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TOWARDS AN UNAMBIGUOUS DETERMINATION OF THE EXCITATION ENERGY OF THE PROJECTILE IN HEAVY-ION REACTIONS ?

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Abstract

The excitation energy of the quasi-projectiles produced in heavy-ion collisions is determined for the ^{58}Ni+^{197}Au reactions at 52 and 90 AMeV. A new method is proposed for isolating unambiguously the particles evaporated by the source. It consists in observing them at small angles along the flight direction of the source.

1. INTRODUCTION

The excitation energy which is transferred to the fragments in the course of a heavy-ion collision is a key parameter for understanding the formation and de-excitation properties of hot nuclei. Such a parameter is particularly important in the study of the multifragmentation of nuclear matter and has to be determined as carefully as possible.

Several procedures have been used up to now. Attempts have been made to reconstruct the projectile source with light charged particles (LCP) and intermediate mass fragments (IMF) surrounding the residue of the projectile: proximity criteria are generally called for [1]. In other studies, a probability is attributed to every particle to be emitted by the source [2]. The excitation energy can also be calculated taking into account only LCP and IMF emitted in the forward hemisphere in the frame of the source to eliminate the particles emitted in non statistical processes [3–5].

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When measuring the energy (or velocity) spectrum of particles emitted by a source, along its flight direction, two kinematical solutions are evidenced: particles emitted either in the forward or in the backward direction, the former case being associated with a higher energy than in the second case. These two components are well separated in energy (or in velocity). Such a technique has been applied in the study of the statistical de-excitation of projectiles [6, 7].

In this report preliminary results on the determination of the excitation energy of the quasi-projectile (QP) produced in the ^{58}Ni + ^{197}Au reactions at 52 and 90 AMeV are presented. The experiments were performed with the standard version of the Indra multidetector [8, 9].

2. A CLEAR INDICATION OF PARTICLES EMITTED BY THE QP

2.1. Kinematical considerations

The velocity spectrum of evaporated particles should exhibit two components when detected at small angles along the flight direction of the source: the first component is located at velocities smaller than the source velocity and the other one at velocities higher than that of the source. The smaller the detection angular domain, the clearer the separation of the two components in the energy spectra of the detected particles. Also the amplitudes of the peaks associated to every kinematical solution should scale in the ratio of the respective solid angles.

With the increase of the emission angle of the evaporated particles with respect to the source direction, the two peaks in the velocity spectrum are expected to approach from each other and finally to merge into one component corresponding to the maximum emission angle of the particles.

For a given type of particle the distance between the two components is proportional to the emission velocity in the source frame. It will increase with the decrease of the mass of the evaporated particle.

2.2. Experimental observations

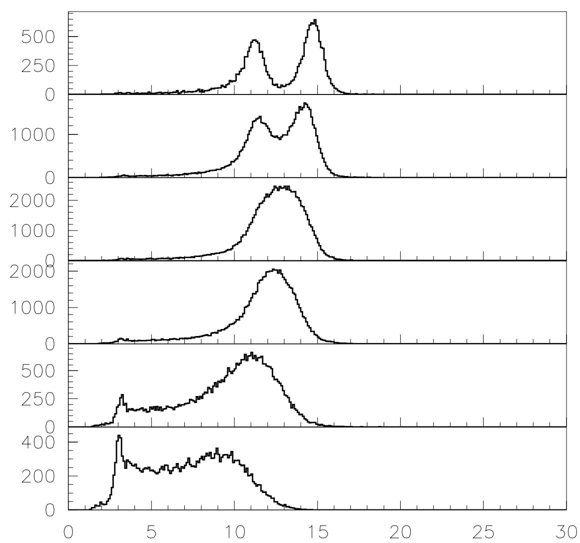

FIG. 1: Evolution of the parallel velocity spectra of alpha particles, in the laboratory frame, as a function of the polar angle (from top to bottom: the detection Indra rings # 2 to 7 with the polar angle varying between 3° and 27° [8]). The velocity abscissa scale is given in cm/ns.

When measuring light particles at very small angles in the laboratory frame, the picture described above is really observed. It is an evidence of a sequential evaporation from the QP: two separated peaks, one backwards and the other one forwards with respect to the projectile velocity (see Fig. 1, first panel corresponding to the first Indra ring with $3° < \theta < 4.5°$).

Such a correlation argues strongly for an emission of the particles by the QP. This shows that, when looking at small angles with respect to the source direction, it is possible to isolate particles coming unambiguously from this source. These characteristics will be used in the following to reconstruct the excitation energy of the QP.

The experimental velocity spectra for alpha particles detected at larger angles (see Fig. 1) also reveal the two peaks coming closer from each other when going away from the recoil direction of the source. As seen in the third panel, only one component appears at $7° < \theta < 10°$. For even larger angles an increase of the yield of particles emitted with velocities in between the projectile and target velocities is noticed. Therefore, at larger angles the clear signature of particles evaporated by the QP vanishes.

3. SELECTION OF THE EVENTS

To study the excitation energy of the QP as a function of the energy dissipation, the total multiplicity has been used as an event selector: the smaller the multiplicity, the less dissipative the collision; the higher the multiplicity, the more central the collision. For that purpose the multiplicity distribution was divided in 10 bins of the same area. The analysis done in this work deals with bins of reduced impact parameter b_{red} = .9 and .7, associated with peripheral and semi-peripheral collisions, respectively.

In heavy-ion collisions very hot nuclei can be formed. These nuclei de-excite by multifragmentation or by emission of LCP and IMF. In this analysis, the residue of the QP has been defined as being the biggest fragment detected in the forward direction with a charge $Z_{max} > 9$ and a velocity $V_{Zmax} > 9$ cm/ns for the Ni+Au reaction at 90 AMeV and $V_{Zmax} > 7$ cm/ns at 52 AMeV.

A further selection requires the events to be well measured: the total detected parallel momentum with respect to the incident momentum is larger than 70%.

4. RECONSTRUCTION OF THE QUASI-PROJECTILE

The objective is to reconstruct the primary QP and to determine its excitation energy from the properties of the decay products [3, 7]. This is done by using the calorimetry technique, where the excitation energy of the hot nucleus is the sum of the kinetic energies of all evaporated particles (charged particles or fragments and neutrons) plus the Q-value of the reaction:

$$E^* = \sum_{k=1}^{M_c} T_k + T_n * M_n - Q \tag{1}$$

The Indra multidetector only detects charged particles. For the neutrons, a correction should be introduced in Eq. (1) as explained in [5].

An accurate reconstruction of the source needs that only particles evaporated by the source have to be taken into account. Without a precise selection of these particles the reconstruction of the QP is meaningless.

On the other hand, the LCP experimental spectra do not allow for an easy selection of the particles coming from the QP, as the sequentially emitted particles and particles originating in non statistical processes are emitted with comparative time scales.

In order to solve this problem, we propose to associate to each detected particle a probability to be evaporated by the QP (as will be detailed in the next sections). The idea is based on the clear correlation observed in Fig. 1 (first panel): as we can put in evidence the particles evaporated by the QP, it should be possible to extract their energy (or velocity) distribution in the frame of the source. This can be done for all types of LCP.

The procedure consists to simulate the velocity distributions for every type of particle evaporated by the QP at any polar angle and to compare them to the experimental spectra. Then the ratio of the simulated (evaporated) yield to the total experimental yield will provide us with the probability for a given type of particle to be emitted by the source. The interest of the method is to rely on the experimental characteristics of the LCP and IMF.

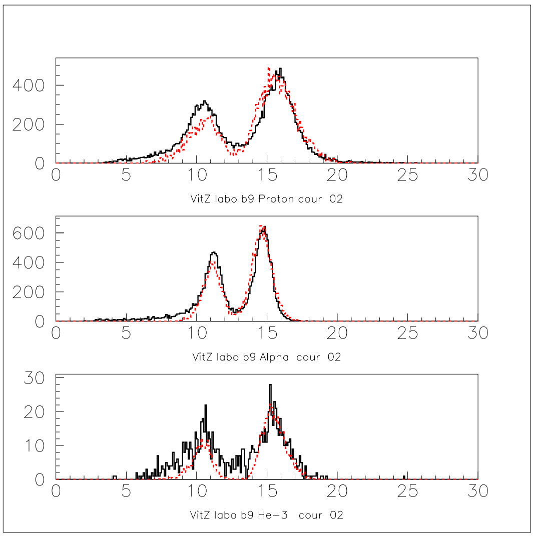

FIG. 2: From top to bottom: parallel velocity spectra of protons, α particles and ^{3}He, respectively, produced in the ^{58}Ni+^{197}Au reaction at 90 AMeV, corresponding to b_{red} = .9 and detected at angles $3^\circ < \theta < 4.5^\circ$. Black lines : experiment, red dotted lines: simulation.

5. SIMULATION OF EVAPORATED PARTICLES

The simulation was performed successively for all types of LCP measured in the experiment: p, d, ^{3}He, α and IMF ($3 \leq Z \leq 8$).

The velocity of the source has been taken as a gaussian distribution with parameters fixed in such a way that the velocity distribution of the QP residue is well reproduced. LCP are assumed to be isotropically emitted in the source frame. A maxwellian distribution is used to describe the LCP kinetic energy distribution. This distribution is a function of two parameters: the Coulomb barrier B and the temperature T. However, it should be stressed that these two quantities are used as simple fit parameters to deduce the proper energy distribution and no particular physical significance will be expected.

The distributions of the parallel velocity of the evaporated LCP are constructed as a function of the polar angle: the range for the polar angles are defined by the angular aperture of the different detection rings of Indra.

Different couples of parameters (B,T) are tested on a large range to reproduce the experimental velocity spectra of LCP which exhibit the two kinematical components, i.e. the distribution associated with a small detection angle with respect to the flight direction of the source (the 2^{nd} Indra ring). The

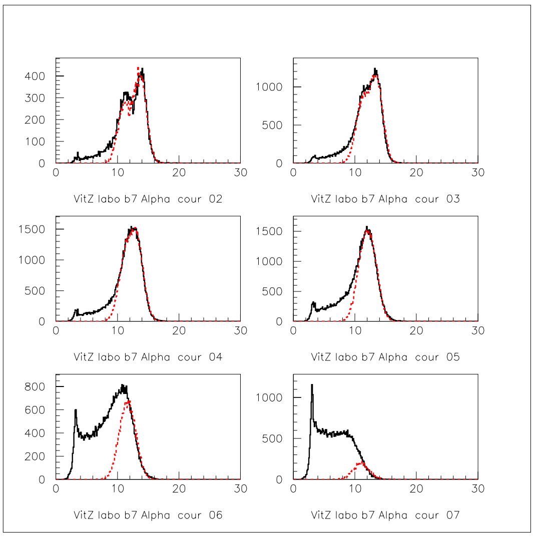

FIG. 3: Parallel velocity spectra of α particles from the ^{58}Ni+^{197}Au reaction at 90 AMeV for b_{red} = .7, as a function of the polar angle (see legend of Fig. 1). Black lines : experiment, red dotted lines: simulation.

best couple of values is deduced with a chi-square minimization procedure. As seen in Fig. 2 a good description is obtained for different types of LCP observed at the small angles $3^\circ < \theta < 4.5^\circ$.

Using the best (B,T) couple, the LCP parallel velocity distributions in the source frame are deduced for the whole angular domain. The simulated distributions are normalized to the experimental ones with the criterion that the high energy part of the two distributions coincide. Some results of the fits are seen in Fig. 3 for alpha particles issued from the ^{58}Ni+^{197}Au reaction at 90 AMeV and for b_{red} = .7.

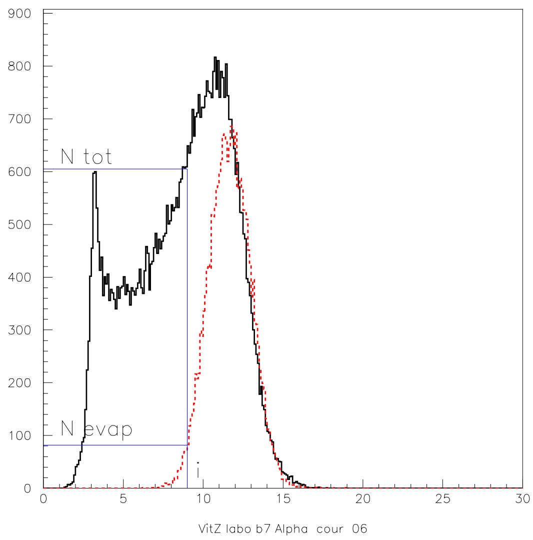

FIG. 4: Experimental (black line) and simulated (red-dotted line) parallel velocity spectra of α particles measured at $14^\circ < \theta < 20^\circ$, with b_{red} = .7, in the reaction Ni+Au at 90 AMeV. For a given channel the evaporation probability is the ratio of the simulated (evaporated) yield to the experimental one.

6. EVAPORATION PROBABILITY

As explained above, the idea is to associate to every detected particle (LCP and IMF), a probability to be evaporated by the QP. Once the evaporation spectra are obtained for the whole detection angular range, for a given type of particle detected at a given polar angle, the evaporation probability is expressed as the ratio of the simulated (evaporated) yield to the total one, in the parallel velocity distributions, as seen in Fig. 4.

The evaporation probability for a particle of a given type depends on the impact parameter (energy dissipation), the polar angle and the parallel velocity (Eq. 2).

$$P(b, type, \theta, v_z) = \frac{N_{evap}(b, type, \theta, v_z)}{N_{tot}(b, type, \theta, v_z)} \tag{2}$$

7. EXCITATION ENERGY OF THE QP

The excitation energy of the QP is determined by the calorimetry method (Eq. 1). Each detected particle is given a weight, the evaporation probability P_k for the k^{th} detected particle in the event, in such a way that the excitation energy is now given by:

$$E^* = \sum_{k=1}^{M_c}(T_k * P_k) + T_n * M_n - Q(P_k) \tag{3}$$

The excitation energies of the QP so deduced are shown for the ^{58}Ni+^{197}Au reactions at 52 and 90 AMeV in Fig. 5.

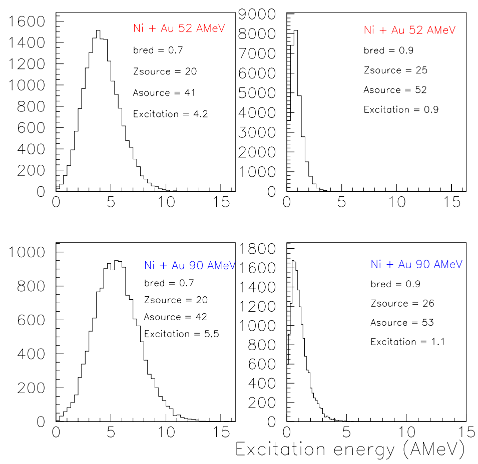

FIG. 5: Excitation energy of the QP. Upper row: ^{58}Ni+^{197}Au reaction at 52 AMeV, lower row: ^{58}Ni+^{197}Au reaction at 90 AMeV. Left column: b_{red} = .7, right column: b_{red} = .9.

In the two reactions, almost the same size is obtained for the QP at the same reduced impact parameter: for b_{red} = .9 the average charge and mass of the QP are Z $\approx$ 25-26 and A $\approx$ 52-53, while at b_{red} = .7 these values become Z $\approx$ 20 and A $\approx$ 41-42.

The excitation energy per nucleon of the QP is slightly larger when the bombarding energy increases: for b_{red} = .9 a value of 0.9 MeV/nucleon is obtained at 52 AMeV and 1.1 MeV/nucleon at 90 AMeV. As for b_{red} = .7, an excitation energy of 4.2 MeV/nucleon is obtained at 52 AMeV and 5.5 MeV/nucleon at 90 AMeV. The small increase of the excitation energy of the QP with the bombarding energy could be an indication that more energy is deposited in the quasi-projectile when increasing the bombarding energy.

To check the validity of the procedure, results were compared with the predictions of the statistical code Gemini [10]. The multiplicities of evaporated particles deduced within the presented method are well reproduced by the code at b_{red} = .7 for the ^{58}Ni+^{197}Au reaction at 90 AMeV [11]. The same agreement is obtained at 52 AMeV for the same impact parameter.

8. CONCLUSION

In this paper preliminary results are reported on the determination of the excitation energy of the quasi-projectile in the ^{58}Ni+^{197}Au reactions measured with the Indra multidetector at 52 AMeV and 90 AMeV.

An attempt was made to select as properly as possible the LCP and IMF really evaporated by the QP. For that purpose, an evaporation probability is attributed to each detected particle and the excitation energy is reconstructed by the calorimetry technique.

Evaporated LCP multiplicities were compared and found consistent with the predictions of the statistical code Gemini, which gives confidence in the method.

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