BRIEF REPORTS

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In-plane particle-residue correlations in the ^{40}Ar(1100 MeV)+^{24}Mg reaction

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With the aim of studying the related phenomena of preequilibrium and statistical decay origin, light charged particles (p,d,t,α) and evaporation residues have been measured in the ^{40}Ar+^{24}Mg reaction performed at 27.5 MeV/nucleon. Proton-residue correlations were investigated and compared to simulations based on a model associating promptly emitted particles (PEP) with binary-scission statistical decay; a satisfactory agreement is obtained. The data evidence phase-space constraints and the competing presence of (i) preequilibrium emission, which dominate at backward angles and which can be described correctly in the context of PEP, and (ii) evaporative emission focused at forward angles. The data show also a substantial complex particle emission at both preequilibrium and evaporation stages demanding their inclusion in future theoretical treatment of preequilibrium.

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The emission of light particles (LP) of preequilibrium (PE) has been evidenced in numerous studies of heavy-ion reactions at incident energy exceeding about 10 MeV/nucleon [1]. This decay occurs at the early state of the reaction before thermal equilibrium of the nuclear system is achieved. It consists essentially of nucleons, restricted in many studies to protons due to the difficulty of detecting neutrons, and to a lesser extent of complex particles and light clusters. This prompt emission is followed by another emission of particles and light fragments corresponding to the statistical evaporation (EV) of the compound nucleus formed after incomplete fusion, at least for the light nuclear systems for which binary fission is weak.

Intensive efforts have been devoted to the study of the related PE and EV emissions for a large variety of projectile-target combinations over an extended domain of bombarding energy [2–18]. Among these works, which are simply examples taken in the literature, an interesting experimental approach consists of analyzing the correlations between LP sequentially emitted [2–6] and between LP and the related heavy residues [7,8]. The particle-particle correlations have been useful to probe the collision dynamics [9], to scale the particle emission time [10,11], and to determine the temperature and the size of the emitting source, though the technique is subject to some question [12]. The particle-residue correlations have also permitted the examination of the dynamical aspects of the reaction [8, 14-17] and the exploration of the nature of hot nuclei and their limits of existence [13-17].

In this work, we present in-plane particle-residue correlations measured for the ^{40}Ar+^{24}Mg reaction performed at the bombarding energy of 27.5 MeV/nucleon (1100 MeV). Restriction to in-plane correlations should not be a severe limitation since earlier analyses have shown that in-plane emission for correlated particles are either favored or not strongly azimuthally dependent [3,4,6]. The ^{40}Ar+^{24}Mg reaction has been selected because of the following. (i) A relatively light system for which incomplete fusion is followed mostly by evaporation since binary fission is weak [8,19]. (ii) Inverse kinematics permit, to some extent, the separation of the PE emission from that of EV [8,20]: On the one hand, due to the large center-of-mass velocity, the evaporative particles are strongly forward focused. On the other hand, the PE emission expected to be dominant from the lighter participant [21] in the reaction, i.e., the target, the PE source should have a low velocity and thus should dominate at backward angles.

The setup used in the present experiment has been described in a previous article [8]. The heavy fragments, identified with a mass resolution $\Delta A_F/A_F \leq 1/50$, were

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measured by means of a time-of-flight path at $\theta_F = 9°$ to ensure that the fragments detected at this angle are EV residues: The peripheral and partially damped reactions have very low cross sections [8,19] since the grazing angle is $\simeq 2°$. The light charged particles were measured with a set of 13 cesium iodide (CsI) scintillators located at ±15°, 25°, −40°, −60°, ±90°, +125°, ±145°, ±165° in the reaction plane formed by the beam axis and the heavy fragment detector. By convention, the positive (negative) angles are defined, with respect to the beam axis, for those in the same (opposite) half plane as the residue-fragment counter. A clear discrimination between *p*, *d*, *t*, ^{3}He, and ^{4}He was obtained by using the scintillation-time-difference method [22]. The overall energy thresholds were typically of 5 MeV/nucleon and the same threshold was taken for all the LP detectors.

Following other authors [6], the correlations $R(\theta_x,\theta_y)$ in the reaction plane are defined as the ratio of the cross section of coincidences σ_{xy} between two particles detected in two counters *x* and *y* and of the product of their individual inclusive cross sections $\sigma_{i=x,y}$:

$$R(\theta_x,\theta_y)=\frac{\sigma_{xy}}{\sigma_x\sigma_y} ,$$

where

$$\sigma_{xy}=\int\int\int\int \frac{d^4\sigma(\theta_x,E_x,\theta_y,E_y)}{dE_x\,dE_y\,d\Omega_x\,d\Omega_y}dE_x\,dE_y\,d\Omega_x\,d\Omega_y$$

and

$$\sigma_i=\int\int\frac{d^2\sigma(\theta_i,E_i)}{dE_i\,d\Omega_i}dE_i\,d\Omega_i ,$$

where E_i is the energy of a particle measured in a detector located at the polar angle θ_i and subtending the solid angle Ω_i. The maximum of the correlation has been normalized to unity.

We have performed simulations based on a recently developed [23] model associating a preequilibrium calculation with an evaporation statistical decay calculation by using the Monte Carlo technique. A promptly emitted particle model [24,25] was used to describe the PE emission phase, and a binary-scission statistical decay model [26,27] was utilized to represent the EV phase. In the following we will refer to this model as PBS. Such an approach has been successfully tested on light systems for describing particle-residue correlations as well as to analyze EV residue distributions [8]. In the present simulation, the PE phase calculation was stopped when the internuclear-center distance between projectile and target was equal to 2 fm. This interruption corresponds to an elapsed time of $\simeq 50$ fm/*c*, time after which the PE emission is practically exhausted. At that time, the temperatures of the two interacting nuclei, which increase during the PE phase, saturate [23]. This constitutes a good indication that the projectile-target system is thermalized and that the statistical deexcitation takes place. Moreover, the calculations also show that, after 50 fm/*c*, PE emission has stopped and more nucleons have been emitted by the target than by the projectile, in agreement with the trend established from a phenomenological approach [21].

In Fig. 1 are presented, from top to bottom, the correlation $R(\theta_F,\theta_p)$ between protons measured at θ_p and (i) all EV residues (with $23 \le A_F \le 43$) detected at $\theta_F = 9°$, (ii) lower mass residues ($23 \le A_F \le 31$), and (iii) higher mass residues ($35 \le A_F \le 43$). A marked correlation is observed between fragments and protons with a strong enhancement for protons detected at negative angles. This is a manifestation of momentum conservation forcing the bulk of the particles to be emitted at negative angles when the residues are detected at $\theta_F = +9°$. Furthermore, depending on the fragment mass bin considered, the maxima of the correlations are located at different angles: It is around 60° for the lighter residues and at about 90° for the more massive. Of course, the correlation for the totality of the fragments shows the result of the two combined effects.

This mass-bin separation has been done for the following purpose: Previous studies [8,19,20,28] have shown that heavier residues are more related to strong PE emission than lighter residues. This is probably because strong prompt emission of fast LP and clusters deexcites substantially the intermediate nuclear system which thus

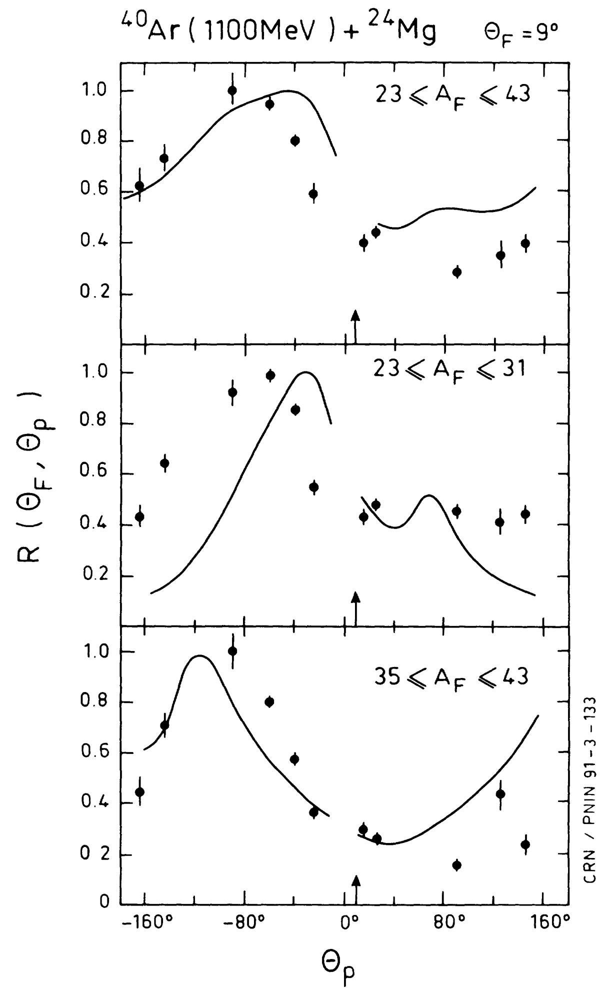

FIG. 1. Correlations $R(\theta_F,\theta_p)$ measured (dots) between protons detected at θ_p and heavy fragments observed at $\theta_F = 9°$ (indicated by arrows) for various mass bins of fragments (A_F). The solid curves illustrate the predictions of PBS calculations.

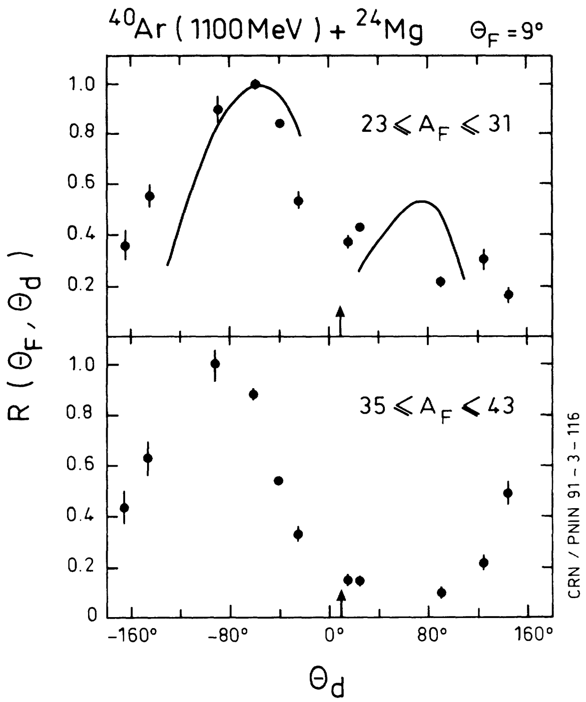

FIG. 2. Correlations $R(\theta_F,\theta_d)$ measured (dots) between deuterons detected at θ_d and heavy fragments observed at $\theta_F=9°$ (indicated by arrow) for two mass bins of fragments (A_F). The solid curves illustrate the predictions for the evaporative part of PBS dynamics.

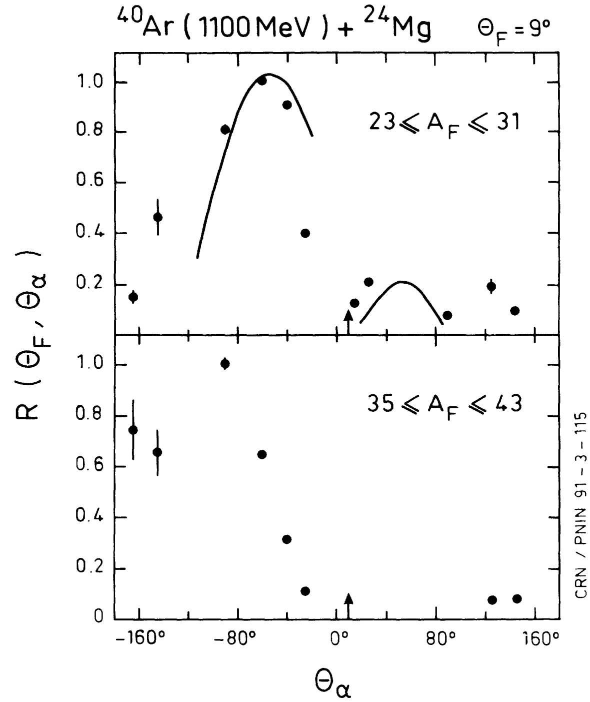

FIG. 3. Same as Fig. 2 for the fragment-α-particle $R(\theta_F,\theta_\alpha)$ correlations.

leads to moderate EV from the compound nucleus, and hence to higher mass residues. On the contrary, weaker PE emission produces a strongly excited compound nucleus which, through intensive EV, yields lighter residues. Hence, the $35 \le A_F \le 43$ bin should be preferentially related to PE protons and inversely, the $23 \le A_F \le 31$ bin should, more likely, result from copious EV. The $32 \le A_F \le 34$ intermediate mass range, not shown here, being influenced in comparable proportions by PE and EV, exhibits the same behavior as the full $23 \le A_F \le 43$ bin.

As visible in Fig. 1, these considerations are supported by PBS calculations (solid curves) run for $b=0.5$ fm. They have been repeated for other impact parameters $b \le 3.5$ fm without yielding any important differences. The calculated correlations, at the end of the PE phase and of the EV phase, are shown in the lower and the middle parts of Fig. 1, respectively. The full (PE + EV) process yields the curve in the upper part of the figure. They peak around $-120°$ for PE and close to $-30°$ for EV, reproducing correctly the experimental trend which, however, does not feature a comparable sharp separation in the mechanisms, and hence any accented effect. The global reaction process is also correctly reproduced. It shows that the momentum conservation plays here quite an effective role. It puts forth the fact that PE emission of protons can be treated in the framework of nucleon-nucleon collisions and is dominantly from a low-velocity source, i.e., the target as evidenced earlier [21].

However, fair yields of deuterons, tritons, and α particles have also been measured and their correlations with heavy fragments studied. Some Li have also been observed. They present the same trend as for protons; in particular, the shift of the maxima of the correlations between the $23 \le A_F \le 31$ and $35 \le A_F \le 43$ mass bins is observed, as shown in Figs. 2 and 3, which illustrate the case of d and α particles, respectively. This indicates that these complex particle emissions occur in both the PE and EV phases of the $^{40}Ar + ^{24}Mg$ reaction. Full comparison with PBS simulations is not possible here since only nucleon emission is considered at the PE stage. The comparison (solid curves in Figs. 2 and 3) is restricted to the case of $23 \le A_F \le 31$ fragments since complex-particle and cluster evaporation is included in PBS and this fragment bin is presumed to be dominated by EV. The experimental trend is correctly reproduced. As for protons, they are characterized by a marked phase-space limitation at positive angles. These results suggest that complex particle emission should be included in future development of PE calculation. Moreover, they also indicate that a complete treatment of PE cannot rely entirely on the nucleon-nucleon interaction, although this appears as a reasonable approach when PE proton emission is considered.

In conclusion, good agreement is obtained between the experimental proton-residue correlations measured in the ^{40}Ar (1100 MeV) $+^{24}$Mg reaction and the predictions of a model associating prompt emitted nucleons (for the preequilibrium phase) with binary-scission statistical decay (for the evaporative phase). The correlations are governed by phase-space constraints resulting fom linear momentum conservation. However, complex particle-fragment correlations have also been studied. They exhibit the same trend as for protons and are also characterized by the competing emissions of complex particles at both the preequilibrium and evaporative stages. Thus, they should be included in future theoretical developments concerning preequilibrium. At the same time they qualify the current interpretation of the PE mechanism, i.e., nucleon-nucleon collisions.

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