# Lecture Notes in Physics

Edited by H. Araki, Kyoto, J. Ehlers, München, K. Hepp, Zürich
R. Kippenhahn, München, H. A. Weidenmüller, Heidelberg
and J. Zittartz, Köln

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# COLLECTIVE FLOW AND INTRANUCLEAR CASCADE DYNAMICS

J. CUGNON,
Université de Liège,
Institut de Physique au Sart Tilman,
Bâtiment B.5
B-4000 LIEGE 1, Belgique

The prospect of having very soon ion beams of high energy in order to test the current ideas about the phase transition between hadronic matter and quark-gluon plasma is very fascinating. However, the question of whether the nuclei are large enough systems to exhibit bulk dynamics, embodied by a quantity like the equation of state (EOS) is worth to be adressed. The answer (or at least a hint to it) can be searched for in the wealth of experimental data accumulated during the past ten years by the Bevalac people as well as in the theoretical effort that it has provoked. However, despite of this considerable effort, it has not yet been possible to determine clearly whether the collision between two heavy ions in the GeV per nucleon energy range proceeds from hydrodynamics or from the intranuclear cascade (INC) dynamics. The former, which can be considered as the short mean free path limit, may also generate EOS effects, whereas the INC model embodies a rather long mean free path situation and corresponds more or less to an ideal gas EOS. It may be more correct to say that in the hydrodynamical approach, all the spatial (and also temporal) fluctuations have been averaged out on all scales smaller than a given length [1], which may be considered as the mean free path. Therefore, the dynamics is thus governed by quantities which are associated with "cells" of linear dimension equal (at least) to the mean free path. A cell usually contains several particles and therefore the hydrodynamics can be considered as being sensitive to the bulk properties of the matter : EOS and transport coefficients.

The inclusive measurements are not very helpful in distinguishing between the two approaches. So the attention has turned to exclusive measurements. The hope is that the so-called global analysis of these measurements, very familar to high-energy physicists, will help to discriminate [2-7]. The basic idea is that bulk properties lead to a correlated flow, namely that if a nucleon is going outward in a given direction, there is a good chance to see other ones in approximately the same direction. The correlated flow will expectedly show up in the orientation of the sphericity ellipsoid, one of the most commonly used global variables constructed with the momenta of the ejectiles. However, as it has been shown by Danielewicz and Gyulassy [6], the correlated flow may be strongly masked by fluctuations due to the finite number of particles. Recently, the plastic ball group published their measurements of Ca+Ca and Nb+Nb at 400 MeV/A [8]. The so-called $dN/d\cos\theta$ plot (which express more or less the frequency of having an ellipsoid with a major axis pointing at an angle $\theta$ from the beam direction in the c.m. frame) clearly shows a peak for Nb+Nb high multiplicity events around $\theta \approx 23°$, whereas the maximum always arises at 0° in the Ca+Ca system.

The Nb+Nb results are more or less reproduced by the hydrodynamical calculations of ref. [9], although few attention is paid to the bias introduced by the detector (see below). Note that hydrodynamics should also predict a peak in the $dN/d\cos\theta$ plot for Ca+Ca, because in this model, the collective flow comes from the large incompressibility of the matter. Both the Ca+Ca and Nb+Nb data are reproduced by the INC calculation of ref. [10]. The detail of the calculation will not be discussed here, but it is necessary to quote its principal features in order to understand the relationship between the collective flow and the observables. The coalescence-invariant [4,5] sphericity tensor (i,j = cartesian indices)

$$Q_{ij} = \sum_{\nu} \frac{1}{2m_\nu} p_i^{(\nu)} p_j^{(\nu)} \quad , \qquad (1)$$

where $\vec{p}^{(\nu)}$ is the momentum of nucleon $\nu$, is constructed for each event after a filter is applied to simulate in the most accurate way the acceptance of the detector : this essentially amounts to discarding the target spectators with a lab energy of less than 20 MeV and the participant free neutrons (see ref. [10] for the detail). Furthermore the number of proton participants $M_\nu$ is calculated and finally the $dN/d\cos\theta$ plot is constructed for various bins in multiplicity $M_\nu$. The results are shown in Fig. 1, along with the data as given by ref. [8] for the largest multiplicity bin. The qualitative features of the results are preserved when changing the filter and the definition of $M_\nu$ in a reasonable way.

It is interesting to have a closer look at the detail of the results. Fig. 2 gives for the most interesting impact parameters the distribution of the projection of the unit vector $\vec{e}_1$ along the major axis of the full ellipsoid (without filter) on the impact parameter axis. For central collisions (b=0) the ellipsoid points in the ave-



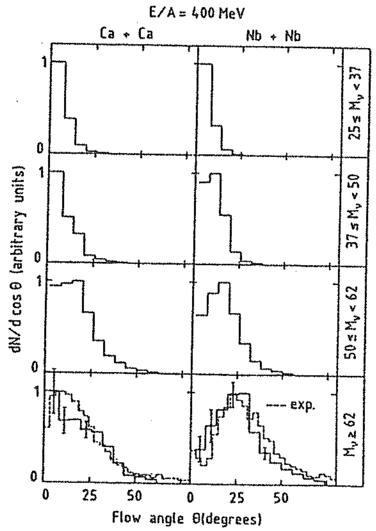


Fig. 1 : Full lines : $dN/d\cos\theta$ plot as calculated in ref. [10] for various charge multiplicity bins (see text for detail). Dotted lines : experimental data of ref. [8] for the largest measured multiplicity bin. The error bars give the precision of the calculation.

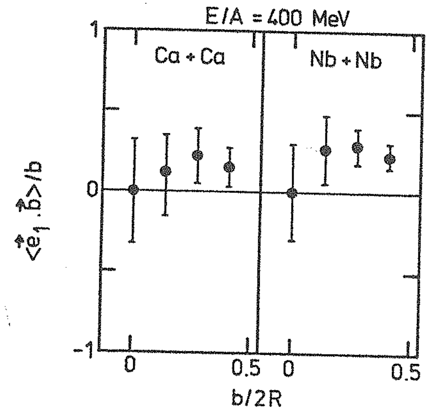


Fig. 2 : Average values (dots) of the cosine of the angle between the major axis of the ellipsoid and the impact parameter vector (see text) as calculated in ref. [10]. The error bars give the event to event fluctuations of the same quantity. The quantity R is the nuclear radius.

rage towards the beam axis, with a large fluctuation however. For intermediate impact parameters, the ellipsoid points towards finite angles indicating an intrinsic sideward collective flow. It is worthwhile to note that the fluctuations are smaller for the heavier system, which according to ref. [6], indicates that the fluctuations are largely dominated by finite particle effects and are probably insensitive to the dynamics itself. The intrinsic collective flow is thus largely dominated by the intermediate impact parameters. The flow angle for Nb+Nb is at most $\sim 15°$ whereas the observed angle is 23°. From Fig. 2, it is also evident that there is an intrinsic flow in Ca+Ca which does not yield a peak in the $dN/d\cos\theta$ plot at nonzero angle. These apparent contradictions are due to the filter and to the fluctuations which act in an intricate way. Fig. 3 illustrates this effect for the most significant impact parameter. The removal of the target spectators shifts the average angle $\bar{\theta}$ towards a larger value,

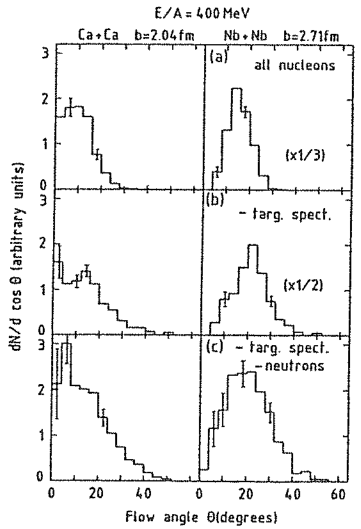


Fig. 3 : dN/d cos θ plot for a typical impact parameter, as calculated in ref. [10]. Part (a) corresponds to the full sphericity tensor. Part (b) is obtained by removing the target spectators. Part (c) is obtained by further removing the free neutrons.

essentially because the spectators are more or less aligned with the beam axis, whereas the participants take the largest contribution to the sideward flow. Furthermore, the elimination of the free neutrons slightly decreases $\bar{\theta}$ . Both operations increase the fluctuations because the number of particles diminishes. In Nb+Nb, a net peak remains. On the contrary, in Ca+Ca, the larger fluctuations are sufficient to wash out the manifestation of the flow, owing to a smaller intrinsic flow angle.

At this stage, it is not possible to say that INC and hydrodynamics are equally good to reproduce the experimental Nb+Nb data, because the acceptance of the detector is treated in a very crude way in ref. [9]. Furthermore, hydrodynamics is unable to predict fluctuations without further assumptions. But, let us consider for the moment that the two approaches are equally good. What are the consequences of that ? In our opinion, they are numerous and important : (1) There is a definite collective flow in heavy ion collisions, even in Ca+Ca (this is rather a consequence of the good success of the INC); (2) With Nb+Nb, the size of the system is large enough compared to the



mean free path for hydrodynamics to be valid, at least for the description of the expansion of the system (this would be in keeping with the result of ref. [11] which shows that the expansion conserves entropy). The collision process starts to be dominated by the bulk dynamics ; (3) The properties of the collective flow would be determined by the maximum pressure, which is more or less the same in both approaches [12] ; (4) The details of the equation of state, if the latter is different in this region from a free gas equation of state do not manifest themselves in a sufficient manner to be observed on the flow angle, which is calculated with an accuracy of a few degrees only. In this perspective, the Au+Au data and calculations are waited for, since all the features would be magnified in this system, according to the above discussion.

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