$^8$Be cluster emission versus $\alpha$ evaporation in $^{28}$Si + $^{12}$C

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Abstract

The possible occurrence of highly deformed configurations in the $^{40}$Ca dinuclear system formed in the $^{28}$Si + $^{12}$C reaction is investigated by analyzing the spectra of emitted light charged particles. Both inclusive and exclusive measurements of the heavy fragments ($A \geq 10$) and their associated light charged particles (protons and $\alpha$ particles) have been made at the IReS Strasbourg VIVITRON Tandem facility at bombarding energies of $E_{\text{lab}}(^{28}\text{Si}) = 112$ MeV and 180 MeV by using the ICARE charged particle multidetector array. The energy spectra, velocity distributions, in-plane and out-of-plane angular correlations of light charged particles are compared to statistical-model calculations using a consistent set of parameters with spin-dependent level densities. This spin dependence approach suggests the onset of large nuclear deformation in $^{40}$Ca at high spin. This conclusion might be connected with the recent observation of superdeformed bands in the $^{40}$Ca nucleus. The analysis of $\alpha$ particles in coincidence with $^{32}$S fragments suggests a surprisingly strong $^8$Be cluster emission of a binary nature.

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I. INTRODUCTION

The formation and binary decay of light nuclear systems in the $A_{CN} \leq 60$ mass region produced by low-energy ($E_{lab} \leq 7$ MeV/nucleon) heavy-ion reactions has been extensively studied both from the experimental and the theoretical points of view [1]. In most of the reactions studied the binary breakup of the compound nucleus (CN) is seen as either a fusion-fission (FF) [1,2] or a deep-inelastic (DI) orbiting [3] process. The large-angles orbiting yields are found to be particularly strong in the $^{28}$Si + $^{12}$C reaction [4], as illustrated by Fig. 1 which summarizes some of the experimental results that have been collected for this system; i.e., orbiting cross sections [4,5] and total evaporation residue (ER) cross sections [6–12]. Since many of the conjectured features for orbiting yields are similar to those expected for the FF mechanism, it is difficult to fully discount FF as a possible explanation for the large energy-damped $^{28}$Si + $^{12}$C yields [3,5]. However, FF calculations [1] significantly underpredict the cross sections measured in the carbon channel by almost a factor of 3, thus suggesting an alternative mechanism (See Fig. 1). FF, DI orbiting, and even molecular-resonance behavior may all be active [13] in the large-angle yields of the $^{28}$Si + $^{12}$C reaction [14,15]. The back-angle elastic scatterings of $^{28}$Si ions from $^{12}$C displays structured excitation functions and oscillatory angular distributions in agreement with the relatively weak absorption of this system [16]. Moreover, the resonant gross structure [14] is fragmented into very striking intermediate width resonant structure [15].

Superdeformed (SD) rotational bands have been found in various mass regions ($A = 60, 80, 130, 150$ and 190) and, very recently, SD bands have also been discovered in the $N = Z$ nuclei $^{36}$Ar [17,18] and $^{40}$Ca [19]. These new results make the $A_{CN} \approx 40$ mass region of particular interest since quasimolecular resonances have also been observed in both the $^{36}$Ar and $^{40}$Ca dinuclear systems [13]. Although there is no experimental evidence to link the SD bands with the higher lying rotational bands formed by known quasimolecular resonances, both phenomena are believed to originate from highly deformed configurations of these systems. Since the detection of light charged particles (LCP) is relatively simple,
the analysis of their spectral shapes is another good tool for exploring nuclear deformation and other properties of hot rotating nuclei at high angular momenta. Experimental evidence for angular-momentum-dependent spectral shapes has already been extensively discussed in the literature [20–34] and, in particular, the $^{24}$Mg + $^{16}$O reaction [35], which reaches the $^{40}$Ca CN, has been studied in detail. Strong deformation effects were also deduced from angular correlation data for the fusion reaction $^{28}$Si($^{12}$C,2$\alpha$)$^{32}$S.g.s. at $E_{lab} = 70$ MeV [36].

We decided to investigate the $^{40}$Ca nucleus produced through the $^{28}$Si + $^{12}$C reaction at beam energies of $E_{lab} = 112$ MeV and 180 MeV. As can be observed in Fig. 1, at the lowest incident energy of the present work the orbiting process is dominant whereas at $E_{lab} = 180$ MeV a large part of the O and N fully-damped yields may also result from a FF mechanism. It is interesting to note that the lower energy, $E_{c.m.} = 33.6$ MeV, corresponds to a well known quasi-molecular resonance (see Fig. 6 of Ref. [16]). In this article we will focus on the LCP’s found in coincidence with heavy fragments. Data have also been collected for the $^{28}$Si + $^{28}$Si reaction (leading to the $N = Z$ nucleus $^{56}$Ni) in the same experimental conditions at two bombarding energies [37–41].

The present paper is organized in the following way. Sec. II describes the experimental procedures and the data analysis. Sec. III presents the inclusive and the exclusive $^{28}$Si + $^{12}$C data (part of the experimental results presented here in detail have already been briefly reported elsewhere [39–43]). The data are analyzed using the Hauser-Feshbach evaporation code CACARIZO [20,21,24] using a consistent set of parameters which has been found to successfully reproduce $^{24}$Mg + $^{16}$O reaction results [35]. The full statistical-model calculations, using Monte Carlo techniques to account for the experimental acceptance when comparing to the experimental exclusive data, are presented in Sec. IV. The unexpected strong cluster emission of $^8$Be as due to a binary decay process is also discussed in this section. We end with a conclusion in Sec. V.
II. EXPERIMENTAL PROCEDURES AND DATA ANALYSIS

A. Experimental procedures

The experiments were performed at the VIVITRON Tandem facility of the IReS Strasbourg laboratory using 112 MeV and 180 MeV $^{28}$Si beams which were incident on $^{12}$C targets (160 and 180 $\mu$g/cm$^2$ thick, respectively) mounted in the ICARE scattering chamber [44,45]. The effective thicknesses of the $^{12}$C targets were accurately determined using Rutherford back scattering (RBS) techniques with $^1$H and $^4$He beams provided by the Strasbourg 4 MV Van de Graaff accelerator [37,38,41]. The carbon buildup corrections were found to be less than 2% of the total of C atoms in the targets. Both the heavy fragments (A $\geq$ 10) and their associated LCP’s (protons and $\alpha$ particles) were detected in coincidence using the ICARE charged-particle multidetector array [44,45] which consists of nearly 40 telescopes. Inclusive data have also been collected for heavy fragments and LCP’s and presented in Sec. III.A.

1. Experimental setup at $E_{lab} = 112$ MeV

For the measurement at $E_{lab}(^{28}$Si) = 112 MeV, the heavy fragments consisting of ER as well as quasi-elastic, deep-inelastic, and fusion-fission fragments, were detected in 8 gas-silicon hybrid telescopes (IC), each composed of a 4.8 cm thick ionization chamber, with a thin Mylar entrance window, followed by a 500 $\mu$m thick Si(SB) detector. The IC’s were located at $\Theta_{lab} = \pm 15^\circ$, -20$^\circ$, ±25$^\circ$, -30$^\circ$, -35$^\circ$, and -40$^\circ$ in two distinct reaction planes (for each plane, the positive and negative angles are defined in a consistent manner as for the LCP detectors described below). The in-plane detection of coincident LCP’s was done using 4 three-element telescopes (TL3) (40 $\mu$m Si, 300 $\mu$m Si, and 2 cm CsI(Tl)) placed at forward angles ($\Theta_{lab} = +15^\circ$, +25$^\circ$, +35$^\circ$, and +45$^\circ$), 16 two-element telescopes (TL2) (40 $\mu$m Si, 2 cm CsI(Tl)) placed at forward and backward angles (+40$^\circ$ $\leq$ $\Theta_{lab} \leq$ +115$^\circ$) and, finally, two other IC telescopes located at the most backward angles $\Theta_{lab} = +130^\circ$ and +150$^\circ$. The CsI(Tl) scintillators were coupled to photodiode readouts. The IC’s were filled
with isobutane at a pressure of 30 Torr for the backward angle telescopes and of 60 Torr for the forward angle detectors, thus allowing for the simultaneous measurement of both light and heavy fragments.

2. Experimental setup at $E_{lab} = 180$ MeV

For the measurement at $E_{lab}^{({}^{28}\text{Si})} = 180$ MeV, three distinct reaction planes were defined. Two for in-plane correlations and a third one, perpendicular to the LCP detection plane, for out-of-plane correlation measurements. The heavy fragments were detected in 10 IC’s located at $\Theta_{lab} = \pm 10^\circ, \pm 15^\circ, \pm 20^\circ,$ and $\pm 25^\circ (\Phi_{lab} = 0^\circ)$ for the in-plane coincidences, and at $\Theta_{lab} = +10^\circ$ and $+20^\circ (\Phi_{lab} = 90^\circ)$ for the out-of-plane coincidences. Both the in-plane and out-of-plane coincident LCP’s were detected using 3 TL3’s placed at forward angles ($2$ at $\Theta_{lab} = +30^\circ$ and one at $\Theta_{lab} = +35^\circ$) and 24 TL2’s placed at forward and backward angles ($+40^\circ \leq \Theta_{lab} \leq +95^\circ$). The IC’s were filled with isobutane at a pressure of 60 Torr.

The acceptance of each telescope was defined by thick aluminium collimators. The distances of these telescopes from the target ranged from 10.0 to 30.0 cm, and the solid angles varied from 1.0 msr at the most forward angles to 5.0 msr at the backward angles, according to the expected counting rates.

B. Data analysis

The energy calibrations of the different telescopes of the ICARE multidetector array were done using radioactive $^{228}$Th and $^{241}$Am $\alpha$-particle sources in the 5-9 MeV energy range, a precision pulser, and elastic scatterings of 112 MeV and 180 MeV $^{28}\text{Si}$ from $^{197}\text{Au}$, $^{28}\text{Si}$, and $^{12}\text{C}$ targets in a standard manner. In addition, the $^{12}\text{C}(^{16}\text{O},\alpha)^{24}\text{Mg}^*$ reaction at $E_{lab} = 53$ MeV \cite{41} was used to provide known energies of $\alpha$ particles feeding the $^{24}\text{Mg}$ excited states, thus allowing for calibration of the backward angle detectors. The proton calibration was achieved using scattered protons from Formvar targets bombarded in reverse kinematics reactions with both $^{28}\text{Si}$ and $^{16}\text{O}$ beams. On an event-by-event basis, corrections
were applied for energy loss of heavy fragments ($A \geq 10$) in the targets and in the entrance window Mylar foils of the IC’s and thin Al-Mylar foils of the Si diodes, and for the pulse height defect in the Si detectors. The IC energy thresholds and energy resolution for heavy fragments are better than 1.5 MeV/nucleon and 0.7%, respectively, as shown in Fig. 2 for the C and O exit fragments for the $^{28}$Si(112 MeV) + $^{12}$C reaction at $\Theta_{lab} = 15^\circ$. The total energy resolution of 8.78 MeV $\alpha$ particles from thorium sources has been found to be better than 2.2% for both the three-element and two-element light-ion CsI(Tl) telescopes. Absolute cross sections of inclusive measurements could be obtained within 10-12% error bars as due to 3-5% uncertainties in the target thickness and to 8-10% uncertainties in the electronic deadtime corrections. More details on the experimental setup of ICARE and on the analysis procedures can be found in Refs. [37,38,40–42] and references therein.
III. EXPERIMENTAL RESULTS

A. Inclusive data

1. Heavy fragments

The fragments with Z = 15-17 have typical inclusive energy spectra of ER’s which are not displayed here, but their LCP exclusive data are discussed in Sec. III.B. We rather focus on inclusive data of the binary fragments with Z = 5-14. The C and O fragment energy spectra measured at $\Theta_{lab} = 15^\circ$ for the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 112$ MeV are displayed in Fig. 2. As expected they are very similar to the spectra measured by Shapira et al. [4] for the same reaction at $E_{lab} = 115$ MeV. The peak identifications are given for the ground states as well as for the single and mutual excited states for the inelastic and $\alpha$-transfer exit-channels, respectively. The measured yields for different binary-channel products (Z = 5 to 11) were converted to center-of-mass cross sections by integrating their energy spectra. The resulting cross sections are shown in Fig. 3 and Fig. 4 for the two bombarding energies $E_{lab} = 112$ MeV and 180 MeV, respectively. In Fig. 3 the present data (open symbols) are in fairly good agreement with the previously measured C, N, and O angular distributions of Shapira et al. [4] (full symbols) obtained at $E_{lab} = 115$ MeV. All angular distributions of Figs. 3 and 4 vary as $1/\sin \theta_{c.m.}$, providing strong evidence that the damped reaction component (of a fusion-fission or DI orbiting origin) has a long lifetime, thus for these light fragment (Z = 5 to 11) a fast DI mechanism seems unlikely to contribute significantly. On the other hand such a fast DI mechanism does appear to be significant for the heavier fragments (Z = 12 to 14).

By integrating their $1/\sin \theta_{c.m.}$ angular distributions, fully-damped cross sections for the binary-channel products can be obtained. The results of the experimental cross sections are given in Table I and compared with the previously measured excitation functions [4,5] in Fig. 1. The agreement between both sets of data is good. However, at the highest bombarding energy $E_{lab} = 180$ MeV ($E_{c.m.} = 54$ MeV) a rather small systematic disagreement
can be observed. This 10% discrepancy is attributed to uncertainties in the target thickness and electronic deadtime corrections.

2. Light charged particles

Typical inclusive energy spectra of $\alpha$ particles are shown in Fig. 5 at the indicated angles for the $^{28}\text{Si}(180\text{ MeV}) + ^{12}\text{C}$ reaction. The solid points (with error bars visible when greater than the size of the points) are the experimental data whereas the solid and dashed lines are statistical model calculations discussed in Sec. IV.B. The $\alpha$-particle energy spectra have a Maxwellian shape with an exponential fall-off at high energy which reflects a relatively high effective temperature ($T_{\text{slope}} \approx \left[8E_{\text{CN}}^*/A_{\text{CN}}\right]^{1/2} = 3.67\text{ MeV}$) of the decaying nucleus. The spectral shape and high-energy slopes are also found to be essentially independent of angle in the c.m. system. These observations suggest a statistical deexcitation process arising from a thermalized source such as the $^{40}\text{Ca}$ CN. Similar $\alpha$-particle spectra have been measured for the lowest bombarding energy. These are also consistent with a previous study at $E_{\text{lab}} = 150\text{ MeV}$ [10]. The velocity spectra of protons and $\alpha$ particles, presented next, are strongly supportive of a statistical deexcitation process.

The velocity contour maps of the LCP Galilean-invariant differential cross sections $(d^2\sigma/d\Omega dE)p^{-1}c^{-1}$ as a function of the LCP velocity are known to provide an overall picture of the reaction pattern. From this pattern the velocity of the emission source can be determined in order to better characterize the nature of the reaction mechanism. Fig. 6 shows such typical plots of invariant cross-section in the $(V_{\parallel}, V_{\perp})$ plane for $\alpha$ particles (left side) and protons (right side), respectively, measured in singles mode. The symbols $V_{\parallel}$ and $V_{\perp}$ denote laboratory velocity components parallel and perpendicular to the beam, respectively. For the sake of clarity the velocity cutoffs arising from the detector low-energy thresholds are indicated for each of the telescopes. The present data at $E_{\text{lab}} = 112$ and 180 MeV have the same trends as the plots measured at $E_{\text{lab}} = 150\text{ MeV}$ (see Fig. 1 of Ref. [10]). The dashed circular arcs, centered on the center-of-mass $V_{\text{c.m.}}$ and defined to visualize the maxima of
particle velocity spectra, describe the data trends rather well. They have radii very close to the Coulomb velocities of α particles and protons in the decay of $^{40}$Ca$^*$ → $^{36}$Ar + $^4$He, and of $^{40}$Ca$^*$ → $^{39}$K + $^1$H, respectively. The apparent worsening of the agreement between the experimental and calculated α-particle spectra (dashed circular arcs) at larger angle results from the relatively large low-energy thresholds of the most backward-angle telescopes. Despite these artifacts, the spectra can be understood by assuming a sequential evaporative process and successive emission sources starting with the thermally equilibrated $^{40}$Ca$^*$ CN and ending with the final source characterised by a complete freeze-out of the residual nucleus. It is clear from this figure that the Galilean-invariant cross section contours fall on the dashed circular arcs centered at $V_{c.m.}$, as expected for a complete fusion-evaporation (CF) mechanism followed by isotropic evaporation.

**B. Exclusive data**

**1. LCP energy spectra**

The exclusive LCP events are consistent with a CF mechanism (as shown in the previous analysis of the inclusive LCP data) as they are mainly in coincidence with ER’s with $Z = 15$-17. Figs. 7 and 8 display the exclusive energy spectra of α particles detected at the indicated angles (from $\Theta^{LCP}_{lab} = +40^\circ$ to $\Theta^{LCP}_{lab} = +65^\circ (+95^\circ)$), in coincidence with individual ER’s ($Z = 15$ and 16) identified in the IC detector located at $\Theta^{ER}_{lab} = -15^\circ$ (and -10°) in the $^{28}$Si + $^{12}$C reaction at $E_{lab} = 112$ MeV and 180 MeV, respectively. The data taken with the IC’s located at more backward angles (larger than -15°) are not considered in the following analysis since the statistics for fusion-evaporation events are too low. The experimental data are given by the solid points, with error bars visible when greater than the size of the points. The spectral shapes of α particles in coincidence with P ($Z = 15$) ER’s, shown in Fig. 8, are very similar to the inclusive energy spectra of Fig. 5. On the other hand the energy spectra of α particles in coincidence with S ($Z = 16$) ER’s are more complicated as they show other
sub-structures which are superimposed on the “statistical” Maxwellian shape. In Fig. 7 for 
$Z = 15$ the high-energy components showing up at the large angles may arise from $\alpha$, $3p$
evaporation cascades.

Fig. 9 presents the corresponding $^{28}\text{Si} + ^{12}\text{C}$ exclusive energy spectra of protons emitted 
in coincidence with individual ER’s ($Z = 15$ and $16$) at $E_{lab} = 180$ MeV. Their spectral shapes 
are also Maxwellian with the typical exponential fall-off at high energy, characteristic of a 
statistical CN decay process.

2. In-plane angular correlations

The in-plane angular correlations of $\alpha$ particles and protons (measured with 
$-115^\circ \leq \Theta^{LCP}_{lab} \leq +115^\circ$) in coincidence with ER’s ($14 \leq Z \leq 17$), produced in the $^{28}\text{Si} + ^{12}\text{C}$ 
reaction, are shown in Figs. 10 and 11 at $E_{lab} = 112$ MeV and $180$ MeV, respectively. The 
angular correlations are peaked strongly on the opposite side of the beam direction from 
the ER detectors which were located at $\Theta^{ER}_{lab} = -15^\circ$ or $\Theta^{ER}_{lab} = -10^\circ$ for the two energies, 
respectively. The observed peaking of the LCP yields on the opposite side of the beam from 
the IC is the result of momentum conservation. The angular correlations of both the protons 
and $\alpha$ particles show the same behavior for all ER’s. The solid lines shown in the figures 
are the results of statistical-model predictions described in the next Section.

3. Out-of-plane angular correlations

Fig. 12 displays the out-of-plane angular correlations of $\alpha$ particles (circles) and pro-
tons (triangles) in coincidence with individual ER’s detected at $\Theta_{lab} = 10^\circ$, produced in the 
$^{28}\text{Si}(180$ MeV) $+ ^{12}\text{C}$ reaction. The angular distributions have a behaviour following a typi-
cal $\exp(-a \sin^2(\theta_{lab}))$ shape [41,47–49], with possibly two components visible for $\alpha$ particles in 
coincidence with $Z = 14$, $15$ and $16$, plus a broadening of the angular correlations at backward 
angles. This broadening effect may result from $\alpha$ particles being able to be emitted at the 
beginning or at the end of the decay chain, where the angular momentum becomes smaller.
towards the end of the chain. As the protons cannot remove as much angular momentum as do the α particles the broadening effect is less significant in the proton angular correlation. The solid lines shown in the figure are the results of statistical-model predictions for CF and equilibrium decay using the Monte Carlo evaporation code CACARIZO [20,21,24], as discussed in the next Section.
IV. DISCUSSION

A. Statistical-model calculations

The evaporation of light particles from a highly excited CN is a well known decay process up to very high excitation energies and spins [50–52]. The interpretation of LCP data requires a careful treatment of the light particle emission properties in the statistical-model description. Most of the available statistical-model computer codes [1, 2, 50–52] are based on the Hauser-Feshbach formalism and are able to follow the CN decay by a cascade of evaporated LCP’s and neutrons. In particular, a detailed analysis of the exclusive data can be undertaken by the use of Monte Carlo versions [51] of some of these statistical-model codes in which the filtering of the events can reproduce the experimental conditions. The statistical-model analysis of the present data has been performed using the Hauser-Feshbach evaporation code CACARIZO [20]. CACARIZO is a Monte Carlo version of the statistical-model code CASCADE [53], which has evolved with many modifications and extensions [20, 21, 24] from the original code. In this program the effective experimental geometry of the ICARE detectors is properly taken into account. It is assumed that a single CN is created with a well defined excitation energy and angular momentum distribution, and the de-excitation chain is followed step by step and recorded as an event file. The generated events are then analyzed using a subsequent filtering code ANALYSIS [21] in which the locations and the solid angles of all the ICARE telescopes are explicitly specified. This program allows the determination of the different types of events of interest. Such events can be sorted (singles events, coincidence events, etc.) and the corresponding particle spectra and angular distributions can be created.

The CN angular momentum distributions needed as the primary input for the calculations were specified using the ER critical angular momentum $L_{crit}$ and the diffuseness parameter $\Delta L$. They were taken from ER cross section data compiled for the $^{28}\text{Si} + ^{12}\text{C}$ fusion process by Vineyard et al. [11], without including fission competition. A fixed value
of $\Delta L = 1\hbar$ (optimized at low energy by a previous statistical-model analysis of this reaction [36]) was assumed for the calculations. It has been checked that the calculated spectra are not sensitive to slight changes in the critical angular momentum or to explicit inclusion of the fission competition. The parameter sets used for the calculations are summarised in Table II.

The other standard ingredients for statistical-model calculations are the formulations of the nuclear level densities and of the barrier transmission probabilities. The transmission coefficients were derived from Optical Model (OM) calculations using potential parameters of light particle induced reactions deduced by Wilmore and Hodgson [54], Perey and Perey [55], and Huizenga [56] for the neutrons, protons and $\alpha$ particles, respectively. For spin regions where the standard rotating liquid drop model (RLDM) [57] as well as the finite-range liquid drop model (FRLDM) [58] still predict essentially spherical shapes, these sets of transmission coefficients have been found adequate in the considered mass region. However, in recent years it has been observed that when the angular momentum is increased to values for which FRLDM predicts significant deformations, statistical-model calculations using such standard parameters cannot always predict satisfactorily the shape of the evaporated $\alpha$-particle energy spectra [20–34]. The calculated average energies of the $\alpha$ particles are found to be much higher than the corresponding experimental results. Several attempts have been made to explain this anomaly either by changing the emission barrier or by using spin-dependent level densities. Adjusting the emission barriers and corresponding transmission probabilities affects the lower-energy part of the calculated evaporation spectra. On the other hand the high-energy part of the spectra depends crucially on the available phase space obtained from the level densities at high spin. 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 with equidistant single-particle levels and a constant level density parameter $a$: 
\[ \rho(E,J) = \frac{(2J+1)}{12} a^{1/2} \left( \frac{\hbar^2}{2J_{\text{eff}}^2} \right)^{3/2} \frac{1}{(E - \Delta - T - E_J)^2} \exp\left( \frac{2[a(E - \Delta - T - E_J)]^{1/2}}{a/E} \right) \]  

where \( T \) is the “nuclear” temperature and \( \Delta \) is the pairing correction \[39\]. The quantity \( E_J = \frac{\hbar^2}{2J_{\text{eff}}} J(J+1) \) is the rotational energy, with \( J_{\text{eff}} = J_0 \times (1 + \delta_1 J^2 + \delta_2 J^4) \) being the effective moment of inertia, where \( J_0 \) at high excitation energy and high angular momentum is considered to be the rigid body moment of inertia and \( \delta_1 \) and \( \delta_2 \) are the “deformability parameters” \[20–22,24,27–34\].

The level density parameter is constant and is set equal to \( a = A/8 \text{ MeV}^{-1} \), a value which is in agreement with previous works \[35,60,61\]. In principle, the value of \( a \) may be affected by dynamical deformation: rotation induces rearrangement of the single-particle level scheme and the altered nuclear surface area \[27\] affects the macroscopic energy of the system. The \( a \) parameter becomes more important when the nuclear deformation increases \[61\]. However, in the present work we assume a constant value and rather introduce deformation effects through the deformability parameters. A constant value of \( a = A/8 \) is in agreement with various authors \[27,33\], as well as with theoretical studies by Shlomo and Natowitz \[60\], by Töke and Swiatecki \[61\], and with experimental results obtained very recently in the \( A_{CN} = 60 \) mass region \[62\].

Rather than to adjust the spin-dependence of the moment of inertia as done here, with effective emission barriers being unchanged, an alternative method to mock up nuclear deformation is to vary the radius parameter \( r_0 \) (from RLDM \[57\] parameters proposed by Myers and Swiatecki \[63\]) of the rigid-body moment of inertia \( J_0 \), as discussed recently for very light nuclear systems such as \(^{31}\)P \[31,34\]. This will affect the transmission coefficients by lowering the effective emission barrier \[27\]. However, a crude increase of the radius parameter (up to 25%) in the OM transmission coefficients has been shown \[27\] to enhance the intensity of the high-energy \( \alpha \) particles in the spectra. Although for hot heavy nuclei at high excitation energy a lowering of the \( \alpha \)-particle emission barriers has to be taken into account \[64\], this artifice has been extensively criticized in the past for lighter systems \[27\]. In fact this would result in a poorer reproduction of the present \(^{28}\)Si + \(^{12}\)C data. Therefore
no attempt was made to modify the transmission coefficients since it has been shown that the effective barrier heights are fairly insensitive to the nuclear deformation [27]. On the other hand, by changing the deformability parameters $\delta_1$ and $\delta_2$ one can simulate the spin-dependent level density [22,24,27,29] associated with a larger nuclear deformation, and thus reproduce the experimental data in a much better way.

### B. Deformation effects in $^{40}$Ca

In the present analysis, following the procedure proposed by Huizenga et al. [27], we empirically modify the phase space open to statistical decay by lowering the Yrast line with adjustment of the deformability parameters so as to fit the available experimental data [22,23]. We take into account the fact that the deformation should be attenuated during the subsequent emission processes: i.e., there is a readjustment of shape of the nascent final nucleus and a change of collective to intrinsic excitation during the particle-evaporation process. A similar analysis was suggested earlier by Blann and Komoto [65], but with the assumption that the deformation is a frozen degree of freedom through the decay chain. Dynamical effects related to the shape relaxation during the de-excitation process have been incorporated into statistical-model codes [25,28]. For the CACARIZO calculations done here, it is assumed that memory of formation details are lost after each step, with only the conserved quantities such as total energy and spin preserved during the decay sequence. The CACARIZO calculations have been performed using two sets of input parameters: the first one with standard liquid drop parameters (parameter set A), consistent with the deformation of RLDM [57] and of FRLDM with finite-range corrections of Sierk [58]; and the second one with larger values for the deformability parameters [37,40,43] (parameter set B) which are listed in Table [II].

The dashed lines in Fig. 5 show the predictions of CACARIZO for $^{28}$Si + $^{12}$C at $E_{lab}$ = 180 MeV using the parameter set A consistent with FRLDM deformation [58]. It is clear that the average energies of the measured $\alpha$-particle inclusive spectra are lower than
those predicted by these statistical-model calculations. The solid lines of Fig. 5 show the predictions of CACARIZO using the increased values of the spin deformation parameters (see parameter set B given in Table II), and the agreement is considerably improved.

The exclusive energy spectra of the $\alpha$ particles in coincidence with individual ER’s ($Z = 15$ and $Z = 16$) are displayed in Figs. 7 and 8 for the two bombarding energies $E_{\text{lab}} = 112$ MeV and 180 MeV, respectively. It can be observed that the spectra in coincidence with the P residues are well reproduced by using the deformation effects $[37,39,40,43]$. The solid lines in Figs. 7 and 8 show the predictions of CACARIZO using the parameter set B with $\delta_1 = 2.5 \times 10^{-4}$ and $\delta_2 = 5.0 \times 10^{-7}$ chosen to reproduce the data consistently at the two bombarding energies. On the other hand, by using the standard liquid drop deformability parameter set A with no extra deformation (i.e. with small values of $\delta_1$ and $\delta_2$), the calculated average energies from the exclusive $\alpha$-particles spectra (not shown in Figs. 7 and 8) are, as found for the inclusive data, lower than those predicted [11] by the statistical model. In this case the CACARIZO parameters are similar to the standard parameters used in a previous study of the 130 MeV $^{16}$O + $^{24}$Mg reaction [35], with the use of the angular momentum dependent level densities.

The exclusive energy spectra of $\alpha$ particles measured in coincidence with individual S ER’s, which are shown in Figs. 7 and 8 for $E_{\text{lab}} = 112$ MeV and 180 MeV, respectively, are quite interesting. A large difference can be noticed when comparing the energy spectra associated with S residues and those associated with P ER’s [10]. The latter are reasonably well reproduced by the CACARIZO calculations, whereas the model does not predict the shape of the spectra obtained in coincidence with S residues at backward angles ($\theta_{\alpha} \geq 40^\circ$ at $E_{\text{lab}} = 112$ MeV and $\theta_{\alpha} \geq 70^\circ$ at $E_{\text{lab}} = 180$ MeV). Additional non-evaporative components appear to be significant in this case. This is consistent with the discrepancies also observed at backward angles in the in-plane angular correlations of Fig. 10. In the following section we will discuss the hypothesis that the discrepancy occurs because a strong cluster transfer reaction mechanism leads to significant $^8$Be production, with the $^8$Be subsequently breaking up into two $\alpha$ particles.
As shown in Fig. 9 CACARIZO calculations are also capable to reproduce the shape of exclusive proton spectra for the $^{28}\text{Si}(180\text{ MeV}) + ^{12}\text{C}$ reaction. Compared to the $\alpha$ particles, it may be mentioned that the energy spectra of the protons do not shift as significantly as the spin-dependent parametrization of the moment of inertia is introduced. The statistical-model results using the two different parameter sets reproduce equally well the experimental velocity spectra and angular correlations. The statistical-model calculations displayed for protons in Fig. 9 have been performed with parameter set B (solid lines) including the deformation effects (calculations with parameter set A are not displayed).

In order to better determine the magnitude of the influence of deformation effects in the CN and the residual nuclei which are suggested by our choice of statistical-model approach, we have proposed a very simple procedure $^{[38,47–49]}$. The effective moment of inertia is expressed as $J_{\text{eff}} = \frac{2}{5}MR^2 = \frac{1}{5}M(b^2+a^2)$ with the volume conservation condition: $V = \frac{4}{3}\pi abc$, where b and a are the major and minor axis, and c is the rotational axis of the CN. In the case of an oblate shape $a = b$ and $J_{\text{eff}} = \frac{2}{5}Ma^2$ and $V = \frac{4}{3}\pi a^2 c$. The axis ratio is equal to $\delta = a/c = (1+\delta_1 J^2+\delta_2 J^4)^{3/2}$. In the case of a prolate shape $a = c$ and $J_0 = \frac{1}{5}M(b^2+a^2)$ and $V = \frac{4}{3}\pi a^2 b$. We obtain the equation: $1+(3-\gamma)x+3x^2+x^3 = 0$ with $x = \left(\frac{b}{a}\right)^2 = \delta^2$ and $\gamma = 8(1+\delta_1 J^2+\delta_2 J^4)^3$. The quadrupole deformation parameter $\beta$ is equal to $\beta = \frac{1}{\sqrt{\pi}}(\frac{4}{3}\delta + \frac{2}{3}\delta^2 + \frac{2}{3}\delta^3 + \frac{11}{18}\delta^4)$.

The effects of the Yrast line lowering (increase of the level density) due to the nuclear deformation and the variation of the deformation parameter $\beta$ can be quantitatively discussed using the values in Table III for several reactions. The values of the minor to major axis ratio $b/a$ and of the deformation parameter $\beta$ have been extracted from the fitted deformability parameters by assuming either a symmetric prolate shape or a symmetric oblate shape, respectively, with sharp surfaces $^{[27]}$. In our analysis we have chosen to follow the procedure proposed by Huizenga et al. $^{[27]}$ and successfully used for the $^{28}\text{Si} + ^{28}\text{Si}$ data $^{[38]}$. No attempt to modify the parametrization of OM transmission coefficients has been undertaken since it has been shown that the effective barrier heights are fairly insensitive to the
nuclear deformation [27]. It is interesting to note that the deformation found necessary to reproduce the $^{28}$Si + $^{12}$C reaction results is smaller than the deformation introduced by the deformability parameter used by Kildir et al. [46], who also change the transmission coefficients.

The in-plane angular correlations of the $\alpha$ particles (circles) and the protons (triangles) in coincidence with individual ER’s at both energies $E_{lab} = 112$ MeV and $180$ MeV are shown in Figs. 10 and 11, respectively. The solid lines shown in the figures are the results of statistical-model predictions for CF and equilibrium decay using the evaporation code CACARIZO. It can be observed in Fig. 10 that for $E_{lab} = 112$ MeV the experimental angular correlations are well reproduced by the evaporation calculations for the data at the opposite side from the ER detector, and this is true for correlations with both S and P ER’s. However the calculations fail to predict the experimental data at the same side as the ER detector. The question of these large yields measured at negative angles remains open [38]. Similarly the CACARIZO calculations reproduce in Fig. 11 the in-plane angular correlations of $\alpha$ particles (circles) and protons in coincidence with all ER’s, at $E_{lab} = 180$ MeV, for the data on the opposite side from the ER detector. They are also able to describe the in-plane angular correlations of protons in coincidence with individual $Z = 14$ and $Z = 15$ on both sides of the beam. However, the excess of yields observed at backward angles ($\Theta_{lab} = +50^\circ$ to $+90^\circ$) for $\alpha$ particles in coincidence with S may indicate the occurrence of a non-evaporative process, possibly of a binary nature.

The solid lines shown in Fig. 12 for the out-of-plane angular correlations are the results of CACARIZO statistical-model predictions. Once again it can be observed that the statistical-model calculations are able to reproduce the proton coincidences well, but they fail to describe the $\alpha$-Cl coincidences and the large yields found in coincidence with P and Si ER’s in the most forward direction. The reason why the experimental anisotropy factor is not well reproduced by the calculations is not well understood. The angular momentum dependence has been tested by performing calculations with two different angular-momentum windows: 10-20\(\hbar\) and 20-30\(\hbar\). Whereas for protons the anisotropy is almost constant with
the L-window, for the α particles the anisotropy is strongly depending of the chosen L-window. Nevertheless the flat behavior shown around 0° is present for the two particle species. The problem of this discrepancy in the out-of-plane angular correlations may need to use a more complete formulation for the angular distribution of the LP which is treated in a semi-classical way.

The main conclusion that can be drawn from the above analysis indicate that the shape of the 40Ca nuclear system is expected to be elongated by rather significant deformation effects during the evaporative processes of α particles. This strong deformation is compatible with the previous analysis of 28Si(12C,2α)32S g.s. angular correlation data [36]. The extent to which these effects can be reasonably well quantified is dependent on the degree of complexity of the experimental device and, in particular, on the power of the coincidence trigger. It is of particular interest to note that the value of β ≈ 0.5 found for the quadrupole deformation parameter of 28Si + 12C (see Table III) might be connected with the recent observation of SD bands in the doubly-magic 40Ca nucleus by standard γ-ray spectroscopy methods [19]. Correlating large deformations in the hot CN with the presence of SD bands in 40Ca is obviously not straightforward, since the deformation deduced from the LCP data is the average, while SD bands are one of the possible configurations. We made the same discussion with the possible comparison between LCP results for the 28Si + 28Si reaction [38] and γ-ray data displaying very deformed bands in the doubly magic 56Ni nucleus [66].

C. Non-statistical 8Be cluster emission

It has been shown from the analysis of Figs. 7 and 8 with CACARIZO that additional non-statistical components appear to be significant at both bombarding energies E_{lab} = 112 MeV and 180 MeV. However no evidence was found for additional processes at the lower bombarding energies E_{lab} = 70 MeV [36] and 87 MeV [57]. To better understand the origin of these components, α particle energies are plotted in Fig. 13 against the energies of the S residues detected at Θ_S = -10° for the 28Si(180 MeV) + 12C reaction for a number of
α-particle emission angles. With increasing α-particle angles an increase of the energy of S residues and a decrease of the α energy is observed which is consistent with kinematics. At $\Theta_\alpha = +40^\circ$, +45°, and +50° the bulk of events in Fig. 13 are of a statistical origin, and consistent with CACARIZO calculations, as demonstrated in Fig. 14 (for $\Theta_\alpha = +40^\circ$). Another statistical-model code PACE 2 [68] gives similar predictions. The calculations suggest that these α particles result from a cascade of a single α, two protons, and x neutrons rather than a 2-α,xn evaporation process. For larger angles, the two branches, corresponding to the contours labelled 1 and 2, although lying outside the “statistical evaporation region”, still correspond to an evaporation process as shown by the CACARIZO calculations displayed in Fig. 14 for $\Theta_\alpha = +40^\circ$ and +70°. These two branches 1 and 2 correspond to a 2-α fusion-evaporation channel with both the α particles emitted respectively at backward and forward angles in the center of mass. However, at more backward angles other contributions, corresponding to the contours labelled 3 and 4, appear more and more significantly as shown for instance in Fig. 14 for +70°. The corresponding “folding angles” are compatible with the two-body kinematics required for the $^{32}\text{S} + ^8\text{Be}$ binary exit-channel. In contrast, the energy correlations for the α particles in coincidence with Cl and P residues (not shown) do not exhibit any of these two-body branches 3 and 4 and, thus, the “statistical evaporation region” is consistent with the CACARIZO predictions, for all the measured angles.

Although in principle the identification of the $^8\text{Be}$ cluster requires the coincident detection and mass identification of both decaying α particles [69], a kinematic reconstruction of this decay process is still possible from the present coincident data to determine the excitation energy of the $^8\text{Be}$ nucleus by assuming a two-body $^{32}\text{S} + ^8\text{Be}^*$ process. On the left side of Fig. 15 the excitation energy of $^8\text{Be}$ is presented for the contributions labelled 2, 3, and 4 (Fig. 14) at the indicated $\Theta_\alpha$ angles. From $\Theta_\alpha = 70^\circ$ to $\Theta_\alpha = 85^\circ$ the strongest peak appears with a very narrow width. This large component, which corresponds to the contribution of the contour 4 visible in Fig. 14, is centered at the energy of the ground state of $^8\text{Be}$ (the relative energy of the two α particles of the $^8\text{Be}$ breaking up in flight is 92 keV) and displayed as the squared part of the left pannel of Fig. 15. From $\Theta_\alpha = 55^\circ$ to $\Theta_\alpha = 95^\circ$
the main bulk of the yields from contour 3 is centered at around $E^* = 3.1$ MeV with an experimental width of approximately 1.5 MeV, which values correspond well to the known energy ($E^* = 3.04$ MeV) and width ($\Gamma = 1500$ keV) of the first $2^+$ excited level of $^8$Be [70]. The short-lived $^8$Be $4^+$ excited level at $E^* = 11.4$ MeV [71] is not clearly observed due to its very broad width ($\Gamma = 3.7$ MeV) and the significant $\alpha$-statistical background arising from the contribution of the contour 2. For the same reasons it is hazardous to assign the bumps around 15 MeV to the known $2^+$ doublet [70] at $E^* = 16.6$ and 16.9 MeV.

The right panels of the Fig. 15 display the reconstructed excitation energy spectra of the S binary fragments measured at $\Theta_S = -10^\circ$ in coincidence with $\alpha$ particles detected at the indicated $\Theta_\alpha$ angles by gating either on the ground state (g.s.) contour 4 (upper panel) or the $2^+$ state contour 3 (lower panel). We have performed fusion-fission calculations (not shown), using the Extended Hauser-Feshbach Method [4]. They fail to reproduce both the excitation energies of the $^{32}$S fragments, and the yields from the contributions 3 and 4 [39]. These contributions might result from a faster binary process governed by the $\alpha$-transfer reaction mechanism $^{28}$Si + $^{12}$C $\rightarrow$ $^{32}$S$^* + ^8$Be, as proposed by Morgenstern et al. [72]. This conclusion is in agreement with previous inclusive results published in Ref. [12]. In the cluster-transfer picture [72] the reaction is characterised by a “Q-value” window centered at the so-called “Q-optimum”, which value can be estimated semi-classically by

$$Q_{opt} = (Z_3 Z_4/Z_1 Z_2 - 1)E_i^{c.m.},$$

where the indices 1,2 and 3,4 indicate the entrance (i) and exit channel, respectively. The corresponding excitation energy $E^* = Q_{gg} - Q_{opt}$, where $Q_{gg}$ is the ground-state Q-value of the reaction. In this case the expected excitation energy in the $^{32}$S nuclei is equal to 12.9 MeV. The right hand side of Fig. 15 represents the calculated excitation energy of $^{32}$S in coincidence with the g.s., and with the first $2^+$ ($E_x = 3.04$ MeV) excited state of $^8$Be, respectively. The dashed lines correspond to $E^* = 12.9$ MeV, the energy expected for $\alpha$-transfer reaction mechanisms. In both cases the excitation energies of $^{32}$S are consistent with these values. In the same way we can also have a $^8$Be-transfer reaction mechanism [12]

$^{28}$Si + $^{12}$C $\rightarrow$ $^{36}$Ar$^* + \alpha$. In this case the $^{36}$Ar$^*$ ejectile has enough excitation energy to emit either one proton or one $\alpha$ particle. This type of “transferlike” reaction can explain
the disagreement observed in Fig. 10 between data and CACARIZO calculation for the in-plane angular correlation between $\alpha$ particles and Cl residues.
V. CONCLUSION

The possible occurrence of highly deformed configurations in the $^{40}$Ca dinuclear system has been investigated by using the ICARE charged-particle multidetector array at the VIVITRON Tandem facility of the IReS Strasbourg. The properties of the emitted LCP’s in the $^{28}$Si + $^{12}$C reaction, have been analysed at two bombarding energies $E_{lab} = 112$ MeV and 180 MeV, and compared with a statistical model that was adopted to calculate evaporation spectra and angular distributions for deformed nuclei. A Monte Carlo technique has been employed in the framework of the well documented Hauser-Feshbach code CACARIZO. The measured observables such as velocity distributions, energy spectra, in-plane and out-of-plane angular correlations are all reasonably well described by the Monte Carlo calculations when they include spin-dependent level densities, and indicate that effects due to differences in nuclear shapes are large enough to be observed. The magnitude of the adjustments in the Yrast line suggests significant deformation effects at high spin for the $^{40}$Ca dinuclear system comparable to recent $\gamma$-ray spectroscopy data for the $^{40}$Ca nucleus at much lower spins [19].

The extent to which the resonant behaviour [13,16] is responsible to the observed nuclear deformation is still an open question. A non-statistical binary component is found in the $\alpha$-particle energy spectra measured in coincidence with S residues that is attributed to the cluster decay of unbound $^{8}$Be nuclei, produced through the $\alpha$-cluster-transfer reaction $^{28}$Si + $^{12}$C $\rightarrow$ $^{32}$S + $^{8}$Be [12]. This new type of “transferlike” mechanism, which does not appear at lower bombarding energies [36,67] below threshold, allows to populate some $N = Z$ nuclei with a well defined excitation energy. Therefore, sophisticated particle-$\gamma$ experiments (see Refs. [73–76] for instance) using sc EUROBALL IV and/or sc GAMMASPHERE should be performed in the very near future in order to well define and understand what are the best types of reaction which can populate significantly the superdeformed bands discovered and/or predicted in this mass region [17–19].
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Beck, and M. Rousseau, J. Phys. G: Nucl. Part. Phys. 27, 1405 (2001).
| Z | $^{28}\text{Si}(112 \text{ MeV}) + ^{12}\text{C}$ | $^{28}\text{Si}(180 \text{ MeV}) + ^{12}\text{C}$ |
|---|---|---|
| 5 | - | 8.4 ± 1.1 |
| 6 | 20.1 ± 1.4 | 58.8 ± 6.6 |
| 7 | 0.5 ± 0.04 | 11.8 ± 1.4 |
| 8 | 3.3 ± 0.3 | 23.1 ± 3.1 |
| 9 | - | 4.7 ± 0.7 |
| 10 | 0.8 ± 0.12 | 18.9 ± 4.0 |
| 11 | - | 15.9 ± 3.4 |

**TABLE I.** Experimental binary fragments cross sections obtained in the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 112$ MeV and 180 MeV.
Angular-momentum distribution in CN

Critical angular momenta $L_{cr} = 21$ ($E_{lab} = 112$ MeV) and $27\hbar$ ($E_{lab} = 180$ MeV).

Diffuseness parameter $\Delta L = 1.0\hbar$.

**OM potentials of the emitted LCP and neutrons**

(1) Neutrons: Wilmore and Hodgson [54]
(2) Protons: Perey and Perey [55]
(3) $\alpha$ particles: Huizenga and Igo [56]
(4) Multiply factor of the OM radius: $\text{RFACT} = 1$

**Level-density parameters at low excitation: ($E^* \leq 10$ MeV)**

(1) Fermi-gas level-density formula with empirical level-density parameters from Dilg et al. [59]
(2) Effective moment of inertia $\mathcal{I} = \text{IFACT} \mathcal{I}_{\text{rigid}}$ with $\text{IFACT} = 1$.

**Level-density parameters at high excitation: ($E^* \geq 20$ MeV)**

(1) Fermi-gas level-density formula with parameters from RLDM (Myers and Swiatecki [63])
(2) Level-density parameter: $a = A/8$ MeV$^{-1}$

**Yrast line**

- Parameter set **A**: FRLDM (Sierk [58])
- Parameter set **B**: $\mathcal{I} = \mathcal{I}_{\text{sphere}}(1 + \delta_1 J^2 + \delta_2 J^4)$ with $\delta_1 = 2.5 \times 10^{-4}$ and $\delta_2 = 5.0 \times 10^{-7}$

**$\gamma$-ray width** (in Weisskopf units)

(1) E1: $B(E1) = 0.001$
(2) M1: $B(M1) = 0.01$
(3) E2: $B(E2) = 5.0$

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**TABLE II.** Parameter sets used in the CACARIZO calculations for the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 112$ and 180 MeV.
### TABLE III. Typical quantities of the evaporation calculations performed using the statistical-model code CACARIZO. The deformability parameters are taken either from the parameter set B (see Table II) for the systems studied in the present work or from similar fitting procedures for the other systems studied in the literature. The minor to major axis ratios b/a and the quadrupole deformation $\beta_2$ values (for a symmetric oblate shape and a symmetric prolate shape, respectively) have been deduced from equations discussed in the text. Note that the $\beta$ values and b/a ratio given for $^{32}\text{S} + ^{27}\text{Al}$ have been deduced assuming the $L_{cr}$ as extracted at the highest bombarding energy.

| Reaction     | C.N. | Energy (MeV) | $L_{cr}$ ($h$) | $\delta_1$ | $\delta_2$ | b/a | $\beta$ | Reference |
|--------------|------|--------------|----------------|------------|------------|-----|---------|-----------|
| $^{28}\text{Si} + ^{12}\text{C}$ | $^{40}\text{Ca}$ | 112 | 21 | 2.5·10^{-4} | 5.0·10^{-7} | 1.3/1.4 | -0.46/0.47 | This work |
| $^{28}\text{Si} + ^{12}\text{C}$ | $^{40}\text{Ca}$ | 150 | 26 | 6.5·10^{-4} | 3.3·10^{-7} | 2.0/2.0 | -0.53/0.53 | [46] |
| $^{28}\text{Si} + ^{12}\text{C}$ | $^{40}\text{Ca}$ | 180 | 27 | 2.5·10^{-4} | 5.0·10^{-7} | 1.7/1.8 | -0.51/0.51 | This work |
| $^{28}\text{Si} + ^{27}\text{Al}$ | $^{55}\text{Co}$ | 150 | 42 | 1.8·10^{-4} | 1.8·10^{-7} | 1.2/1.3 | -0.44/0.46 | [29] |
| $^{28}\text{Si} + ^{28}\text{Si}$ | $^{56}\text{Ni}$ | 112 | 34 | 1.2·10^{-4} | 1.1·10^{-7} | 1.5/1.6 | -0.48/0.49 | [38] |
| $^{28}\text{Si} + ^{28}\text{Si}$ | $^{56}\text{Ni}$ | 180 | 37 | 1.2·10^{-4} | 1.1·10^{-7} | 1.6/1.7 | -0.49/0.50 | [41] |
| $^{30}\text{Si} + ^{30}\text{Si}$ | $^{60}\text{Ni}$ | 120 | 34 | 1.2·10^{-4} | 1.1·10^{-7} | 1.6/1.7 | -0.49/0.50 | [38] |
| $^{35}\text{Cl} + ^{24}\text{Mg}$ | $^{59}\text{Cu}$ | 260 | 37 | 1.1·10^{-4} | 1.3·10^{-7} | 1.6/1.7 | -0.50/0.51 | [40] |
| $^{32}\text{S} + ^{27}\text{Al}$ | $^{59}\text{Cu}$ | 100-150 | 27-42 | 1.3·10^{-4} | 1.2·10^{-7} | 2.0/2.0 | -0.46/0.53 | [27] |
| $^{16}\text{O} + ^{54}\text{Fe}$ | $^{70}\text{Se}$ | 110 | 34 | 2.5·10^{-5} | 3.0·10^{-8} | 1.2/1.3 | -0.45/0.46 | [32] |
FIGURES

Figure 1: Experimental C (solid squares), N (solid triangles), and O (solid circles) cross sections measured in the $^{28}\text{Si} + ^{12}\text{C}$ reaction [4,5] as compared to the calculations (dotted curves) performed with the equilibrium model of orbiting [3]. The solid curves are the predictions of the transition-state model [1]. The open squares, triangles and circles are the present data of the C, N, and O fully-damped yields with error bars smaller than the size of the symbols. The full diamonds correspond to ER cross sections quoted in Refs. [6–12].

Figure 2: Energy spectra for the C and O fragments measured at $\Theta_{lab} = 15^\circ$ for the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 112$ MeV. The peak assignments are discussed in the text.

Figure 3: Angular distributions (open symbols) of heavy fragments (C, N, O, and Ne) measured in the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 112$ MeV. The full symbols are the C, N and O data taken from Ref. [4,5] at $E_{lab} = 115$ MeV. The Ne angular distribution has been scaled down by a factor 10 for the sake of clarity. The curves correspond to $1/\sin\theta_{c.m.}$ functions.

Figure 4: Angular distributions of heavy fragments (Z = 5 to 11) measured in the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 180$ MeV. The N and Na angular distributions have been scaled down by a factor 10 for the sake of clarity. The curves correspond to $1/\sin\theta_{c.m.}$ functions.

Figure 5: Inclusive energy spectra of $\alpha$ particles measured in the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 180$ MeV between $\Theta_{lab}^{LCP} = 30^\circ$ and $55^\circ$. The experimental data are shown by the solid points with error bars visible when greater than the size of the points. The solid and dashed lines are statistical-model calculations discussed in the text.
Figure 6: Two-dimensional scatter plots of Galilean-invariant cross sections \( (d^2\sigma/d\Omega dE)p^{-1}c^{-1} \) of inclusive \( \alpha \) particles (left side) and protons (right side) measured in the \((V_\perp, V_\parallel)\) plane for the \(^{28}\text{Si} + ^{12}\text{C}\) reaction at \(E_{\text{lab}} = 112\) MeV (up) and 180 MeV (down). The experimental detector thresholds are drawn along the laboratory angles of each telescope. The circular arcs are centered on the velocity of the center of mass.

Figure 7: Exclusive energy spectra of \( \alpha \) particles emitted at the angles \( +40^\circ < \Theta^{LCP}_{\text{lab}} < +65^\circ \), in coincidence with individual P and S ER’s detected at \(-15^\circ\) in the \(^{28}\text{Si} + ^{12}\text{C}\) reaction at \(E_{\text{lab}} = 112\) MeV. The experimental data are given by the solid points with error bars visible when greater than the size of the points. The solid lines are statistical-model calculations discussed in the text.

Figure 8: Exclusive energy spectra of \( \alpha \) particles emitted at the angles \( +40^\circ < \Theta^{LCP}_{\text{lab}} < +95^\circ \), in coincidence with individual P and S ER’s detected at \(-10^\circ\) in the \(^{28}\text{Si} + ^{12}\text{C}\) reaction at \(E_{\text{lab}} = 180\) MeV. The experimental data are given by the solid points with error bars visible when greater than the size of the points. The solid lines are statistical-model calculations discussed in the text.

Figure 9: Exclusive energy spectra of protons emitted at the angles \( +40^\circ < \Theta^{LCP}_{\text{lab}} < +70^\circ \), in coincidence with individual P and S ER’s detected at \(-10^\circ\), at the indicated laboratory angles, in the \(^{28}\text{Si}(180\text{ MeV}) + ^{12}\text{C}\) reaction. The solid lines are statistical-model calculations discussed in the text.
Figure 10: In-plane angular correlations of coincident $\alpha$ particles (circles) and protons (triangles) measured in the $^{28}$Si + $^{12}$C reaction at $E_{lab} = 112$ MeV. The proton correlations have been multiplied by a factor $10^{-3}$ for the sake of clarity. The arrow indicates the position of the IC detector at $\Theta_{lab} = -15^\circ$. On the abscissa, the positive angle refer to the opposite side of the beam from the direction of the ER detected in IC. The solid lines correspond to statistical-model calculations discussed in the text.

Figure 11: In-plane angular correlations of coincident $\alpha$ particles (circles) and protons (triangles) measured in the $^{28}$Si + $^{12}$C reaction at $E_{lab} = 180$ MeV. The proton correlations have been multiplied by a factor $10^{-2}$ for the sake of clarity. The arrow indicates the position of the IC detector at $\Theta_{lab} = -10^\circ$. On the abscissa, the positive angle refer to the opposite side of the beam from the direction of the ER detected in IC. The solid lines correspond to statistical-model calculations discussed in the text.

Figure 12: Out-of-plane angular correlations of coincident $\alpha$ particles (circles) and protons (triangles) measured in the $^{28}$Si + $^{12}$C reaction at $E_{lab} = 180$ MeV. The proton correlations have been multiplied by a factor $10^{-2}$ for the sake of clarity. The ER’s are detected at $\Theta_{lab} = -10^\circ$. The solid lines correspond to statistical-model calculations discussed in the text.

Figure 13: Energy-correlation plots between coincident $\alpha$ particles and S ER’s produced in the $^{28}$Si + $^{12}$C reaction at $E_{lab} = 180$ MeV. The heavy fragment is detected at $\Theta_S = -10^\circ$ and the $\alpha$-particle angle settings are given in the figure. The dashed lines correspond to different contours with their associated labellings discussed in the text.
Figure 14: Experimental (left side) and calculated (right side) energy-correlation plots between coincident $\alpha$ particles and S ER’s produced in the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 180$ MeV. The S is identified at $\Theta_S = -10^\circ$ and the $\alpha$ particles are detected at $\Theta_\alpha = +40^\circ$, and $+70^\circ$, respectively. CACARIZO calculations are discussed in the text.

Figure 15: Excitation-energy spectra calculated for the $^{28}\text{Si} + ^{12}\text{C}$ reaction at $E_{lab} = 180$ MeV for $^8\text{Be}$ (left side) and $^{32}\text{S}$ (right side) in coincidence with the g.s. (above) and first excited level (below) of $^8\text{Be}$. The solid line corresponds to the energy of the first excited state of $^8\text{Be}$ (3.08 MeV). The dashed lines correspond to an excitation energy in $^{32}\text{S}$ expected for an $\alpha$-transfer process.
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