μm, Si 300 μm, 2 cm CsI(Tl)) or 24 two-elements telescopes (Si 40 μm, 2 cm CsI(Tl)) and two double telescopes (IC, Si 500 μm) located at the most backward angles. The IC's were filled with isobutane and the pressures were kept at 30 Torrs and at 60 Torrs for detecting heavy fragments and light fragments, respectively. The acceptance of each telescope was defined by thick aluminium collimators.

3. Experimental results

3.1 *Exclusive energy spectra*

The LCP spectra obtained in both the reactions have Maxwellian shapes with an exponential fall-off at high energy (their shape and high-energy slopes are essentially independent of c.m. angle) which reflects a relatively low temperature of the decaying nucleus.

This is the signature of a statistical de-excitation process arising from a thermalized compound nucleus like source. The energy spectra of the coincident α-particles, for the reactions ^{28}Si + ^{28}Si and ^{28}Si + ^{12}C at $E_{\rm lab} = 180$ MeV, have been displayed in figures 1 and 2 respectively [19].

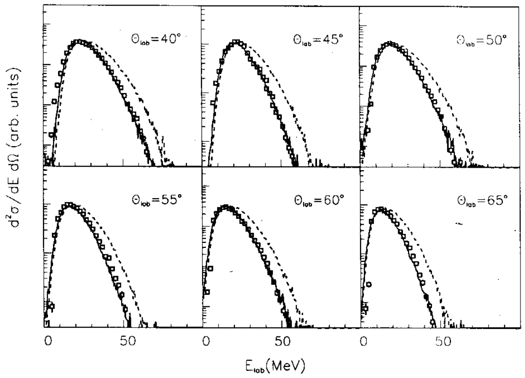

Figure 1. Exclusive energy spectra of α-particles emitted, at the indicated laboratory angles, in the 180 MeV ^{28}Si + ^{28}Si reaction. The solid and dashed lines are statistical-model calculations discussed in the text.

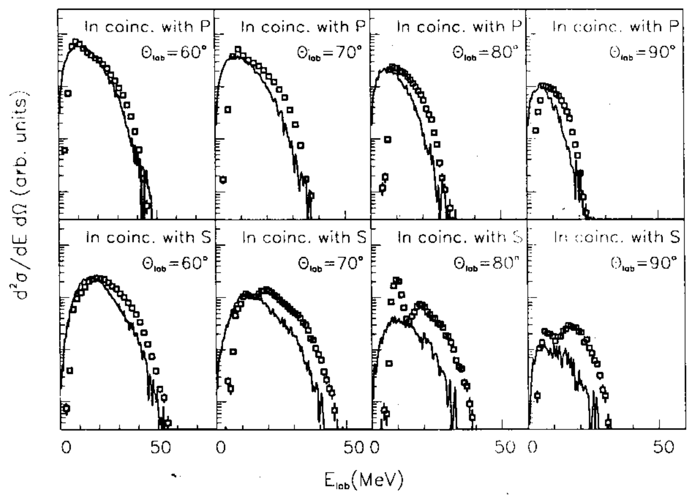

Figure 2. Exclusive energy spectra of α-particles emitted in coincidence with S and P ER's detected at $-10°$, at the indicated laboratory angles, in the 180 MeV ^{28}Si + ^{12}C reaction. The solid lines are statistical-model calculations discussed in the text.

3.2 *Analysis and discussions*

The analysis of the data has been performed using CACARIZO [12], the Monte Carlo version of the statistical-model code CASCADE [22] . The informations on the main ingredients of the statistical description, i.e., the nuclear level densities and the barrier transmission probabilities, are usually obtained from the study of the evaporated light particle spectra. In recent years, it has been observed that the standard statistical model could not predict satisfactorily, the shape of the evaporated α-particle energy spectra [12–16] and the measured average energies of the α-particles were much lower than the corresponding theoretical predictions. Several attempts have been made in the past few years to explain this anomaly either by changing the emission barrier or using a spin-dependent level density [12,13,15,16]. In hot rotating nuclei formed in heavy-ion reactions, the energy level density at higher angular momentum is 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:

$$\rho(E,J) = \frac{(2J+1)}{12} a^{1/2} \left(\frac{\hbar^2}{2\mathcal{J}_{\text{eff}}}\right)^{3/2} \frac{1}{(E-\Delta-t-E_J)^2} \exp(2[a(E-\Delta-t-E_J)]^{1/2}). \tag{1}$$

where a the level density parameter is taken equal to $A/8, t$ is the 'nuclear' temperature, and Δ is the pairing correction, $E_J = \frac{\hbar^2}{2\mathcal{J}_{\text{eff}}} J(J+1)$ is the rotational energy, $\mathcal{J}_{\text{eff}} = \mathcal{J}_0 \times (1 + \delta_1 J^2 + \delta_2 J^4)$ is the effective moment of inertia, $\mathcal{J}_0$ is the rigid body moment of inertia, and δ_1 and δ_2 are the deformation parameters [22].

By changing the deformability parameters δ_1 and δ_2 one can simulate the spin-dependent level density [12,13,15]. The CACARIZO calculations have been performed using two sets of input parameters: one with a standard set consistent with the deformation of the finite range liquid drop model (FRLDM) [23], and another with a spin-dependent moment of inertia and non-zero values for the deformability parameters.

As observed at $E_{\text{lab}} = 112$ MeV data [17], the energy spectra of the α spectra is well reproduced after including the deformation. The dashed lines in figure 1 show the predictions of CACARIZO using the standard FRLDM deformation parameter set. It is clear that the average energies of the measured α energy spectra are lower than those predicted by the standard statistical-model calculations. The solid lines show the predictions of CACARIZO using the parameter set with non-zero values δ_1 and δ_2.

The exclusive energy spectra of α-particle measured in coincidence with individual S and P ER's, which are shown in figure 2 for the reaction ^{28}Si + ^{12}C at $E_{\text{lab}} = 180$ MeV, are quite interesting. The spectra associated with S are completely different from those associated with P. The latter are reasonably well reproduced by the CACARIZO curves whereas the model could not predict the shape of the spectra obtained in coincidence with S. An additional non-statistical components appear to be significant in this case. Similar results have been observed at the lower bombarding energy $E_{\text{lab}} = 112$ MeV [17,18]. These non-statistical components may come from the decay of unbound ^{8}Be (in g.s. and the two first excited states) produced in the binary reaction $^{40}\text{Ca} \rightarrow {}^{32}\text{S} + {}^{8}\text{Be}$ of a massive transfer type [24].

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