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SEARCH FOR DYNAMICAL EFFECTS IN THE MULTIFRAGMENTATION PROCESS AT INTERMEDIATE ENERGY

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Search for dynamical effects in the multifragmentation process at intermediate energy.

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Abstract

Inclusive energy spectra of fast protons arising from Ar+Ta collisions at 94 MeV/u have been measured at large angles. These data are analysed in the framework of a one-body transport theory simulated by the BNV code emphasizing the primordial origin of these protons. A possible extension of such an analysis is derived using correlation functions in relative angle between two protons emitted in the mid rapidity region of the Xe + Sn reaction at 50 MeV/u.

I. INTRODUCTION

The origin of the multifragmentation process experimentally observed in heavy ion collisions at intermediate energies remains difficult to understand: this mechanism could include both statistical [1] and dynamical effects [2]. It is then interesting to search for experimental

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observables which are relevant to dynamical effects. During a heavy ion collision, particle emission can occur at every time of the reaction. Protons are known to be relevant to both the pre-equilibrium phase and the evaporative phase which takes place when the equilibration is achieved. Therefore, correlation studies between protons and fragments appear to be an interesting procedure to follow the evolution of multifragmentation. Among the wide array of the possible processes, the dynamical story of the reaction appears to be washed out in its final stage when the formed nuclear subsystem is highly excited and leads to a complex multichannel decay: then, the memory of the story is lost. An interesting alternative is to study subsystems at low excitation energy, in which one may hope that the part of that energy devoted to the compression/expansion is important compared to the thermal part. A possible way could be to look for a possible "proton trigger" for a specific "cold" multifragmentation process defined as follows: if a large amount of energy is extracted from the interacting nuclei at an early stage of the reaction by removing fast (pre-equilibrium?) particles, this would restrict the available excitation energy for the residual system and lead to the formation of a relatively cold composite; in the framework of the nuclear equation of state, such a low temperature could favour a possible spinodal disassembly when the system expands [3].

In this paper, we first report a measurement of energy spectra of protons emitted at high transverse momentum in collisions induced by 94 MeV/u Argon projectiles on Tantalum nuclei. The experiment was aimed at answering this question: are the high energy spectra in agreement with the usual statistical or dynamical descriptions or are there here some indications for another exotic process as suggested by dynamical fluctuations [4,5] or ternary nucleon collisions [6])? Another purpose of this experiment was to check if we observe a high energy component in proton emission able to account for ΛK production via incoherent nucleon-nucleon collisions. In this scenario [7,8], proposed to explain the surprisingly high cross-sections [9,10] measured for very sub-threshold Kaon production at such a low energy as 94 MeV/u, dynamical fluctuations at the beginning of the reaction could induce collisions between very energetic nucleons reaching the associated ΛK production threshold in their center-of-mass frame (330 MeV).

A further insight about the role of fast protons in nuclear processes could be obtained from exclusive data for the system Xe + Sn at 50 MeV/nucleon with the INDRA multidetector [11]. Recent studies [12,13] have shown that we can clearly isolate the mid-rapidity region and emission sources for this system. We shall conclude this paper by presenting two proton correlation functions built on relative angle distributions obtained from these data .

II. INCLUSIVE MEASUREMENTS OF PROTON ENERGY SPECTRA

A detailed analysis of the inclusive proton data is reported elsewhere [14]. The experiment was performed at the GANIL facility which delivered a 94 MeV/u Argon beam impinging on a $50 mg/cm^2$ Tantalum target. Energetic protons were detected by two telescopes consisting of a plastic Ne102 scintillator followed by a CsI-BGO phoswich. The telescopes were set at 75^o and 105^o with respect to the beam direction. Particle identification is obtained in the phoswich by pulse shape analysis of the light outputs which are integrated twice during a short (fast signal Q_f) and long time gate (slow signal Q_s) [15].

The phoswich length allows proton detection up to 450 MeV; a good energy resolution is obtained only for protons of more than 180 MeV.

The efficiency of the NE102+phoswich telescope has been determined from a simulation performed with the GEANT [16] code. The energy calibration of both telescopes was achieved in specific runs: secondary beams of light particles delivered by GANIL provided an energy calibration over the full range of interest, i.e. for proton energies between 150 and 300 MeV: protons selected by magnetic spectrometry were directly detected at 0^o in the laboratory. The correlation between the Q_f response of the phoswich and the proton energy is displayed in fig. 1, which shows that this calibration is rather good over the whole energy range of interest, with an accuracy better than 2%.

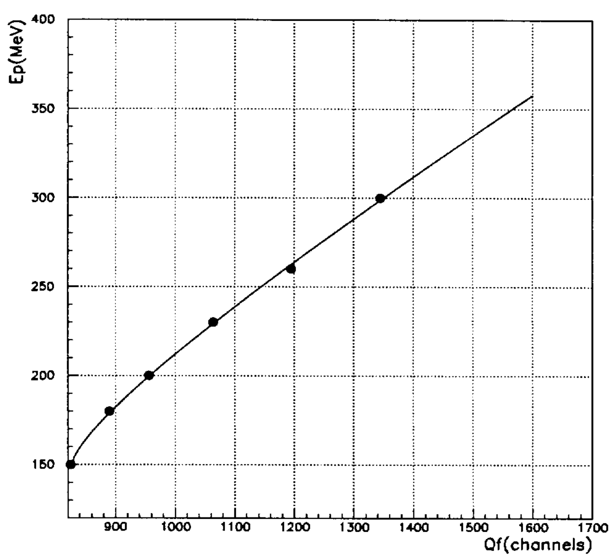

fig. 1: Absolute calibration of the Q_f variable. The continuous curve is the fit $Ep(MeV) = 2.48 * \sqrt{Q_f - 825} + 0.18 * Q_f - 3.2$ *used to calculate the proton energy.*

An absolute normalization of the measured cross-sections was obtained from the integration of the beam current by a Faraday cup intercepting the whole Ar incident flux after interaction with the target.

The resulting energy spectra are presented on fig. 2. Only the high energy parts we are interested in are displayed at 75^o and 105^o in the laboratory: they show an exponential fall-off with energies reaching 350 MeV; the latter value corresponds to nearly four times the beam energy per nucleon. Very fast protons have already been observed, but mainly in the backward hemisphere: they are explained by cooperative effects [17]. Other particles have also been observed at "anomalous" energies: for instance ^3He emission from an expanding hot source [18] formed in Xe + Sn interactions at 50 MeV/u; hard γ particles in Kr + Ni collisions at 60 MeV/u [19] which may be attributed to first chance np collisions, but the energies reached cannot be explained by the boost due to Fermi momentum. On fig. 2, the possible role of internal Fermi momentum is illustrated by the arrow "F" indicating the limit imposed at 75^o by a sharp cut-off of the Fermi motion at 270 MeV/c: we see that protons are produced far beyond this limit.

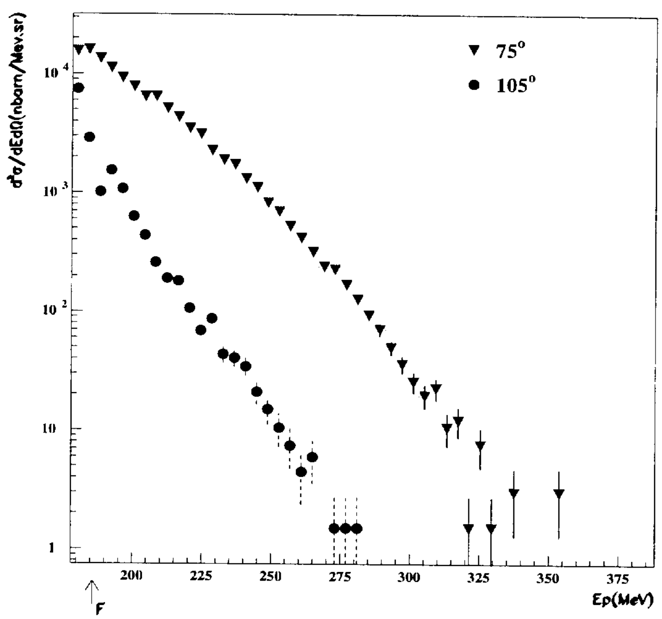

fig. 2: Proton energy spectra obtained from 94 MeV/u Ar+Ta interactions at 75^o *and* 105^o *it in the laboratory. The arrow labelled "F" indicates the kinematical limit it due to Fermi momentum, according to a "sharp cut-off" at 270 MeV/c. Only statistical errors are shown.*

The first part (from 180 up to $\simeq$ 250 MeV) of the spectrum at 75^o accounts for a slope parameter of about 20 MeV, compatible with that observed in previous measurements at this beam energy [20]. But the data points at higher energy exhibit a more rapid fall-off characterized by a lower value of $\simeq$ 15 MeV. A priori, these spectra might be interpreted by the evaporative decay of a hot participant zone, but the quantitative estimate of such a process depends strongly [20] on the size of that zone. In the context of these inclusive data, we are not able to determine this size, if any exists. Moreover, the aim of our work is to evaluate the role of non-equilibrium effects in the high energy part of the proton spectra. Therefore, we shall now analyse these data in the framework of a dynamical model.

III. BNV SIMULATIONS

Standard models like BUU, BNV or Landau-Vlasov do not allow predictions of reliable cross sections for protons of energies higher than $\simeq$ 200 Mev because of their statistical limits. Therefore, in order to get a deeper insight into the origin of the very fast observed protons, we have performed a Boltzmann-Nordheim-Vlasov (BNV) calculation which includes, together with the standard binary collision term, the possibility of ternary collisions [6]. This model [21] has already been applied with some success to sub-threshold pion and photon production [6]. A ternary collision can be viewed as a cooperative process, since the extra energy of the third nucleon can be used to boost a particle far from the Fermi sea, and at the same time it represents a preequilibrium contribution. As a matter of fact, the probability of a three body collision roughly scales as

$$\Pi_{col} \propto \rho^2 \sigma^{5/2} < 1 - f >^3 \tag{1}$$

where ρ is the baryon density, σ the nucleon-nucleon cross section, and $< 1 - f >$ the average occupation factor. Due to the ρ^2 factor, ternary collisions are negligeable except in the space-time regions where the density considerably exceeds normal nuclear matter density (for the present case, this corresponds to $t \leq 25$ fm/c); therefore particles issued from such a process represent a probe of the early stage of the reaction. Even if the probability of a three body encounter is not negligible at 94 MeV/u [6], the final yield of protons issued by this production mechanism turns out to be small due to both the Pauli blocking factors in eq(1) and final state interaction in the nuclear medium, the latter including inelastic scattering and absorption. In order to calculate with sufficient statistics such low probabilities, we have performed a perturbative calculation [22]: this means that we follow the mean dynamics as given by the standard BNV algorithm, and for each two or three body collision we calculate the probability that the collision will create a proton of a given energy and solid angle (here, we concentrate on protons of energy exceeding 180 MeV in the laboratory).

The particles thus created are propagated in the time dependent nuclear medium generated by the average dynamics, allowing rescattering and reabsorption. This turns out to be equivalent to a suppression in the final yield given by the factor

$$\Pi_{int} = \int_r^\infty e^{(-d/\lambda(r))} dr \tag{2}$$

where r is the production point, d is the distance that the proton has to travel before leaving the reaction region, and $\lambda = 1/\sigma\rho(r)$ the local mean free path. The continuity between the standard BNV at low energy and its perturbative extension at high energy has been checked at all angles and found to be very good. This calculation was made at both experimental angles: 75° and 105°. The integration is performed over the whole range of impact parameters concerned in the Ar+Ta system. The impact parameter corresponding to a maximum yield of high energy protons is about 5 fm at 75° and 3 fm at 105°. The comparison between BNV calculation and experimental spectra is done on absolute values without any normalisation. The results are shown in fig. 3, where it is seen that the standard binary processes are insufficient to account for the very energetic part of the spectra, and that the most energetic protons come from ternary collisions: this is particularly obvious at 105° where the binary component vanishes above 200 MeV. However the model tends to underestimate the data, especially for the most "sub-threshold" production at backward angles, suggesting that even more cooperative processes (higher order collisions) or off-shell contributions are needed to explain the proton yield.

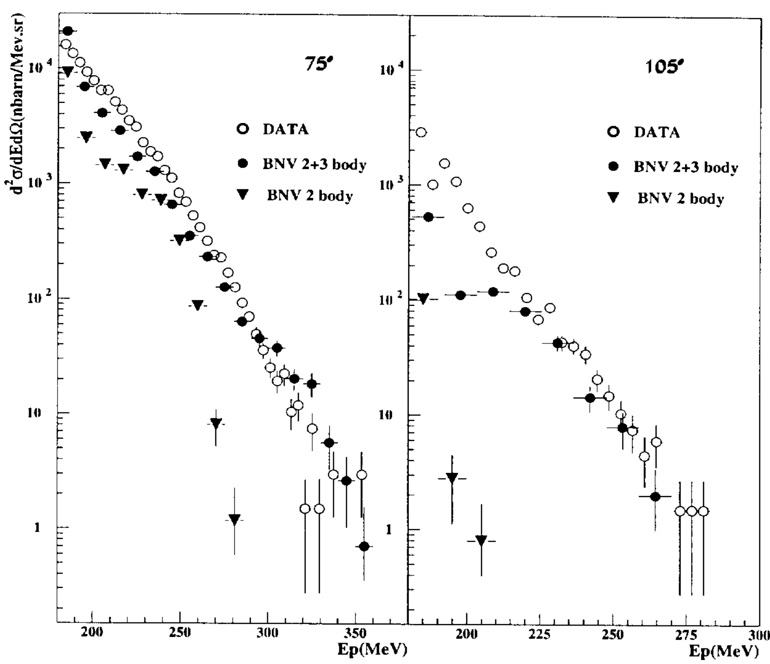

fig. 3: Comparison between experimental and BNV simulated proton energy spectra for 94 MeV/u Ar + Ta interactions at 75° and 105°. The BNV calculation is performed over an angular interval of ∓5°.

IV. EXCLUSIVE ANALYSIS FROM INDRA DATA

The main purpose of the present study is to establish a link between early (fast) proton emission and the multifragmentation process. We have demonstrated in the preceding BNV analysis that fast protons originate from the very early stage of the reaction. The removal of these energetic protons leaving the residual system with a lower excitation energy, we might expect that this low temperature favours some critical situation like spinodal disassembly. Transport theory approaches imply that the onset of dynamical fluctuations which could play a determinant role in that process occurs at the beginning of the reaction [23]: the experimental approach consists of studying the role played by protons in multifragment emission. High momentum protons emitted in collisions at 94 Mev/u are out of the detection range of INDRA. However the role of primordial emission of nucleons and clusters has been pointed out in the Xe + Sn system at 50 MeV/u [12,13]. Two proton correlation functions built on relative angle distributions appear as a a possible signal of some memory effect of the primary stage of the reaction.

The events of interest were selected according to the criteria of reference [13]. In order to characterize the violence of the collision, we used the transverse energy carried by Z=1 and Z=2 isotopes. We can see on fig. 4 that we have a rather good correlation between the transverse energy E_T and the total multiplicity detected, E_T being more sensitive for the more central events than the multiplicity. There are other variables to select the collision violence [24], but the construction of correlation functions requires high statistics so we didn't use a too precise selection: we defined two bins in transverse energy E_T: $E_T < 240MeV$ which corrresponds to the "rather peripheral" collisions and $E_T > 460MeV$ which corrresponds to the "rather central" collisions.

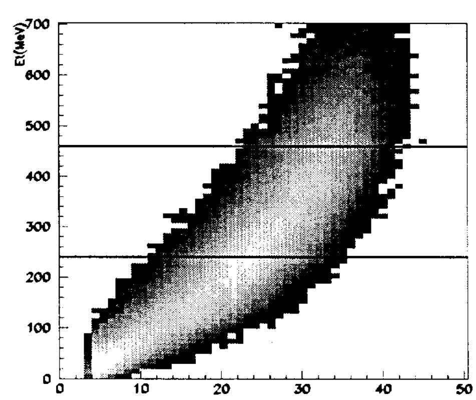

fig. 4. Correlation between total multiplicity detected and E_T for Xe+Sn at 50 MeV/u. The two lines define the bins of interest.

Before constructing the correlation function in relative angle α between 2 protons in the center of mass of the event, we selected a proton "emission source". A previous study [12] has shown that a non negligible part of the mid-rapidity region is due to a non statiscical process. In this region we can expect, especially for the fast protons, to be less sensitive to the evaporative component from both the "projectile like" and the "target like". As we are interested in searching for a link between multifragmentation and out-of-equilibrium emitted protons, we chose the protons emitted in the mid-rapidity region. Transport calculation indicate that this "mid-rapidity" emission is at the origin of most of the pre-equilibrium emission, corresponding to the onset and de-excitation of an excited overlap volume between the two nuclei.

The "mid-rapidity" region is defined by selecting protons with a polar angle in the range $60^o - 120^o$ in the center of mass of the reaction.

The correlation function in relative angle between two particles is defined as:

$$C(\alpha) = N(\alpha)/D(\alpha) \quad (3)$$

were N(α) stands for the yield of particles belonging to the same event and D(α) the uncorrelated background generated from particles belonging to different events of the same bin in transverse energy.

Fig. 5 shows the correlation functions in relative angle between proton pairs for Xe + Sn at 50 MeV/n events, selected in the "mid-rapidity" region for our two selections in transverse energy. We clearly observe that the correlation function exhibits an isotropy when constructed with protons of energy higher than 20 MeV in the center of mass of the event frame, in the "rather peripheral" case. Of course this shape is contained in the correlation function constructed with all protons for the same E_T selection, but is then diluted by all the other pairs of protons. This shape reveals that protons ($E_p(CM) > 20MeV$) seem to be emitted at very small relative angles or back-to-back preferentially for the "rather peripheral" events in the "mid rapidity" region.

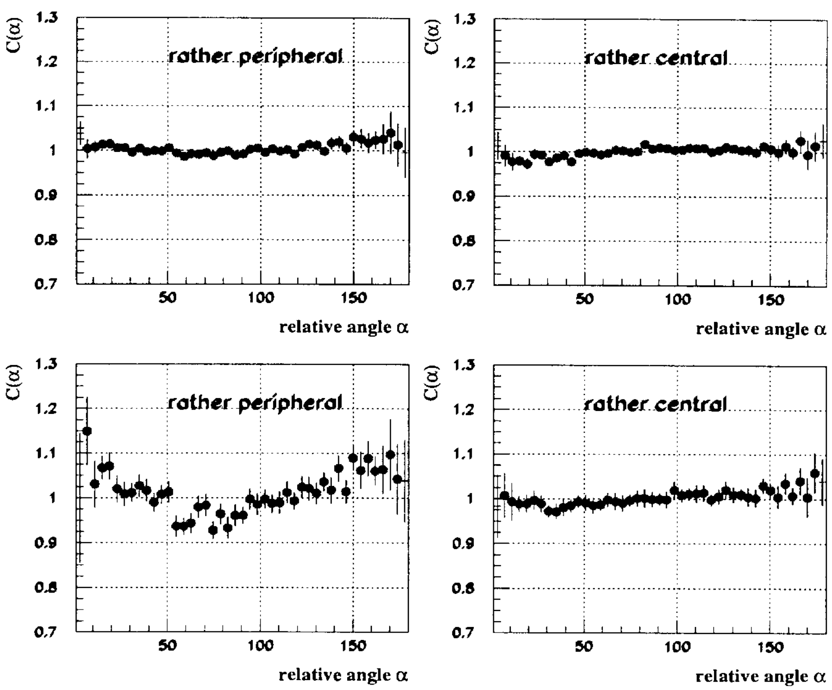

fig. 5: experimental correlation functions in relative angle between 2 protons emitted in the "mid-rapidity region". Top: without any selection of the proton energies, bottom: $Ep > 20MeV$ *in the center of mass of the event.*

First of all, we have to verify that this experimental observation is not associated with a systematic kinematical bias: we performed a simple two sources (projectile-like and target-like) simulation. The parameters of the sources (charge, mass, velocity, etc...) were extracted from INDRA data [13].

Fig. 6 shows the simulated correlation function for two sources whose characteristics correspond to the experimental selection of "rather peripheral" collisions. The simulated correlation functions are quite flat, even when we select more energetic protons ($E_p(CM) > 20MeV$). We can conclude that under the assumption of an isotropic emission of uncorrelated particles from two sources, no structure is expected due to either the detector geometry or the kinematical cut corresponding to the emission zone selection.

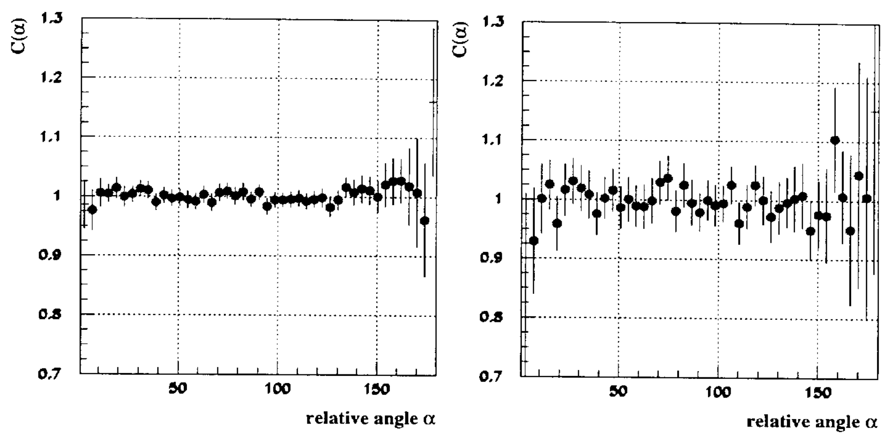

fig. 6: simulated correlation function in relative angle between 2 protons emitted between 60^o *and* 120^o*. Left: all the protons, right: proton energies* > 20 *MeV in the center of mass frame. The result is filtered by the INDRA granularity.*

We presently cannot conclude for the "rather central" events. For those events, we cannot see any preferential emission, but there can be several reasons for this:
- The proton energy cut is not high enough for those events, but we are restricted by statistics when selecting larger proton energies.
- Our centrality selection bin is quite large: we are mixing several classes of events. The most central ones can be associated to a "hot expanding source" [18], where the proton emission is expected to be isotropic.
- The "mid rapidity" region is then less well defined: if we still have two source events in the "rather central" selection, their velocities are closer and the "mid-rapidity" region can be very polluted by pure evaporation.

This short investigation has to be improved by a more complete analysis. Since the violence of the collision selection is more qualitative than precise, we have to look at the fragment distribution associated with the pairs of protons emitted at small relative angles or back-to-back in the mid-rapidity region. We could have multifragmentation events characterized by a lower transverse energy and then a lower excitation energy deposit, i.e. a "cold" system associated to those protons. This analysis is in progress.

V. CONCLUSION AND OUTLOOKS

Energy spectra of large transverse momentum protons emitted in Ar + Ta collisions

at 94 MeV/u have been measured. These inclusive data do not show any evidence of the expected signal related to possible instabilities expressed by dynamical fluctuations [5]. A straightforward consequence of that result is that Kaon production does not proceed via simple nucleon-nucleon collisions.
One needs the cooperation of a third nucleon in BNV transport theory to account for the high energy tail. The good agreement observed with the 3-body BNV simulation leads to an interesting consequence: high transverse momentum protons are emitted at the very beginning of the reaction and characterize the pre-equilibrium phase. We have started to investigate the question of their possible link with the cold multifragmentation process and its further consequence on the spinodal disassembly, which remains wide open: correlation functions in relative angle between pairs of protons might provide a good clue to answering that question. We have shown that in the "mid-rapidity" region, for the rather peripheral events, pairs of protons are emitted preferentially at very small relative angles or back-to-back. We attribute this feature to a manifestation of the entrance channel memory effect due to the very early phase of the corresponding particle emisssion in the "mid rapidity" region. Nevertheless such a study needs further investigation about the associated fragment emission.

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