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Abstract

The formation and the deexcitation of the composite nucleus formed during the Ni + Al reaction at 28 A·MeV has been studied with the 4π multidetector AMPHORA. A rigourous selection of the experimental data is described in order to extract a central collision sample. Then different models are compared to the data. The incomplete fusion process is in agreement with the data. The azimuthal angle correlations of He-Li and Li-Li pairs have been used to discriminate sequential or instantaneous emission. The sequential deexcitation is more consistent with all the data. The different analysis allow to describe all the characteristics of the compound nucleus and finally a fusion cross section of 300 ± 100 *mbarn* have been measured.
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1 Introduction

Heavy ion studies have taken a new interest since 4π detectors were designed. Indeed the accuracy of the measurement has been improved and allows a better understanding of the basic mechanisms in nuclear collisions. In the experiment described hereafter, we are interested in the deexcitation process of a hot source created by the reaction between the nickel projectile and the aluminium target for an incident energy of 28 A.MeV. We will focus more specifically on light charged particles and Intermediate Mass Fragment emission (IMF is defined as a fragment with charge $Z \geq 3$ and $Z \leq Z_{proj}$). The points we would like to address are the following :
-do we form a "single source"? If so, how to select the single source data to determine the characteristics of this source?
-concerning the deexcitation of this source, do we observe a sequential or instantaneous IMF emission?
Obviously these points are related to the observation of the composite system multifragmentation in the central collisions. The incident energy of this experiment is in the transition region between :
-the low energies ($E_{inc} \leq$ 15-20 A·MeV) where the reaction mechanisms are governed essentially by the long range part of the nuclear force, hence by mean field [1]. Complete or incomplete fusion is observed for central collisions and the compound nucleus deexcitation is mainly composed by light charged particles evaporation. Binary dissipative collisions are observed for peripheral collisions and the deexcitation process of both excited quasi-target and quasi-projectile is identical to the compound nucleus one.
-the high energies ($E_{inc} \geq 100$ A·MeV) where the reaction mechanisms is governed by nucleon-nucleon interaction leading to the so called participant-spectator picture [2].
In-between the situation is more complicated, since experimentally the IMF production appears to be relevant of

the low energy mechanisms evolution or/and of the apparition of new ones. This region creates a large interest since the question of the phase transition has appeared recently [3]. The composite system multifragmentation has been observed for both light systems [4],[5] like the Ca + Ca 35 A·MeV reaction [6] and heavy systems [7],[8] like the Xe + Sn 50 A·MeV reaction [9]. The present paper describes the results of the Ni + Al reaction at 28 A·MeV which is in the low part of the transition region where the multifragmentation process is expected to appear.

Section two will present the experimental set-up, section three will describe the event selection, section four will focus on the data analysis and then section five will discuss the results.

2 Experimental procedure and data reduction

The experiment was performed at the SARA facility, in Grenoble, using the AMPHORA multidetection array. This experiment involved a 28 A·MeV ^{58}Ni beam on a ^{27}Al target. AMPHORA is an azimuthally symmetric multidetector made of 140 charged particle detectors covering 82% of 4π (AMPHORA has been described in detail in previous work[10]). It is divided into a forward wall section which contains 48 CsI (2° - 16°) and a 92 CsI backward ball (16° - 165°). Thin plastic scintillators (100 and 200 μm) set in the front of the CsI detectors (up to 38°) allow identification of charge up to $Z = 30$ within ± 1 charge unit. For CsI detectors at polar angles larger than 38° , the identification was limited to charge $Z \leq 3$. A multiplicity threshold of two was imposed during the experiment with the aim of rejecting the most peripheral collisions.

The energy calibration was carried out in a separate experiment with the same beam and target. During this calibration experiment, silicon tri-telescopes (50, 150 and 500 μm) were used together with a 3cm CsI(Tl) crystal which measured energy spectra at each polar angle covered by the AMPHORA detectors. For each polar angle ring of AMPHORA one detector was selected as a reference and the gains for other detectors in the same ring were adjusted to reproduce the reference detector spectrum. It was then sufficient to calibrate the reference detector using the energy spectra measured in the calibration run at the corresponding polar angles.

For detectors equipped with plastic scintillators it has been found (by extending the work of [12] and [13]) that the energy of an ion with charge Z can be written as :

$$\mathrm{E_r = A * L + B * ln(1 + C * L)} \tag{1}$$

where, for each Z, $\mathrm{E_r}$ is the energy deposited in the CsI crystal, L is the light output of the CsI crystal minus the light corresponding to the energy loss in the plastic scintillator and :

$$\begin{aligned} A &= (\alpha_1 * Z + \alpha_2)Z \\ B &= (\beta_1 * Z + \beta_2)Z \\ C &= (\gamma_1 * Z + \gamma_2)Z^2 \end{aligned}$$

where $\alpha_i, \beta_i, \gamma_i$ are constants determined for each reference detector.

Calibration for charge one was eased by the observation of punch through energies in the CsI detectors.

The energy thresholds for the CsI crystals are 4 MeV for protons, 7 MeV for alpha particles and 10 MeV for lithium. For the plastic foils of 200 μm thickness, they are 4 MeV for protons, 14 MeV for alphas, and 6-10 A.MeV for ions of charges $Z = 5$-15.

In order to prevent particle contamination from other beam bursts, we have checked particle time origin. For all detectors equipped with a plastic foil, a time signal was measured using a start given by the cyclotron radio frequency. The effective time gate of the data acquisition included two beam bursts. During off-line analysis we retained only events coming from the same burst. More precisely, if an event contains at least one particle which does not belong to this burst the full event is rejected. We have checked that the rejection rate is negligible.

3 Event selection

Due to the AMPHORA design and to the reverse kinematics of this reaction, it has been possible to detect quasi-complete events, involving at least 80% of the total charge detected ($33 \leq Z_{\text{total}} \leq 41$). Figure 1 shows for each event the total parallel momentum versus the total charge for experimental data. It can be noticed that the requirement of quasi-complete detection of the total charge implies the detection of at least 60% of the incident parallel momentum (13 GeV/c).
The first goal is to select central collisions, the fragments produced in peripheral collisions for this system, are mainly emitted along the beam axis (quasi-projectile fragments) and then go through the forward hole or are stopped in the plastic detectors (quasi-target fragments) due to energy thresholds. Consequently by requiring quasi-complete measurement of the total charge, we detect mostly central events.
For a quantitative illustration of this correlation between the total detected charge and the centrality of the reaction we have performed numerical simulations with the DBS code ("Diffusion Binaire Séquentielle") [14], which describes the full range of impact parameters from central collisions ($b \simeq 0\,\text{fm}$) to the most peripheral collisions ($b = 8.7\,\text{fm}$). The results of these calculations are afterwards filtered by the SIR code ("SImulateur de Réponse" [15]) in order to simulate the detector response.

- The DBS code simulates the nuclear collision dynamics taking into account preequilibrium emission and the deexcitation following the reaction. The calculation is performed for a given impact parameter generated by randomly drawing from a triangular distribution. The fusion and the Deep Inelastic Process (DIP) probability is estimated by solving the classical dynamical equations [17]. Trajectory equations take into account Coulomb, nuclear conservative and nuclear friction dissipative forces. The entrance channel leads to either the formation of an excited composite nucleus or a binary process resulting in a quasi-target and a quasi-projectile both excited. Then the GEMINI code [18] is used to describe sequential decay for the excited composite nucleus or for the excited quasi-target and quasi-projectile .

In figure 2 we show the correlation between the impact parameter and the total detected charge for simulated events. Most of the events detected with the largest total charge corresponding to the most central collisions are related to the lowest impact parameters. In the figure three parts can be observed. For total charge lower than 23, the events are poorly detected. This corresponds to binary events where one or several fragments are missed and the lack of information give difficulties to analyze these data. For total charge greater than 23, two bumps are visible, the first one covering impact parameters from 0 to 3 fm where the fusion process is expected, the second one from 3 to 8 fm where the deep inelastic process is involved. Therefore the first event selection, in order to isolate the most central collisions, is the selection of quasi-complete events ($\geq$ 80 % of Z_{Total}, see corresponding line in the figure). Nevertheless by requiring quasi-complete detection of the total charge, the DBS code calculations indicate that 56% of simulated events originate from the deep inelastic process (DIP). This contribution comes mainly from the large impact parameters ($b \geq 3$ fm) as it can be seen in figure 2.

To reduce the DIP proportion we have employed the reconstitution source method [19]. The selected sample with the first criteria are analysed within the following procedure.
This method is based on the heaviest fragment detected in each event. In a first iteration the heaviest fragment determines the source velocity. In this source frame three velocity spheres are built. The first for $Z = 1$, the second for $Z = 2$, the last for $Z \geq 3$. The radii are respectively equal to $0.6 v_{beam}$, $0.5 v_{beam}$ and $0.4 v_{beam}$. All particles which are in these spheres are supposed to be emitted by the source. In figure 3 we report this reconstitution process for the experimental data (figure 3 *a*)and for simulation for fusion followed by sequential deexcitation (DBS code, figure 3 *b*)and for deep inelastic process followed by sequential deexcitation (DBS code, figure 3 *c*) and for fusion followed by an instantaneous multifragmentation (MMMC code, Multifragmentation