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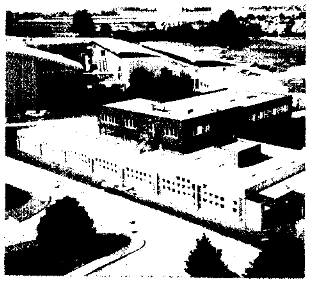

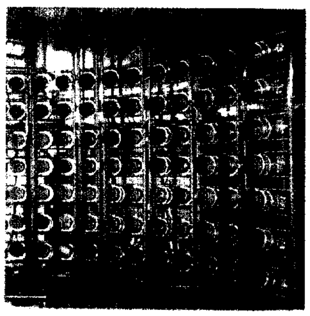

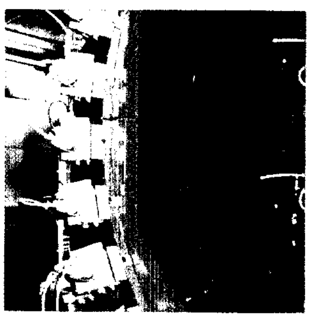

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(INDRA Collaboration)

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Measurement of small flows in heavy ion collisions around the balance energy.

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1 Introduction

The study of collective motions in the reaction plane, called sideward flow or in-plane flow (not to be confused with radial flow analysis), is used to provide information on the in-medium nucleon-nucleon interaction. By comparing the experimental results to dynamical calculations, it is possible to extract the value of the in-medium nucleon-nucleon cross section σ_{nn} , and the incompressibility modulus of the infinite nuclear matter K_∞ [1-11]. Of particular interest is the determination of the balance energy $E_{\rm bal}$, defined as the incident energy for which sideward flow is null, which may put high constraints on the σ_{nn} value [2].

For a defined collision (fixed incident partners, incident energy and impact parameter) different values of flow have been actually measured for different types of particles [3, 6, 12, 13]. These different flow values may reflect different emission processes. Indeed, dynamical calculations [14] have shown that sideward flow could be due to particles emitted at different

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times: one contribution comes from the decay of the so called quasi-projectile and quasi-target and/or neck emission, and the other from the particles emitted in the first moments of the collision. The aim of this contribution is to present the results of the sideward flow analysis for central Ar + Ni and Ni + Ni collisions, and the experimental problems linked to the measurement of small flow values.

The study presented here has been performed on the $^{36}Ar +^{58} Ni$ system from 32 to 95 A.MeV and on the $^{58}Ni +^{58} Ni$ system from 32 to 90 A.MeV. These experiments have been done at the GANIL facility with the 4π INDRA detector. This detector can be schematically described as a set of 17 detection rings centred on the beam axis. The detection of charged particles was provided in each ring with two or three detection layers: the most forward ring, $2° \leq \theta_{\rm lab} \leq 3°$, is made of phoswich detectors (NE102 + NE115); between 3° and 45° eight rings are constituted by three detector layers: ionization chambers, silicon and CsI(Tl); beyond 45°, the eight remaining rings are made of double layers: ionization chambers and CsI(Tl). For the Ar + Ni experiment the ionization chambers beyond 90° were not present. The total number of detection cells is 336. The overall geometrical efficiency of the INDRA detector correponds to 90% of 4π. Isotopic separation is achieved up to Z=4 in the last layer (CsI(Tl)) over the whole angular range ($3° \leq \theta_{\rm lab} \leq 176°$), except for low energy particles. Charge identification is carried out up to Z=54 for the forward rings ($3° \leq \theta_{\rm lab} \leq 45°$) and up to Z=16 in the backward rings ($\theta_{\rm lab} \geq 45°$). Globally the energy resolution is better than 5%. A detailed description can be found in [15, 16].

Even if INDRA is a highly efficient detector, it is not a perfect one. Before doing any analysis, one has to be sure that enough information has been collected. The events with a detected total parallel momentum above 70 % of the projectile momentum are analysed. This selection mainly removes the most peripheral collisions in which neither the quasi-target nor the quasi-projectile residues were detected.

Theoretical calculations have shown that sideward flow depends on impact parameter. Thus, one has to sort out events according to a global variable which is correlated to the impact parameter. We have chosen the total transverse energy E_{trans} which is defined as follows:

$$E_{trans} = \sum_{i=1}^{Multiplicity} E_i^{kin} \times sin^2(\theta_i) \qquad (1)$$

where E_i^{kin} is the kinetic energy of particle i, and θ_i its angle relative to the beam direction. Assuming that the most central collisions correspond to the highest values of E_{trans} , and a geometrical correspondence between E_{trans} and the impact parameter, one can define an "experimental" impact parameter $b_{\rm exp}$ (E_{trans}). The limiting values of each bin in E_{trans} are determined so that the total cross section of each bin corresponds to an integer value of $b_{\rm exp}$.

2 Experimental results

2.1 Flow parameters

To evaluate the flow parameters, one needs first to determine event by event the reaction plane. The transverse momentum method [17] and the momemtum tensor method [18] were used. These methods have been found to be equivalent [6, 12], and to give a better accuracy on the reaction plane determination than the azimuthal correlations method [19].

In order to avoid the so called "auto-correlation" effect, the particle of interest has been removed from the reaction plane determination, and a corrective momentum has been added to the momentum of other particles [13]. A detailed description and comparison of these methods will be done in section 3.

Once the reaction plane is determined, the projection of transverse momenta on the reaction plane can be evaluated. For each reduced rapidity bin $Y_r = Y / Y_{proj}$, its mean value $\langle p^{x'}/A \rangle$ is calculated, where A is the mass of the particle. The flow parameter F is then defined by:

$$F = \frac{1}{2}\left(\frac{\partial\left\langle p^{x'}/A\right\rangle}{\partial Y_r}\right)_{(Y_r=0.5)} \tag{2}$$

With this definition, the flow parameter F corresponds to the slope of the function $\langle p^{x'}/A \rangle = f(Y_r)$ at mid-rapidity. With these reaction plane reconstruction methods, the $\langle p^{x'}/A \rangle$ values should be positive for particles emitted by the QP and the $\langle p^{x'}/A \rangle$ values should be negative for those emitted by the QT. As a result, the measured flow parameter values F_{exp} should be always positive.

2.2 Evolution of the flow parameters with the incident energy.

The evolution of the flow parameter with the incident energy for the most central collisions ($b_{exp} \leq 3$ fm) are shown in figure 1 for the Ar + Ni system and in figure 2 for the Ni + Ni system, for different types of particle. The reaction plane has been determined with the transverse momentum method. The typical U shape can be seen on each plot. The incident energy which corresponds to the minimum flow value is located around 82 A.MeV whatever the particle type for the Ar + Ni system, and around 70 A.MeV for the Ni + Ni system. These energies correspond to the expected balance energies for both systems [2]. But there is an unexpected observation: for some particles, a negative value is obtained, whereas according to previous analyses only positive values should be measured.

A possible explanation for the negative values is given by AMD calculations [14]. It is found that for light charged particles, the sign of the flow of promptly emitted particles can be opposite to that of the flow of "evaporated" particles (emitted from the QP and the QT). Due to the reaction plane determination methods, the flow of evaporated particles is always positive. So, if prompt emissions are dominant, negative flow values can be obtained. This explanation is very tempting for the lighter particles: deuterons, tritons

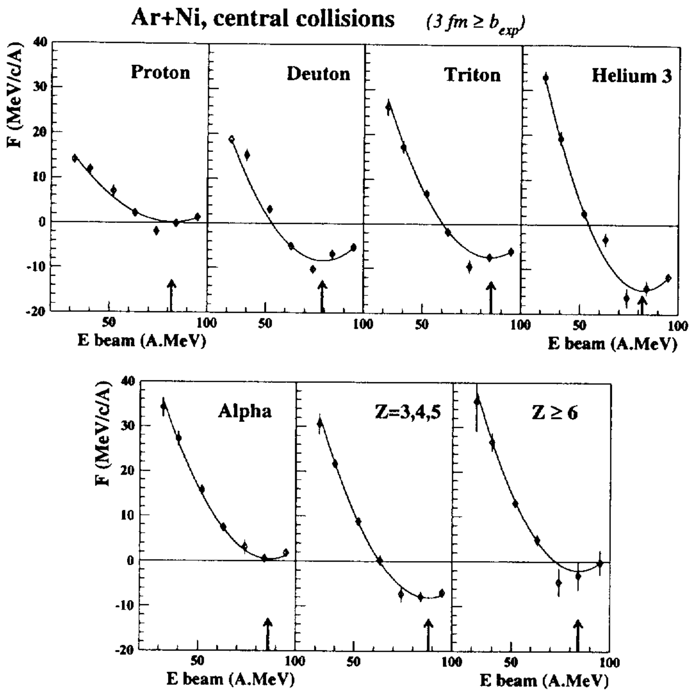

Figure 1: *Evolution of the flow parameter as a function of the beam energy for different types of particles, for the central collisions of the Ar + Ni system. The arrow on each plot corresponds to the balance energy* $E_{\rm bal}$ *defined here as the energy for which the flow parameter value is minimum.*

and ^3He are found to be predominantly emitted in the mid-rapidity regions [12, 20, 21], whereas protons and alpha particles are as much emitted by the QP and QT as by the mid-rapidity area.

This explanation is consistent with the observed positive values of flow for alpha and protons and the negative values observed for deuterons, tritons and ^3He. But this does not explain the negative values observed for heavier products. It is hard to believe that such fragments are promptly emitted via collisions of preexisting heavy fragments. For the QP and the QT residues, this observation is even in contradiction with the reaction plane orientation which is normally always oriented along the direction of the quasi-projectile velocity. The solution of this puzzle has to be found elsewhere.

3 Test of the methods

3.1 Reaction plane estimation methods

To characterize the collective motion in the reaction plane (via the flow parameter value), the first step is to rebuild this plane from the experimental data. We have checked

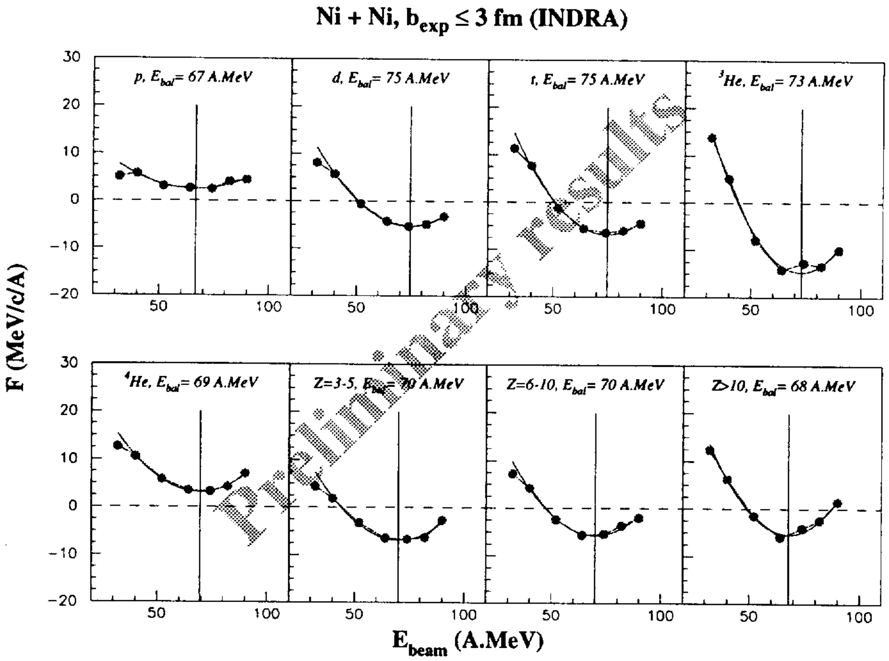

Figure 2: *Evolution of the flow parameter as a function of the beam energy for different types of particles, for central collisions of the Ni + Ni system (preliminary results). The vertical line on each plot corresponds to the balance energy* E_{bal} .

the performances of three commonly used methods: the transverse momentum method [17] (labelled DANIELEWICZ on the figures), the momentum tensor method [18] (labelled TENSOR on the figures) and the azimuthal correlations method [19] (labelled WILSON on the figures).

Danielewicz-Odyniec method

The transverse momentum method, explained in details in [17], is based on the fact that the sum of transverse momenta of particles emitted by the quasi-projectile $\overrightarrow{P_{QP}}$ is opposite to the sum of the transverse momenta of particles emitted from the quasi-target $\overrightarrow{P_{QT}}$. These vectors belong to the reaction plane. In order to maximize the efficiency of the method, one has to calculate the difference of the two vectors $\overrightarrow{Q} = \overrightarrow{P_{QP}} - \overrightarrow{P_{QT}}$. Usually, $\overrightarrow{Q}$ is determined the following way:

$$\overrightarrow{Q} = \sum_{j=1}^{N} \omega_j \overrightarrow{P_j^{\perp}} \tag{3}$$

where N is the total number of particles in the event, $\overrightarrow{P_j^{\perp}}$ is the transverse momentum of particle j and ω_j a weight defined as follows:

$$\omega(Y_r) = \begin{cases} -1 & \text{if} \quad Y_r - Y_{rcm} < -\delta \\ 0 & \text{if} \quad -\delta \leq Y_r - Y_{rcm} \leq \delta \\ 1 & \text{if} \quad Y_r - Y_{rcm} > \delta \end{cases} \tag{4}$$

where Y_r is the reduced rapidity of the particle, Y_{rcm} the center of mass reduced rapidity and δ a parameter which allows to remove mid-rapidity particles from the reaction plane estimation. $\overrightarrow{Q}$ and the beam direction define the reaction plane. With this definition, the reaction plane is positively oriented along the quasi-projectile velocity ($<p^{x'}/A>$ is positive for the particles emitted by the quasi-projectile).

Tensor method

Another way to estimate the reaction plane is to calculate and diagonalize the energy tensor $T_{\mu,\nu}$. The eigenvector corresponding to the higher eigenvalue defines, with the beam axis, the reaction plane. As for the transverse momentum method the reaction plane is positively oriented along the direction of the quasi-projectile. The tensor is defined in the following way:

$$T_{\mu\nu} = \sum_{j=1}^{N} \Omega_j \times P_j^{\mu} \times P_j^{\nu} \quad \text{with} \quad \mu, \nu = x, y, z \tag{5}$$

where P_j^{μ} is the momentum component along the μ axis ($\mu = x, y, z$) for particle j and N the total multiplicity. Ω_j is a weight which is usually set to the inverse of the mass A_j of the particle.

Wilson method

The azimuthal correlation method is based on the following obervation: in case of strong in-plane emission, the sum of the distances of particle momenta with respect to that plane are minimum [19]. This sum D^2 is calculated as follows:

$$D^2 = \sum_{j=1}^{N} \left[\left(P_j^x\right)^2 + \left(P_j^y\right)^2 - \frac{\left(P_j^x + aP_j^y\right)^2}{1 + a^2} \right] \tag{6}$$

where N is the total multiplicity, P_j^x and P_j^y are the transverse momentum components along the Ox and Oy axis respectively and $a = \tan(\varphi)$, where φ is the angle of the reaction plane relative to the Ox axis. Experimentally, one has to find the value of φ which minimizes D^2. With this method, the orientation of the reaction plane is not defined. One has to use the transverse momentum method to find it. In case of strong out-of-plane particle emission (side-splash), the estimated reaction plane angle is wrong by $\pi/2$.

To compare the relative efficiencies of these methods, a first simple test can be done: on can plot the distribution on the difference $\Delta\Phi$ between the true and the reconstructed reaction plane directions. Such a plot has been shown in figure 6 of reference [6]. It is shown that the distribution of $\Delta\Phi$ is larger for the Wilson's method than for the transverse momentum and tensor methods. This justifies the use of the transverse momentum method for the experimental data.

3.2 Testing procedure

The general procedure of the test is the following: a known flow parameter value F_{init} is set for a sample of generated events (from the SIMON code); then the reaction plane estimation method is applied on that sample and the "experimental flow parameter" F_{exp} is determined. A method is considered effective if the experimental value F_{exp} is equal or close to the initial one F_{init} .

To set a known flow parameter value to an event, an in-plane component P_x^a is added to the initial in-plane component of each particle. The amplitude of this in-plane component depends on the reduced rapidity of the particle:

$$P_x^a(F, Y_r, A) = \begin{cases} -\frac{A\times F}{2} & \text{if} \quad Y_r < 0.25 \\ 2F(Y_r - 0.5) & \text{if} \quad 0.25 \leq Y_r \leq 0.75 \\ \frac{A\times F}{2} & \text{if} \quad Y_r > 0.75 \end{cases} \tag{7}$$

where F is the flow parameter value to be set on, Y_r is the reduced rapidity of the particle (Y/Y_{proj}), A its mass and $P_x^a(F, Y_r, A)$ the added in-plane component. The effect of the "in plane momentum deformation" is to add the value of F to the original flow parameter value, leading to the F_{init} value.

The test has been performed on two systems Ar + Ni at 74 MeV/u and Xe + Sn at 50 MeV/u. These two systems have been studied with INDRA and their comparison allow to check the mass effect on the transverse flow measurement. These incident energies have been chosen because they are close to the expected balance energies for these systems. For each system, 15000 events have been generated using the SIMON code, in which entrance channel includes a preequilibrium emission of protons and neutrons [22].

3.3 Auto-correlation effect

Since the transverse momentum is used for both the reaction plane estimation and the projection, auto-correlations are expected. This can be seen in figure 3: the measured value F_{exp} is sytematically higher than the initial one F_{init} . The overestimation is bigger for the light particles and for small F_{init} values. It is weaker for the Xe + Sn system than for the Ar + Ni system and also weaker for the tensor method.

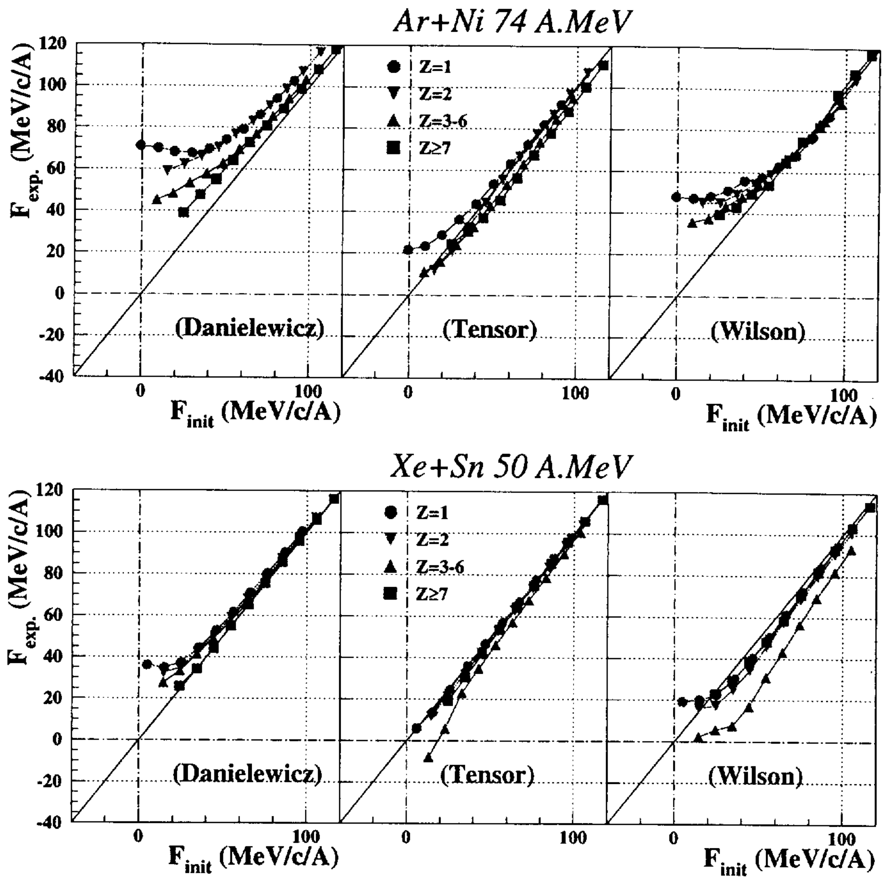

Figure 3: *Measured flow parameter versus initial flow parameter values for the Ar + Ni system at 74 A.MeV (upper row) and for the Xe + Sn system at 50 A.MeV (lower row). These plots have been obtained with the SIMON code. One plane per event is determined. The different symbols correspond to different types of particles.*

The usual way to fix the auto-correlation problem is to remove the particle which has to be projected from the estimation of the reaction plane. To take into account the non conservation of total momentum, due to the removal of the particle of interest, an additional corrective component $\overrightarrow{P_j^{cor}}$ is added to the remaining particles of the event. Its definition is the following:

$$\overrightarrow{P_j^{cor}} = -\frac{A_j}{\sum_{k=1,k\neq i}^{N} A_k} \times \overrightarrow{V_i} \tag{8}$$

where i is the removed particle, $\overrightarrow{V_i}$ its velocity, A_j the masss of particle j and N the event multiplicity. In this case, one plane is determined for each particle of the event.

3.4 Removal of the particle of interest from the plane determination

The dependence of F_{exp} with the initial value of the flow parameter is shown in figure 4 (one plane per particle). One can see that the procedure used to remove auto-correlations seems to be efficient for particle with charge 1. For higher values of the charge, the F_{exp} is systematically below F_{init} . This underestimation increases with increasing charge. For the same F_{init} value, the underestimation is lower for Xe+Sn system than for Ar+Ni. Finally, the amplitude of this underestimation decreases with increasing value of F_{init} . For the tensor method, the same trends are observed as for the transverse momentum method. As seen in references [6], these two methods give similar results. The same observations are made for the Wilson's method.

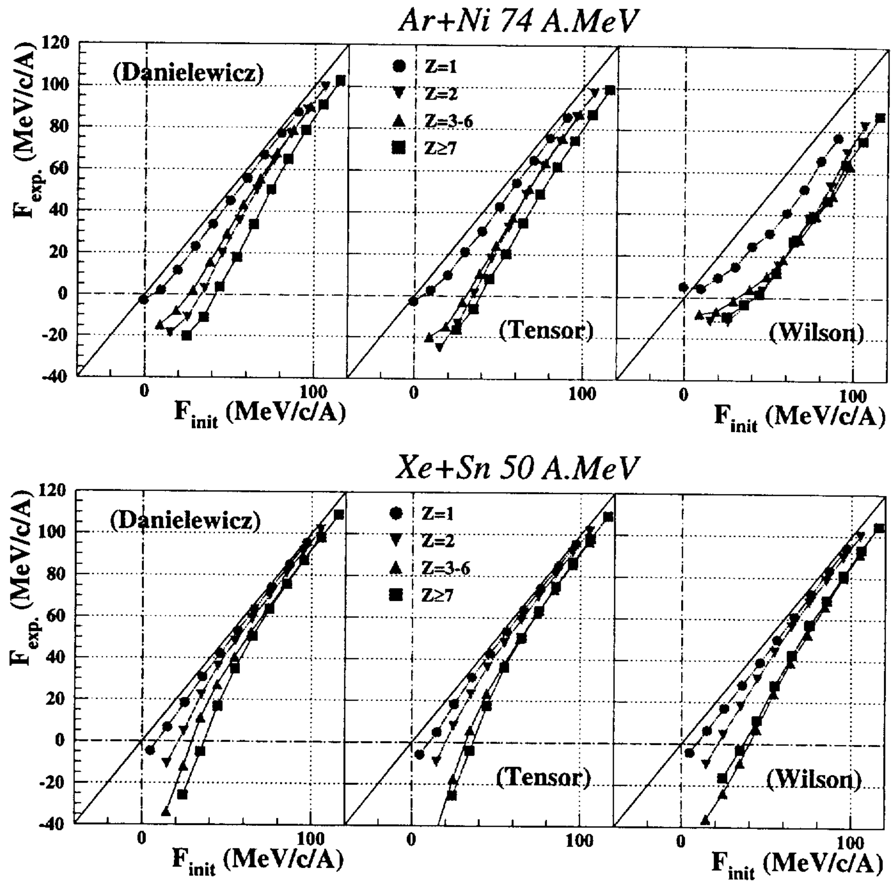

Figure 4: *Measured flow parameter values versus initial flow parameter values for the Ar + Ni system at 74 A.MeV (upper row) and for the Xe + Sn system at 50 A.MeV (lower row). These plots have been obtained with the SIMON code. One plane per particle is determined. The different symbols correspond to different types of particles.*

3.5 Influence of the experimental setup

In order to check the effect of the experimental set-up, a routine which simulates the INDRA detector has been applied on the generated events. The reaction plane determination procedures have then been applied on the so called "filtered" events. The result is shown on figure 5, in which the correlation of F_{exp} with F_{init} is plotted for the three methods (one plane per particle) and for the two systems studied here. The results are very similar to those shown on figure 4 with a perfect detection: the measured flow value is systematically below the initial one. The underestimation is a little bit bigger for the Ar + Ni system. The detector has a very weak effect compared to the reaction plane determination procedure. This conclusion is identical to those made in ref [8].

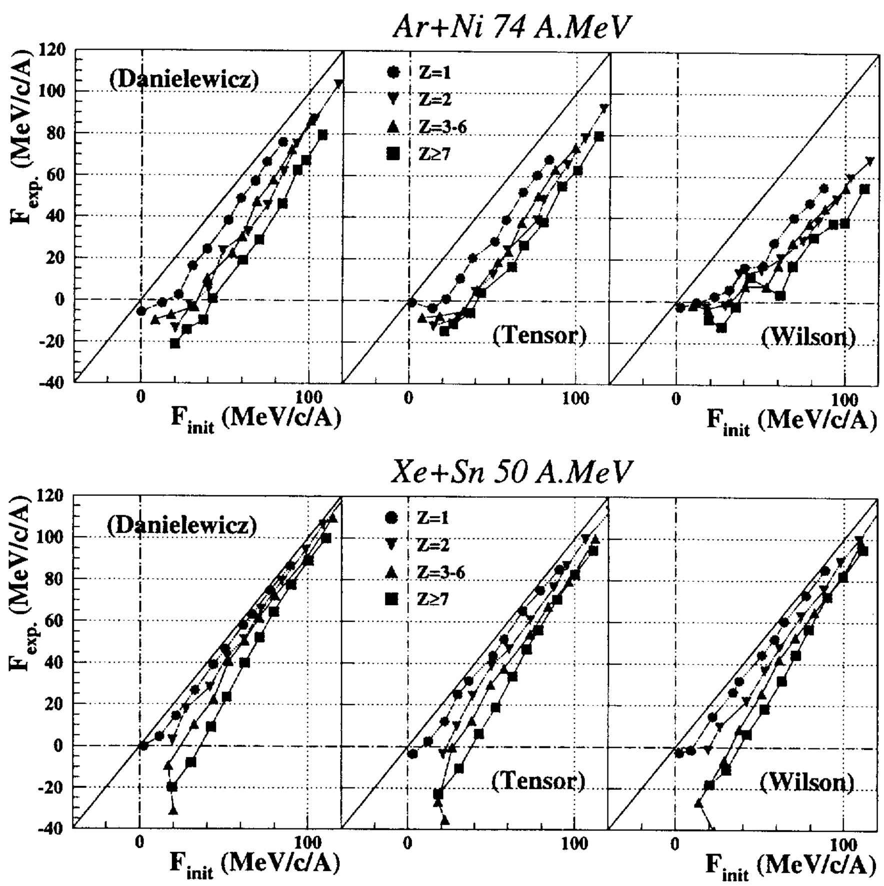

Figure 5: *Measured flow parameter values versus initial flow parameter values for the Ar + Ni system at 74 A.MeV (upper row) and for the Xe + Sn system at 50 A.MeV (lower row). These plots have been obtained with the SIMON code. The detector efficiency is taken into account. One plane per particle is determined. The different symbols correspond to different types of particles.*

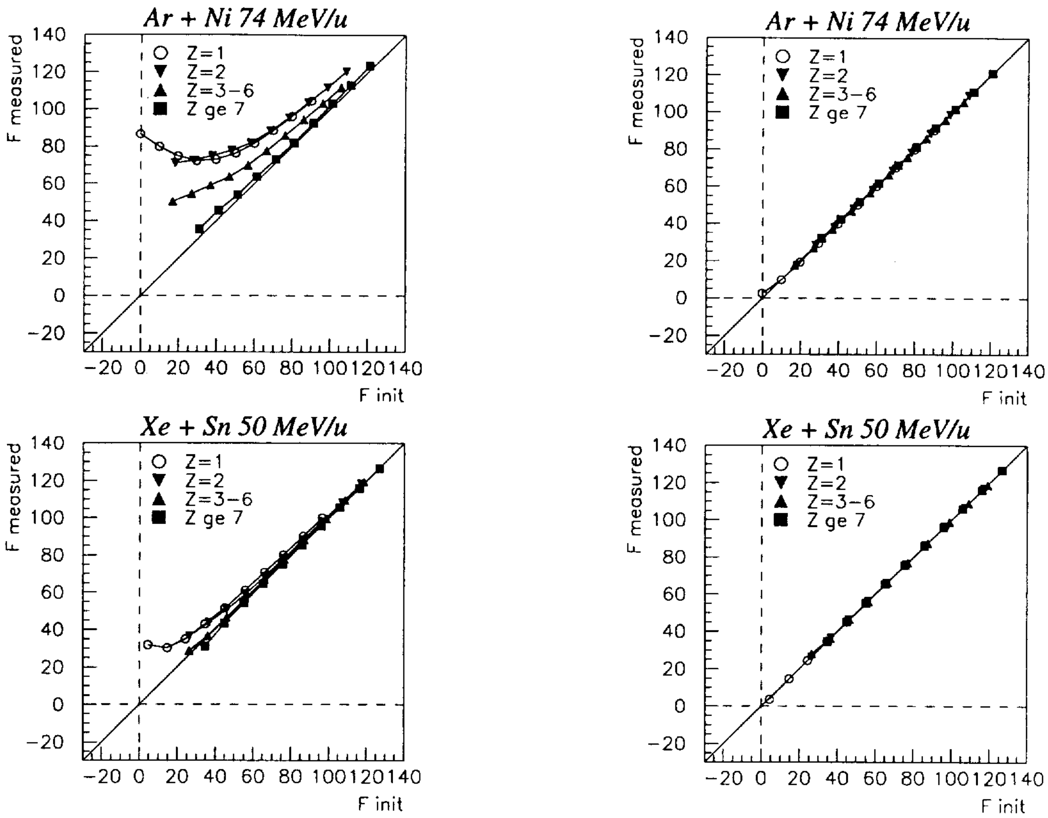

Figure 6: *Measured flow parameter values versus initial flow parameter values for Ar + Ni system at 74 A.MeV (upper row) and for the Xe + Sn system at 50 A.MeV (lower row). These plots have been obtained in case of a real binary scenario. One plane per event is determined using the tranverse momentum method. In the left column, the usual weights are used. In the right column, weights are set according to the origin of the particles (see text). The different symbols correspond to different types of particles.*

3.6 Origin of the auto-correlations

The following conclusions can be drawn from the previous study:

- The bad determination of the reaction plane is mainly due to the estimation procedure and the effect of the detector efficiency is not prominent.
- Removing the particle of interest from the reaction plane introduces an anti-correlation which is not balanced by adding a corrective momentum $\overrightarrow{P_j^{cor}}$ to the momentum of other particles.

- The amplitudes of anti or autocorrelation effects are higher for small F_{init} values and for small system sizes.
- Both effects depend on the nature of emitted products. Autocorrelation effects are higher for lighter particles. Unlikely, anticorrelation effects are higher for heavier products.

This shows us that the methods developed at high energies, for which amplitudes of sideward flow are above 100 MeV/c, are not well suited for intermediate energies where the flow parameter values are typically around or below 30 MeV/c/A [2]. Furthermore, the amplitude of the anti or auto correlation depends on the nature of the particle. That makes the study of flow with respect to the nature of the particle quite difficult to achieve.

Let us try nevertheless to identify, if possible, the origin of the so-called "auto-correlations" at intermediate energies. First of all, one has to make the following remark: if a method was able to perfectly reconstruct the reaction plane from the momentum of all particles, no "auto-correlation" effect would be seen. The usual explanation of the "auto-correlation effect" does not seem to be the right one. If so, where does this "auto-correlation" effect come from ?

In the transverse momentum method, one assumes that the particles emitted above Y_{cm} are all coming from the decay of the quasi-projectile, and those emitted below Y_{cm} are all coming from the decay of the quasi-target. But at intermediate energies, the contributions from the quasi-target, the quasi-projectile and from the mid-rapidity area are mixed, especially for the most violent collisions [20] (which correspond to our experimental results). This could lead to the effect previously seen: as a wrong weight is attributed to the particles, the estimated reaction plane has nothing to do with the real one, and is oriented along the particles which have the highest momenta. In this respect, the orientation of the plane is auto-correlated to the particles with the highest momenta. If the right weight was attributed to the right particles, this effect should vanish.

This can be checked with the help of a simulation assuming a real binary scenario: the quasi-projectile and the quasi-target are formed without any prompt emission and deflected in the real reaction plane. The results are shown on figure 6 where the measured value of the flow parameter F_{exp} is plotted as a function of the initial one F_{init} . In this simulation, one plane per event is determined, using the transverse momentum method. When the origin of the particles is kept unknown (figure 6, left column), the weight is attributed the usual way (depending on the reduced rapidity of the particle, see equation 4). When the origin of the particles is taken into account (figure 6, right column), the weight of the particles is attributed according to their origin: +1 for the particles emitted by the quasi-projectile, -1 for those emitted by the quasi-target. It is clearly seen that the effect of "auto-correlation" is cancelled when the origin of the particles is taken into account even for the smaller flow values, whereas this "auto-correlation" effect is seen when the rapidity dependent weights are used.

The so called "auto-correlation" effect seems to come from a loss of information (the origin of the detected particles), instead of the use of the transverse momenta in both the reaction plane determination and in the projection.

4 Conclusions

The studies detailed in this contribution lead to the following conclusions: i) the standard methods for the reaction plane determinations are not well suited for low flow values, and then for incident energies around the balance energy; ii) the higher is the system mass and the particle charge (only for one plane per event), the better is the measurement of the flow parameter; iii) by removing the particle of interest from the reaction plane determination, an anti-correlation is introduced, whose effect is higher for heavier particles; iv) the so-called "auto-correlation" effect seems to come from the loss of the knowledge of the emitter of the particles.

This indicates that the negative flow values observed in experimental data can be attributed to method effects, especially for the heaviest fragments. For the light charged particles, the physical effect can not be completely removed, since positive values of flow are observed for alphas, whereas negative values are expected if the reaction plane determination methods effects are dominant. For such particles, the two effects are probably mixed and more detailed studies have to be performed to establish their relative weights in the observed values.

Indeed, the "auto-correlation" effect seems to be badly labelled. To correct it, a complete knowledge of the origin of particles is needed. This can be achieved only for the less violent collisions and/or at higher energies where the sideward flow values are much higher. For the most violent collisions, such a knowledge is unreachable unless assumptions are made. But in this case, the flow values obtained could only result from these assumptions. Since the correction of experimental data seems to be impossible, it could be easier to apply on theoretical calculations the experimental filter and the analysis procedures. Most of the available dynamical calculations have to evolve to enable this process, since most of them are following the time evolution of the one body density, and not the evolution of the particles.

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