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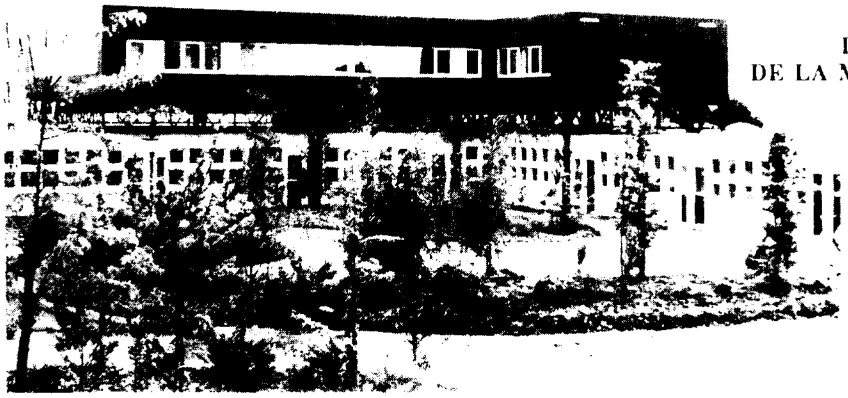

STUDY OF INPLANE FLOW AND AZIMUTHAL DISTRIBUTION WITH 4π DETECTORS.

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Abstract: The measurement of in-plane flow can provide informations on the in-medium nucleon-nucleon interaction. Data from GANIL experiments are shown and compared to theoretical calculations. Other collective effects such as rotation like behaviour and/or out of plane emission can be used to constrain the theoretical models.

1.Why measuring in-plane flow?

The collective in-plane flow is mainly due to the interaction of particles emitted at the beginning of the collision (participant zone). At low energy (below 50 MeV/u for light systems), this interaction is attractive and the participant nucleons are deflected in the opposite side of the projectile, the flow is negative. At higher energies (typically above 100 MeV/u), the interaction is repulsive and the participant nucleons are deflected to the same side of the projectile, the flow is positive. In between this two extremes, there is an energy for which the actractive and repulsive part balance each other. There is no more deflection: the flow is null. This balance energy, noted E_{bal}, is related to the characteristics of the in-medium nucleon-nucleon interaction.

This can be seen on figure 1 which shows the evolution of the flow parameter, which will be defined in the next part, as a function of the incident energy in the frame of the BUU model [1], for a collision between a A=40 projectile and a A=40 target. This evolution is controlled by σ_{nn}, the effective nucleon-nucleon cross section in nuclear matter, and K_∞, the incompressibility modulus of nuclear matter, which is related to the stiffness of the nuclear equation of state (EOS).

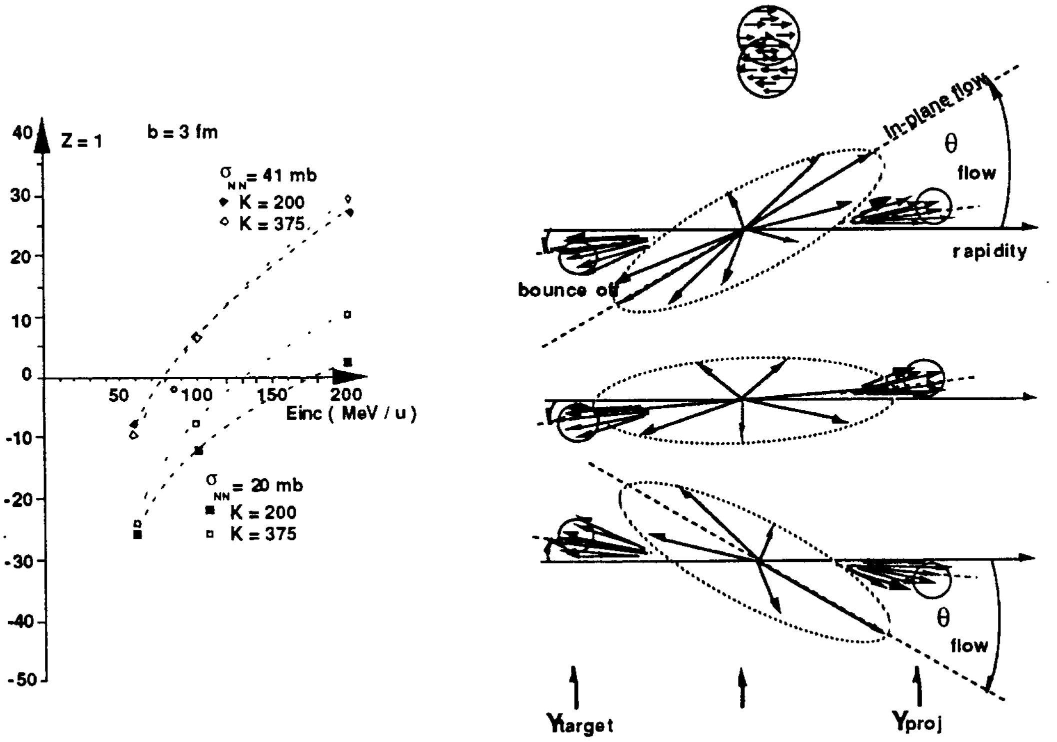

Figure 1: Theoretical prediction of the evolution of the flow parameter for a Ca+Ca collision for Z=1 particles at b=3 fm (reference 1). Schematic views of the collision are shown in case of negative flow ($E_{inc}<E_{bal}$, lower), in case of positive flow ($E_{inc}>E_{bal}$, upper) and in case of no flow ($E_{inc}=E_{bal}$, middle)

Hence, measuring experimentally the evolution of the flow parameter as a function of the incident energy for a given impact parameter gives access to a determination of these two key parameters.

As it will be shown further, those measurements require the most complete detection of each event. This will allow a good sorting with respect to the impact parameter and a analyzed. Experimental set-up limitations and disturbances induced by the analysis could be correctly taken into account (see for exemple the study presented in reference 17).

To achieve this task, theories have to produce "physical" events, i.e. events containing particles with well defined velocities or energies in a well defined direction. Unfortunately, some models, such as BUU or LVUU, only follow the time evolution of the one body distribution which is rather difficult to associate to a physical event.

Another difficulty is due to the use of local or non-local forces in those models. As seen in figure 9, the use of a local force can lead to a wrong conclusion. In the two examples shown [9,18], a soft Gogny force, which includes the momentum dependance of the nucleon-nucleon interaction, gives similar results as a hard local force. Since it is known that nucleon-nucleon interaction is momentum dependant, theoretical calculations have to be performed with non-local forces in order to make valuable comparison with experiments.

7.Conclusions

It has been shown that the measurement of in-plane flow can provide informations on the in-medium nucleon-nucleon interaction. In the present status, comparisons between experimental data and theoretical calculations indicate that the value σ_{nn} is located in between 20 and 40 mb and the value of K_∞ is around 250 MeV if Gogny forces are used. More theoretical and to a less extend experimental work has to be done to improve the confidence of the comparison between theory and experiment, and hence to increase the accuracy of the determination of σ_{nn} and K_∞.

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6.General remarks.

Since the determinations of σ_{nn} and K_∞ are theory dependant, a dramatic attention has to be put on the comparisons between experiments and theoretical calculations.

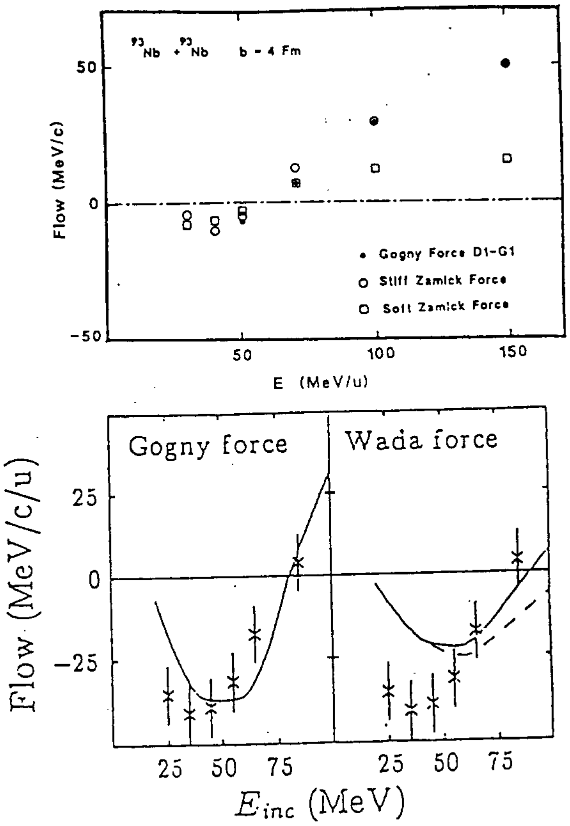

Figure 9: Comparison of the effect of the use of non-local and local forces in theoretical calculation. Soft non-local forces have the same effect as hard local forces in case of LVUU calculations [9] (upper) and QMD calculations [18] (lower).

For the experimental point of view, the detectors are not perfect in the sense they are not able to detect all kinds of particles with the same efficiency and miss those go through the dead areas. The energy and/or the velocity of each particle is also not perfectly measured. Additional disturbances can be induced by the method of analysis used. The way the events are sorted into several samples will obviously have a big influence on the final result, since nobody has a direct acces to the impact parameter value of each event. It is the same for the reconstruction of the reaction plane, since transverse momentum of each particle has to be projected on it and no direct access to this plane is possible. It could be possible in principle to unfold all those experimental effects in order to get the "real" values of flow parameter. Unfortunately, due to the complexity of the detectors and of the analysis, it is almost impossible to achieve such a task. Some estimations of the errors due to the reconstruction of the reaction plane were nevertheless done [16], but the effect of the sorting had never been taken into account.

Hence, it seems easier to "filter" theoretical calculations through experimental set-up and analyse those filtered events in the same way as the experimental events are

$f(\varphi)= a_0 + a_1 \cos(\varphi) + a_2 \cos(2\varphi)$

The ratio a_1/a_0 is related to the in-plane flow. The ratio a_2/a_0 is related to the squeeze-out effect if negative and to rotation-like behaviour if positive. The evolution of a_2/a_0 with the impact parameter for the Ar+Al system is shown in figure 7. The stars are the result of a BUU calculation with a local force [11]. The best fit is obtained for K_∞ = 375 MeV and σ_{nn} = 33 mb. The ratio a_2/a_0 is always positive which shows that the rotation like behaviour is dominant at low incident energy. The decrease of this ratio with the impact parameter is expected, since rotation effect decreases with decreasing impact parameter. The predominance of rotation-like behaviour decreases with increasing incident energy, indicating the growing of out of plane emission.

For Zn+Ni data at 69 MeV/u, a_2 becomes negative for an incident energy a little bit lower than the balance energy [12] (figure 8). Here squeeze out effect becomes predominant, as already seen at hogher incident energies [10]. This out of plane enhancement could be due to compression effect coupled with nuclear shadowing [13,14]. In any case, this evolution has to be reproduced by theoretical calculations and should constrain the parameters of the used nucleon-nucleon interaction.

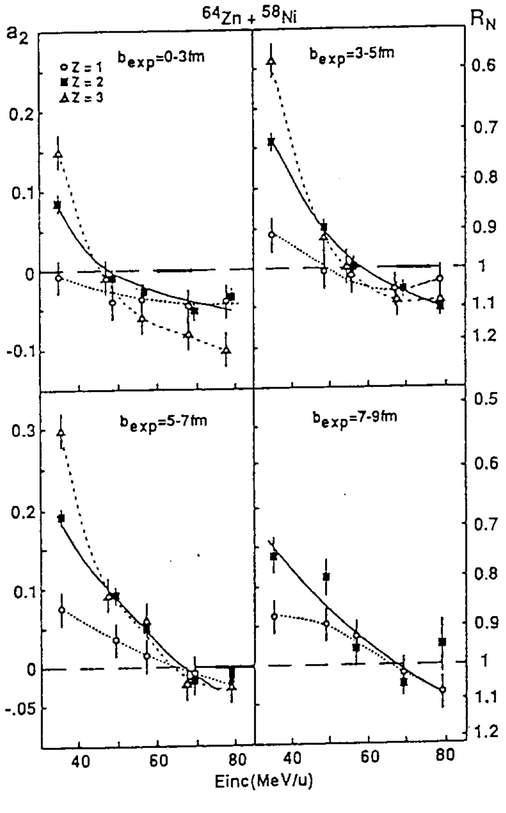

Figure 8: Evoltion of a_2 with respect to the incident energy for the Zn+Ti system at different impact parameter bins. Note the enhancement of the out of plane emission (negative values of a_2) for an energy slightly below the balance energy.

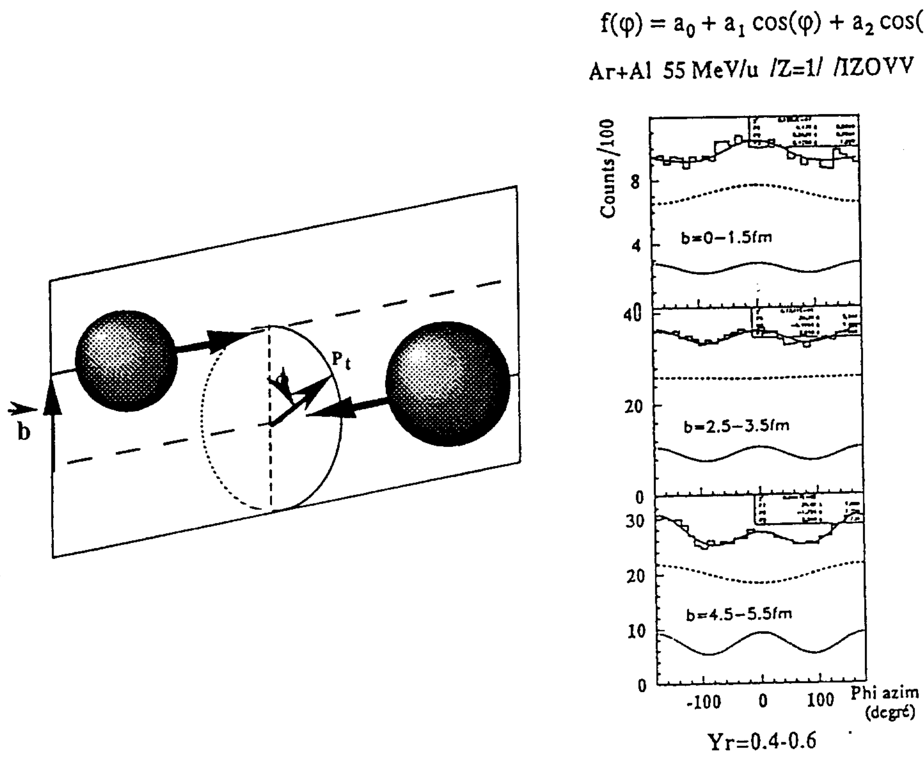

Figure 6: Example of azimuthal distributions for Z=1 mid-rapidity particles for peripheral (lower), intermediate (middle) and central (upper) collisions for the Ar+Al system at 55 MeV/u [16].

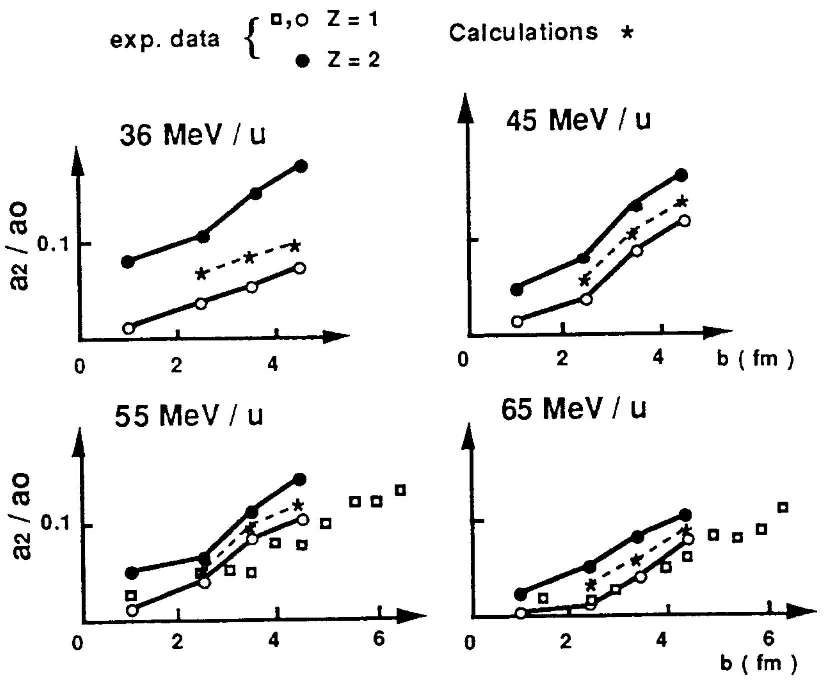

Figure 7: Comparison of the evolution of the a_2/a_0 ratio with b for the ar+al system at 36, 45, 55 and 65 MeV/u. The stars correspond to the theoretical calculation of reference 11 (BUU, local force). The best fit is obtained for $K_\infty = 375$ MeV and $\sigma_{nn} = 33$ mb.

around E_{bal} and the discrimination between the two incompressibility moduli is only possible well above E_{bal}.

Both calculations are in qualitative agreement with the experimental results.

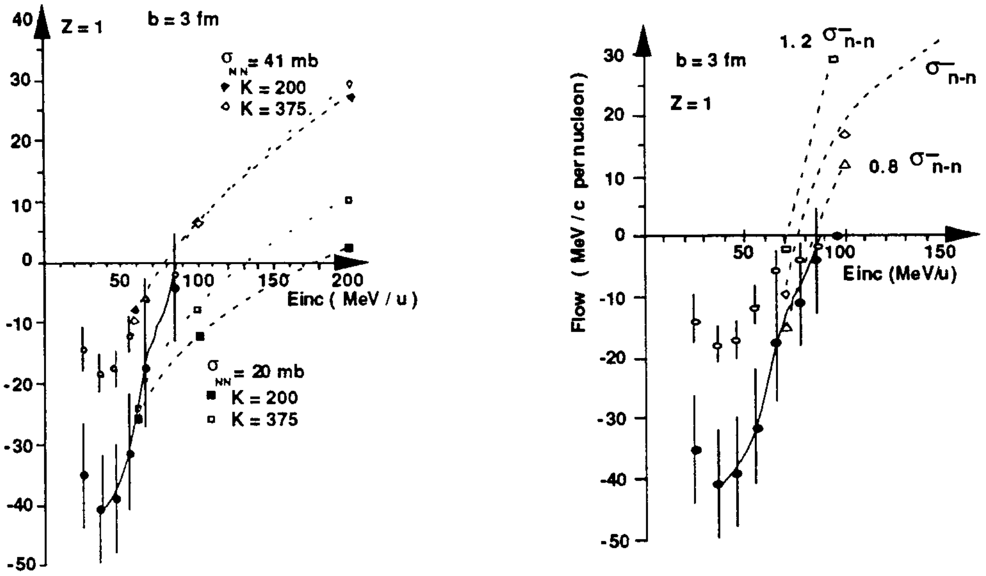

Figure 5: Comparison between experimental values of flow parameter and theoretical predictions for Ar+Al system from 25 to 85 MeV/u, for b=3 fm. Open dots correspond to uncorrected values and full dots correspond to corrected values. Only the indetermination on the reconstruction of the reaction plane is taken into account in the correction. Left hand side: calculation of reference 1 (BUU with local force). Right hand side: LVUU calculations using the Gogny force and different values for the effective nucleon-nucleon cross section [7] (σ_{n-n} is here the standard in medium cross section)

5.Azimuthal distributions

Other effects, such as squeeze-out or rotation-like behaviour, are superimposed to the in-plane flow. Such effects have already been observed in other experiments [10]. Those collective effects can also provide informations about the in-medium nucleon-nucleon interaction.

To search for these components, one has to consider the azimuthal distribution of mid-rapidity particles with respect to the reaction plane. An example of these distributions is shown on figure 6 for Z=1 at three different experimental impact parameters. The maxima observed are the result of three cumulative contributions. The squeeze-out effect would produce maxima at ϕ=+90° and ϕ=-90°. Rotation-like behaviour would produce maxima at ϕ=0° and ϕ=180°. The in-plane flow is expected to produce maxima at ϕ=±180° or at ϕ=0° depending on the rapidity bin and the impact parameter. In order to disentangle the different contributions, the azimuthal distributions are fitted with the following function:

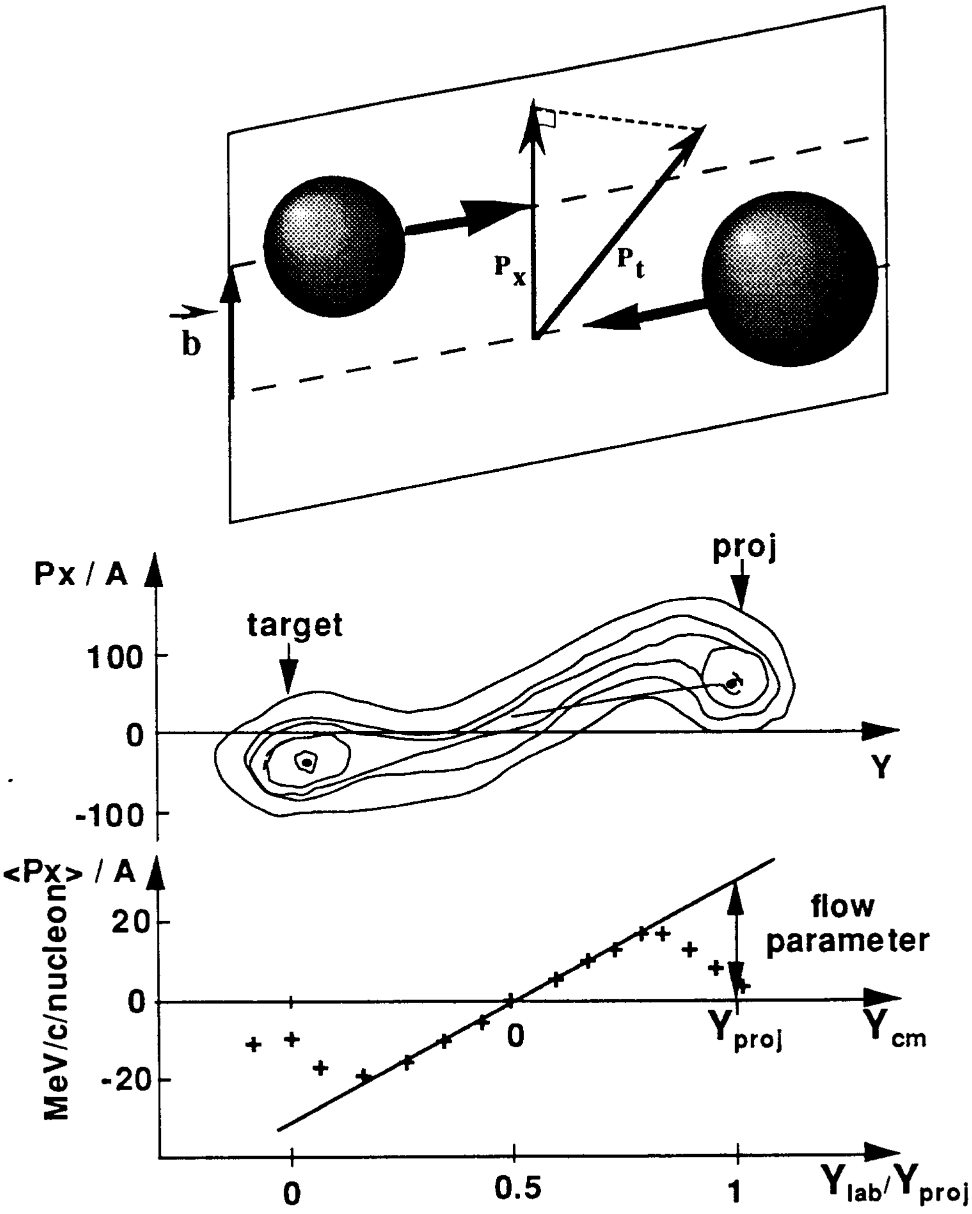

Figure 4 : Determination of the flow parameter.

INDRA is able to detect and identify particles from Z=1 up to Z=56 with an isotopic discrimination for Z≤4. It covers polar angles from 2° to 176°.

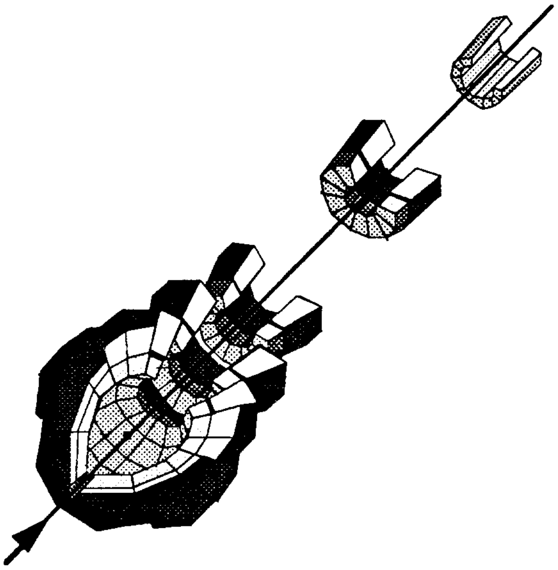

Figure 3: Schematic view of INDRA.

The energy calibrations of the second set of experiments is not yet achieved and only results from the first set will be shown [5,6].

3.How to measure in plane-flow?

The events have first to be sorted with respect to their impact parameter. The method described in the reference [7] is used. The best results are obtained with the global variable V_{av} for the NAUTILUS multi-detectors.

The in-plane flow can be characterized by the flow parameter which is determined the following way. The reaction plane is first reconstructed by the method first proposed by Danielewicz and Odyniec [8]. The transverse momentum of each particle is then projected on that plane. The distribution of the average value of those projections as a function of the particle rapidity is then plotted (see figure 4). The flow parameter is then defined as the slope of this distribution around the nucleon-nucleon rapidity Y_{nn}.

4.Results from NAUTILUS experiments.

Figure 5 shows the evolution of the flow parameter with the incident energy for the Ar+Al system at $b_{exp}\approx 3$ fm and a comparison with LVUU calculations [9] (right) and BUU calculations [1] (left). The balance energy is around 95 MeV/u. In the LVUU frame, this value is consistant with a value of σ_{nn} around 80% of the standard in-medium nucleon-nucleon cross-section, which value is 20 mb. In the BUU frame, the value of E_{bal} is consistant with σ_{nn} close to the free nucleon-nucleon cross section (40 mb). It seems extremely difficult to extract K_{∞} from those data, since the maximum incident energy is proper recontruction of the reaction plane in an event by event analysis. This can only be achieved by using 4π multi-detectors.

2.The GANIL experiments

To make those in-plane flow measurements, we took advantage of the existence at GANIL of two multidetectors.

A first set of experiments was performed with the NAUTILUS multidetectors (figure 2): The MUR [2], which is a plastic wall covering the forward polar angles between 3° and 30° with 96 plastic scintillators arranged in 7 concentric rings, and the TONNEAU [3], a plastic barrel covering the polar angles from 30° to 150° with 72 half-stalves. The following systems were studied:

- ^{40}Ar + Al from 25 to 85 MeV/u
- ^{40}Ar + Ni from 35 to 65 MeV/u
- ^{36}Ar + Al and ^{36}Ar + Ti from 55 to 95 MeV/u
- ^{64}Zn + Ni from 35 to 79 MeV/u

Those two multi-detectors are able to detect and identify particles and light nuclei up to Z=8 and measure with a good accuracy their velocity vector.

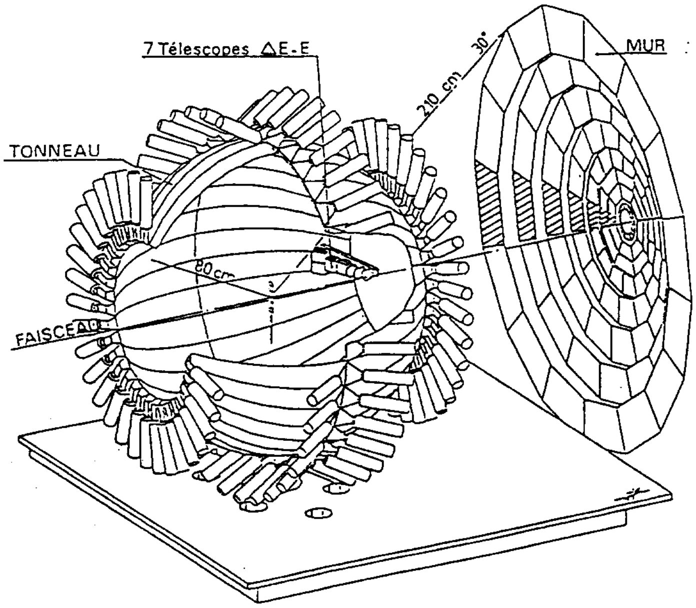

Figure 2: The NAUTILUS experimental set-up with MUR and TONNEAU.

A second set of experiments was performed with INDRA [4] (figure 3, and C.O.Bacri contribution to this symposium):

- ^{36}Ar + Ni from 32 to 95 MeV/u
- Ni + Ni from 32 to 95 MeV/u (this experiment is coupled with an experiment performed at SIS with FOPI multi-detector)