# Components of Collective Flow in Nucleus-Nucleus Collisions at Intermediate Energies

J. Péter[1], J.C. Angélique[1], A. Péghaire[2], G. Auger[2], G. Bizard', R. Brou·
A. Buta[1-a], C. Cabot[2], Y. Cassagnou[3], E. Crema[1-b], D. Cussol[1], Y. El Masri[4]
Ph. Eudes[5], M. Gonin[6], K. Hagel[6], Z.Y. He[8], A, Kerambrun[1], C. Lebrun[5]
R. Legrain[3], J.P. Patry[1], R. Popescu[1-a], R. Regimbart·, E. Rosato[7]
F. Saint-Laurent[2], J.C. Steckmeyer[1], B. Tamain[1], E. Vient[1], R. Wada[6]

*1)* LPC Caen, ISMRA, *IN2P3-CNRS,* 14050 Caen Cedex, France
2) GANIL, BP 5027, 14021 CAEN Cedex, France
3) DAPNIA, CEN Saclay, 91191 Gif-Sur-Yvette, France
4) Institut de Physique Nucléaire, UCL, *1348* Louvain-la-Neuve, *Belgium*
*5)* Laboratoire de Physique Nucléaire, 44072 Nantes Cedex 03, France
6) Cyclotron Institute, Texas *A & M University,* College Station, Texas *77843,* USA
7) Dipartimento di Scienze Fisiche, *Univ.* di *Napoli,* 80125 *Napoli,* Italy
8) Institute of Modern Physics, Lanzhou 730000, China
a) Permanent address: I.F.A., Heavy Ion *Department,* Bucharest, Romania
*b)* Permanent address: Instituto de Física, Universidade de São Paulo, *01498-90,* São Paulo, SP, Brazil

Received November 10, 1993

Flow parameter values and azimuthal distributions relative to the reaction plane have been obtained as a function of the impact parameter for the systems $^{36}Ar + ^{27}Al$ from 55 to 95 MeV/u, $^{64}Zn + ^{27}Al$ and $^{64}Zn + ^{58}Ni$ from 35 to 79 MeV/u. The azimuthal distributions show an in-plane enhancement ("rotation-like" effect) for the lighter system. For the heavier system, it evolves from in plane enhancement at low energies to out-of-plane enhancement (squeeze-out effect) at high energies. The balance energy for central collisions agrees with the (Asystem)-1/3 behaviour of LVUU calculations. Comparisons with several model calculations are shown. The possibility to obtain informations on the nucleon-nucleon cross section in medium and the equation of state (incompressibility modulus) is discussed.

## I. Motivation

The dynamics of nucleus-nucleus collisions at intermediate energies can be viewed as a succession of stages - more or less separated - from the overlap of nuclear matter in the interaction zone to the formation and deexcitation of hot nuclei.

During the first stage, nucleons and clusters are emitted and their study provides information on nuclear matter in the interaction zone of the two nuclei (participant nucleons). The directed collective motion of these nucleons and clusters in the reaction plane (transverse flow) is a signature of the interaction[1]. It had been first expressed via the average direction of these nucleons, the flow angle which is, for symmetry reasons, located in the reaction plane: Fig. 1 top. Even on this idealistic figure, it is difficult to distinguish between nucleons emitted from the interaction region and nucleons emitted later from the "spectator" nuclei. In addition, the flow angle values are very sensitive to detector limitations. Therefore, a specific analysis method[1] has been developed which uses the component of the transverse momentum $P_t$ in the reaction plane[2]: P,. This analysis gives the in-plane flow parameter value (loosely called flow) which is the increase of $< P_x >$ per nucleon in the interval between mid-rapidity and projectile rapidity: Fig. 1 bottom. Note the different scales for $P_x/A$ and $< P_x/A >$: flow is a relativity weak shift of a broad distribution, therefore an accurate detector calibration is required.

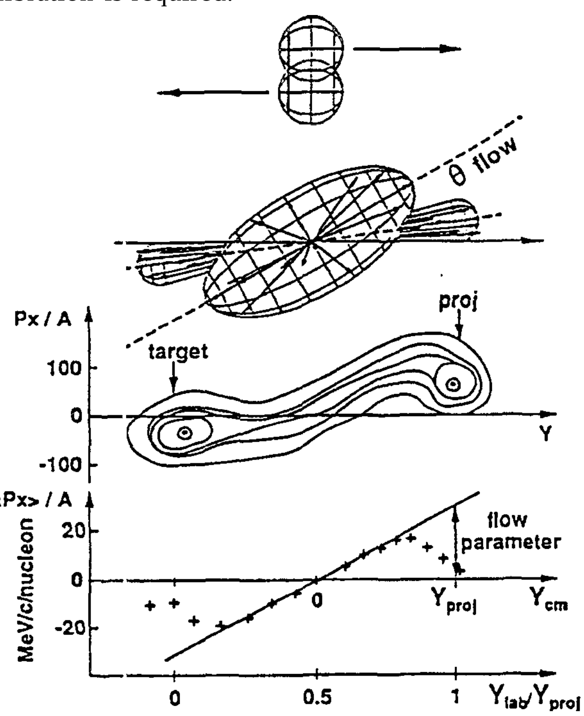


Figure 1: Top: mid-rapidity and "spectator" particles and residues emitted in one event, in the c.m. frame. Middle: distribution of Z = 1 particles emitted in many events versus their rapidity Y and the projection $P_x/A$ of their transverse momentum per nucleon $P_t/A$ on the reaction plane. Bottom : $< P_x/A >$ versus $Y$. The slope at mid-rapidity is used to obtain the flow parameter value: increase of $< P_x/A >$ in the interval between mid-rapidity and projectile rapidity.

For easier comparisons between different systems and incident energies, the plots in this paper use the rapidity relative to the projectile rapidity in the lab. frame (i.e. target rapidity = 0). Therefore, mid-rapidity means around 0.5 (0 in c.m. frame) At high energies, the interaction is dominated by two-body collisions, the flow is attributed to a repulsive momentum transfer in the compressed interaction region. Conversely, at a few tens of MeV/u, the interaction is dominated by the attractive mean field. There, fragments have been shown to be deflected to negative angles. Of course, at some intermediate energy, the flow is zero. This energy is called inversion energy or, since two body effects counterbalance mean field effects, balance energy ($E_{\rm bal}$)[13].

Azimuthal distributions relative to the reaction plane have also been studied, since measurements for light systems (Ar + Al[23] and Ar + V[15]) at low incident energies have shown an in-plane enhancement, quite different from the out-of-plane enhancement due to squeeze-out effects observed at high energies[12].

The continuous evolution from negative to positive flow values as a function of incident energy has been studied with the Boltzmann equation[3,20,27,28], the microscopic Landau Vlasov model[4,17,30] and QMD calculations[19]. The flow and azimuthal anisotropy values are sensitive both to the nucleon-nucleon cross section sNN in nuclear medium and to the equation of state through the incompressibility modulus $K$ of infinite nuclear matter. The first calculations indicated that it was sufficient to measure $E_{\rm bal}$ for several impact parameter values and several systems[3]. Experimentally, $E_{\rm bal}$ can be extracted rather easily. Unfortunately, recent calculations have shown that $E_{\rm bal}$ values alone are not sufficient. Instead, calculated and measured flow values must be compared over a broad range of incident energies[4–8].

BUU calculations have recently been made on the azimuthal distributions[27].

Following measurements of the system $^{40}$Ar+ $^{27}$Al from 36 to 85 MeV/u with the multidetector array Mur + Tonneau[10], we have performed a complete experimental study of 3 systems up to the maximum bombarding energy delivered by the GANIL accelerator : $^{36}$Ar + $^{27}$Al from 55 to 95 MeV/u, $^{64}$Zn + $^{27}$Al and $^{64}$Zn + $^{58}$Ni from 35 to 79 MeV/u.

LVUU calculations for these systems are under way.

## II. Experiments and sorting of events

Seven Si telescopes were set up to cover the angular range from 3 to 30°, in order to correctly identify the charge of the heaviest fragment (projectile-like fragment or evaporation residue). Other fragments were detected in the Mur + Tonneau (charge identification up to $Z = 9$): Fig. 2. Particle and fragment velocities were derived from time-of-flight, thus providing reliable values of the momenta per nucleon which are used to determine the flow.

Since all $4\pi$ arrays have some dead areas and detection thresholds, the first step in the event-by-event analysis is to retain only the well characterized events, i.e. to reject these events for which insufficient information has been recorded. This is easily checked by looking at the total measured longitudinal linear momentum[7]. Very peripheral reactions are lost, since the projectile-like fragments escape the detector through the beam hole (0-3.2°). For other impact parameters values, around 80% of the initial momentum is measured and we keep all events above 60%.

Since the flow parameter is a function of the impact parameter b, the events have to be sorted in terms of b. Several global variables related to the violence of the collisions have been tried. The best ones are "the total transverse momentum" and "the average (mass weighted) parallel velocity"[7]. Both have been used, since they are almost independent from each other. They lead to nearly identical results. The correlation between $b_{exp}$ and the real $b$ value has a FWHM around 1.5. fm.

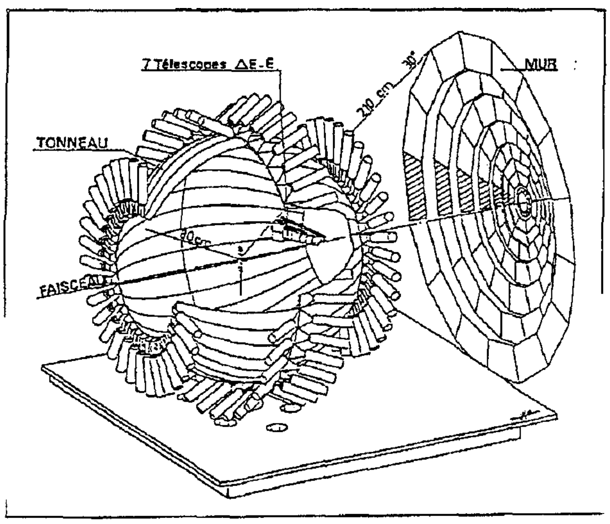


Figure 2: Experimental set-up.

An example of the distribution of $Z = 2$ and $Z \geq 6$ final fragments is shown in Fig. 3 for two impact parameter bins: peripheral and very central collisions. There are three sources of fragments: a very slow target-like source (hardly located, since most fragments are below the detection threshold), a fast projectile-like source, a mid-rapidity source for $Z = 2$.

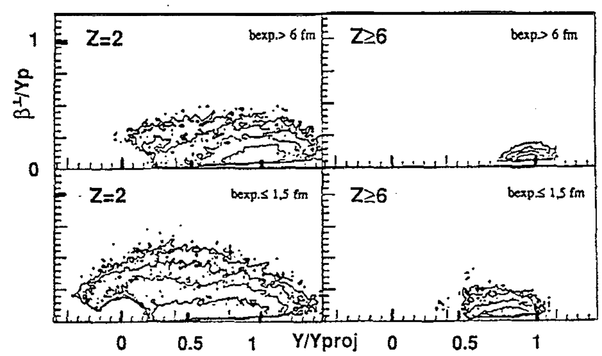


Figure 3: Invariant cross section contour plots at 45 MeV/u for semi-peripheral (top) and central collisions (bottom), Z = 2 and Z = 6 particles detected at polar laboratory angles between 3.2" and 150°. The axis are rapidities relative to the projectile rapidity.

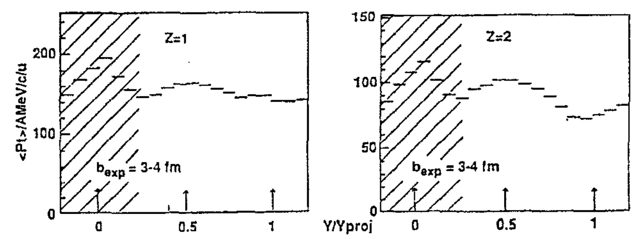


Figure 4: Average transverse momentum per nucleon of Z = 2 fragments versus their rapidity relative to the beam rapidity. The bump around $Y/Y_p = 0$ is due to the detection threshold (see Fig. 3). The mid-rapidity bump is the same at other impact parameter values $^{36}Ar$ on $^{27}Al$ at 95 MeV/u.

This mid-rapidity source shows up clearly in Fig. 4: mid-rapidity particles ("participants" emitted early in the nucleus-nucleus encounter) have a larger transverse momentum than particles emitted by the excited quasi-projectile ("spectator").

The reaction plane is estimated using the method of Danielewicz and Odyniec[1]. It deviates from the real reaction plane by an angle which can be large when the flow parameter has a small value, thereby leading to an underestimation of the flow[9]. For the most part, this deviation is not caused by experimental limitations (at least when a good quality $4\pi$ array is used). It is mostly due to finite number effects and to the randomly oriented thermal motion superimposed on the oriented collective motion. One can either calculate the correction factor for each case[16] or, preferably, introduce the method of Danielewicz-Odyniec and the detector limitations in the theoretical calculations[17].

### III. In-plane Wow parameter values

The flow parameter is derived in the usual manner, shown in Fig. 1. Since the initial direction of the impact parameter vector cannot be known, one measures the absolute value of flow (i.e. the slope at mid-rapidity is always positive). Some examples are shown in Fig. 5.

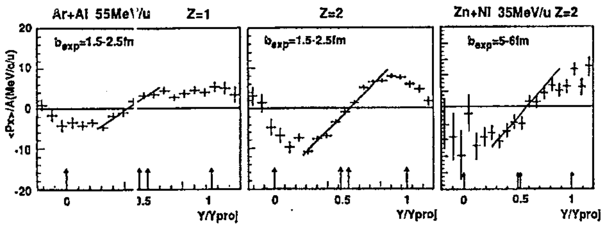


Figure 5: Messured mean transverse momentum per nucleon projected onto the estimated reaction plane ($< p'_x > /A$) versus the laboratory particle rapidity relative to the projectile rapidity.

Around 0.5 one clearly sees the linear increase of $< P'_x > /A$ vrrsus the rapidity which characterizes directed collective motion. At large and small rapidities, particles emitted by the "spectator" nuclei constitute the main contribution.

The complete set of flow parameter values obtained for $Z = 2$ versus bexp at 5 incident energies is displayed in Fig. 6. For this system $^{36}$Ar on $^{27}$Al, $b_{\text{grazing}}$ is around 8 fm Flow values decrease rapidly at small bexp values, since they must be zero at $b = 0$.

The flow variation with incident energy is displayed in Fig. 7 for 3 impact parameter bins of $^{64}$Zn + $^{58}$Ni reactions ($b_{\text{grazing}} = 10$ fm). The top left figure shows the measured absolute values for $Z = 1$: a decrease down to zero followed by an increase. In the other figures, the low energy values are plotted as negative. Sometimes there is an uncertainty as to whether a point is negative or positive. The balance energy increases from $65 \pm 3$ MeV in central collisions up to more than 75 MeV/u in semi-peripheral ones. This shift of the balance energy with the impact parameter value is in agreement with theoretical expectations. It has been seen already for $^{40}$Ar on $^{27}$Al[1] and we got similar data for $^{36}$Ar on $^{27}$Al from 55 to 95 MeV/u and $^{64}$Zn on $^{27}$Al from 35 to 79 MeV/u.

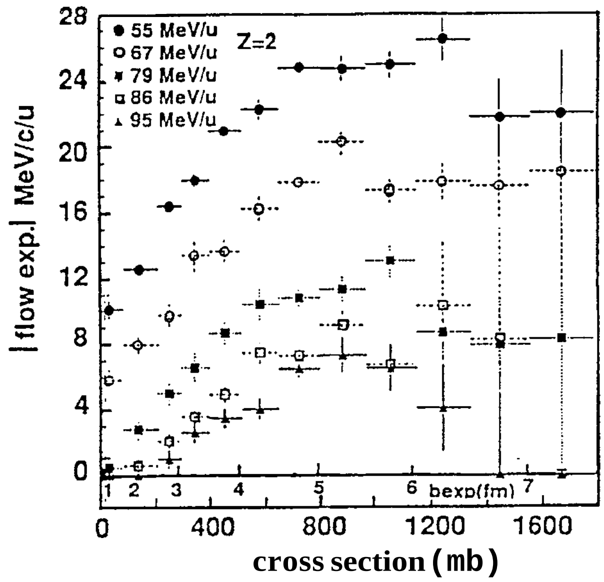


Figure 6: Flow (absolute value) as a function of the experimentally determined impact parameter value, for $Z = 2$ fragments (mostly alpha particles) emitted in $^{36}$Ar on $^{27}$Al collisions from 55 to 95 MeV/u. These values are not corrected for the difference between the true and measured reaction planes and are thus smaller than the real values.

On this figure, an intriguing point is the possible dependence of the balance energy on the emitted mass. It one assumes that $E_{\text{bal}}$ is independent of the fragment mass, one can find a common value for $Z = 1$ and $Z = 2$ fragments in Fig. 3. However, if they are analyzed independently, $Z = 2$ balance energies are above $Z = 1$ values, within experimental uncertainties. If confirmed, this fact would mean that heavier products are emitted from different locations in the participant zone and/or at different interaction times. Therefore, careful experimental and theoretical studies should be made to address this point.

### IV. Out-of-plane flow and azimuthal distributions

As seen in Fig. 1, the azimuthal distribution of the particles around the beam axis is symmetric with respect to the reaction plane, it is not isotropic. Let us look at azimuthal distributions for different rapidity bins. If only the in-plane transverse flow were present, the azimuthal distribution should be peaked at 0° near the projectile rapidity, peaked at 180° near the target rapidity, and isotropic near mid-rapidity. Other effects

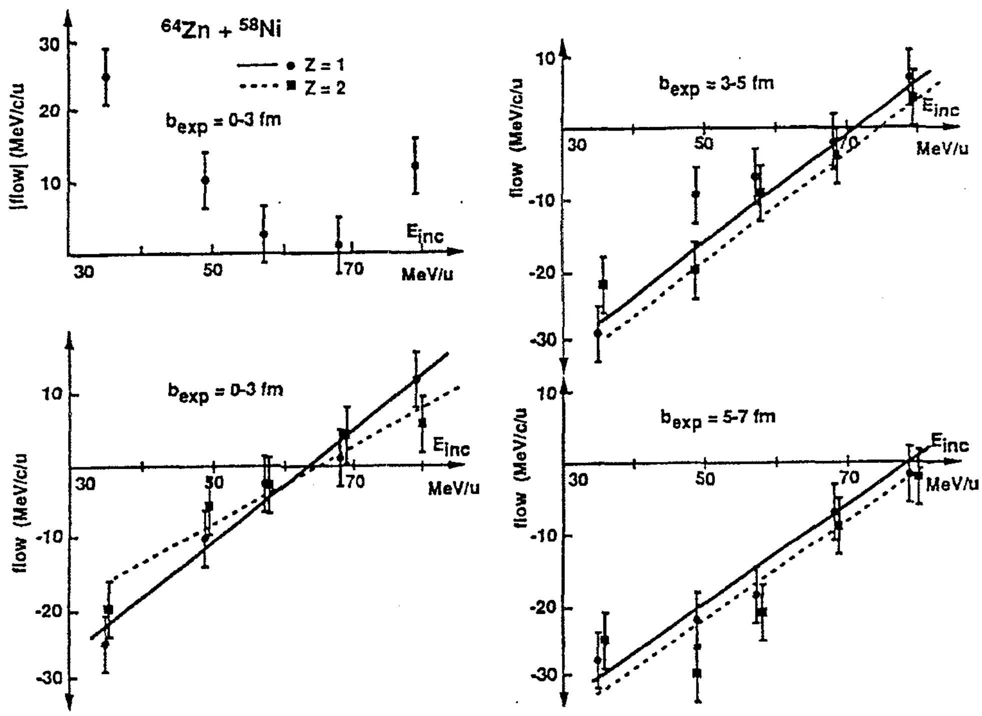


Figure 7: Excitation function of the uncorrected flow parameter for 3 impact parameter bins, in $^{64}$Zn on $^{58}$Ni collisions (see text).

can be superimposed on the transverse flow and modify the shape of the azimuthal distribution.

Fig. 8 shows the azimuthal distribution of mid-rapidity protons from 55 MeV/u $^{40}Ar + ^{27}Al$ reactions. These distributions were fitted to a Legendre polynomial expansion up to the second order, as in ref. 21:

$$dN/d\phi = a_0 + a_1 \cos\phi + a_2 \cos(2\phi)$$

The solid line is the fit to the experimental data, the dashed line is the $a_1 \cos\phi$ contribution (shifted up by $\sim 0.75a_0$), which simply reflects the in-plane flow contribution. The dotted line is the $a_2 \cos(2\phi)$ contribution (shifted up by $\sim 0.25a_0$). No enhancement is observed around $\pm 90°$, which means that the squeeze-out effect which was seen at higher energies ($>$ 200 MeV/u)[24] or for much heavier systems at the same energy per nucleon (Kr + Au at 43 MeV/u)[25] is not seen for this light system in our energy range. This squeeze-out effect is attributed to the shadow of target or projectile-matter[24]. Oppositely, the emission at 0° and 180° is enhanced here ($a_2$ is positive). This enhancement is also present in the azimuthal variation of $< P_t >$: Fig. 9. Not only more particles are emitted close to the reaction plane, but their velocity is larger.

How does this in-plane enhancement vary as a function of impact parameter, incident energy and system mass ? As seen in Figs. 8 and 9, the enhancement (expressed by the anisotropy ratio $a_2/a_0$) increases with the impact parameter. This could be caused by a rotation of the participant zone (angular momentum perpendicular to the reaction plane, hence the name of "rotation-like behaviour"[15]). The decrease of $a_2/a_0$ with incident energy, however, does not fit with this explanation, since $a_2/a_0$ decreases when the energy increases: Fig. 10. At the highest energies reached, the anisotropy is close to zero for $^{36}Ar + ^{27}Al$ and slightly negative for $^{64}Zn + ^{58}Ni$.

When mean field effects are dominant, the time spent by a nucleon in the interaction zone allows it to be preferentially deflected in the direction of rotation of the system, i.e. towards the reaction plane. At larger incident energies, this time decreases. When the two systems are compared at the same impact parameter relative to the maximum impact parameter value and for the same energy shift below the balance energy, $a_2/a_0$ is slightly lower for the heavier system. Shadow effect due to the "spectator" nuclei begins to play a role for these medium-mass nuclei. At the energies studied here, the mean free path of nucleons in nuclear matter decreases and shadow effect becomes more effective when the energy increases. In the competition between rotation due to mean field (leading to in-plane enhancement) and shadow effect (leading to out-of-plane enhancement), when the energy and mass of the system increase, shadowing effect becomes dominant : a slight out-of-plane enhancement is observed for Zn + Ni above 69 MeV/u.

## V. Theoretical studies of flow

The direction of the collective matter flow is depending on two main parameters. The first one is the incompressibility modulus of nuclear matter $K_\infty$ which is the rate of variation of the pressure versus the density in the infinit: nuclear matter phase diagram. Clearly the deflection angle must depend on $K_\infty$. The other parameter is th: nucleon-nucleon cross section in nuclear medium $\sigma_{NN}$, since it will govern the role of repulsive nucleon-nucleon collisions relative to the role played by the mean field. As said above, one-body and two-body effects balance each other at the balance energy. In the first calculations based on the Boltzmann equation[3], the flow values - and therefore the inversion energies - were found tc be strongly dependent both on $\sigma_{NN}$ and *Ii.* Recent calculations include Coulomb effects and non local fortes and do not give such a strong dependente.

The Eantlau-Vlasov method with the Uehling-Uhlenbeck collision term (LVUU) has been used in ref. 4, 17, 30. It uses mostly the Gogny force, which is non local, anc also a local Skyrme force (Zamick force) which allows one to easily shift from a stiff to a soft EOS (i.e. $K$ from 380 MeV/c/u to 200). Quantum Molecular Dynamics has been also used[19] with the Gogny force and a local force (the Wada force). The Boltzmann-Uehling-Uhlenbeck equation, with a Lattice Hamiltonian inethod, has been solved for a soft and a stiff EOS, and several sNN values[20,28]. Which conclusions can be drawn from these studies ?

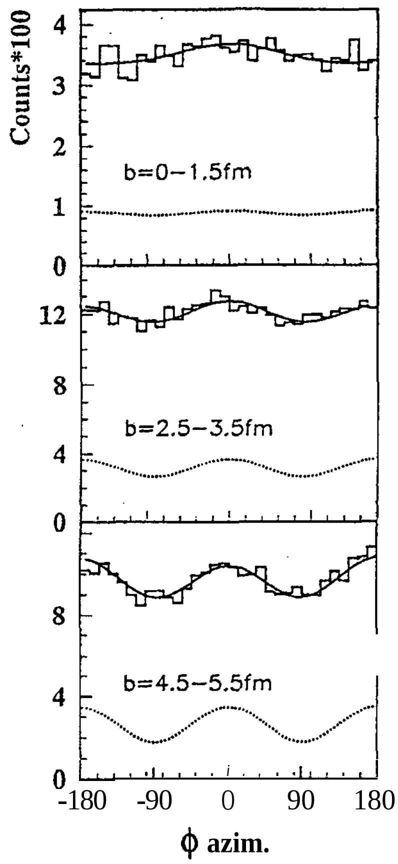


Figure 8: Azimuthal distributions of mid-rapidity $Z = 2$ fragments emitted in 55 MeV/u $^{36}$Ar on $^{27}$Al reactions. Histogram: data Solid line: fit with second order Legendre polynomial. Dotted line: $a_2 \cos 2\phi$ component (shifted up by $a_0/3$).

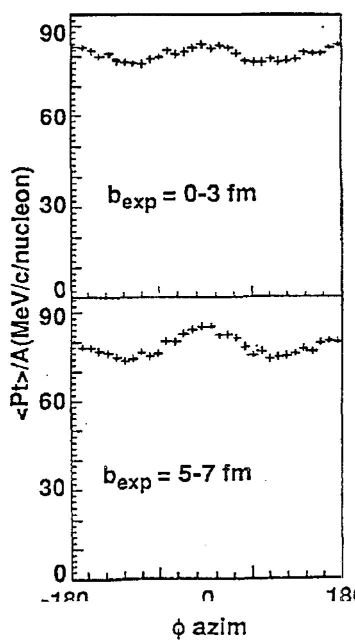


Figure 9: Azimuthal variation of $< P_t >$ at mid-rapidy ($^{64}$Zn on $^{58}$Ni at 35 MeV/u, Z = 2 fragments) for 2 impact parameter bins.

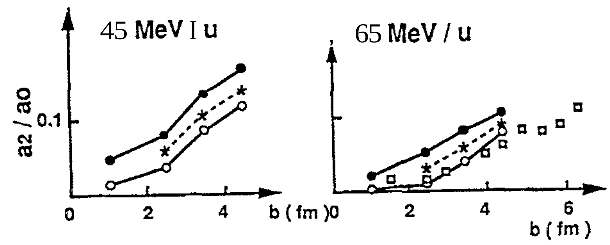


Figure 10: Measured anisotropy ratio, $a_2/a_0$, for mid-rapidity $Z = 1$ and 2 nuclei emitted in $^{40}$Ar + $^{27}$Al collisions versus the impact parameter value. The stars are BUU calculations taking into account the error in the reaction plane determination[27].

### V.1. Sensitivity to the EOS

In LVUU calculations, the set of parameters in the Gogny force has been modified to study the sensitivity to $K$[17]. The flow value is quite insensitive to K, unless the effective mass is taken close to unity: this unrealistic value makes the Gogny force to be almost local and the dependence on $K$ becomes similar to that of a local force (Zamick). Clearly, the velocity dependence of the nuclear interaction makes the flow almost insensitive to the incompressibility value.

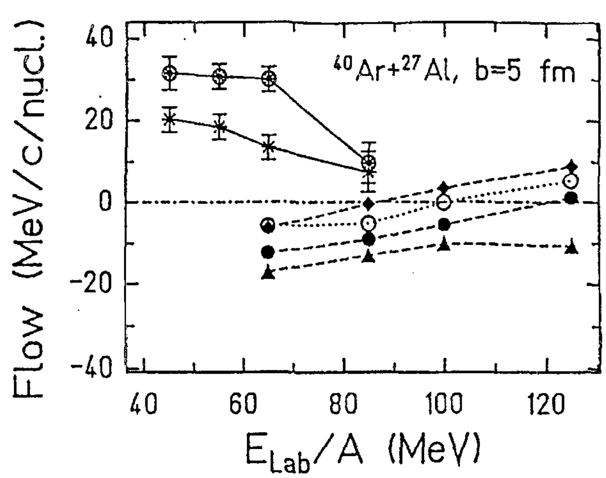


Figure 11: Flow parameter as a function of rapidity for $^{40}$Ar + $^{27}$Al collisions calculated at $b = 5$ fm. The solid triangles, circles, and diamonds display the BUU calculations with a stiff equation of state and $\sigma_{NN}$ = 25, 35, 45 mb, respectively. The open circles are calculations with a soft equation of state and $\sigma_{NN}$ = 35 mb. The open and closed stars indicate experimental data for particles with charge $Z$ = I, and Z = 2, respectively, taken from ref. 9 (more detailed data have been obtained: ref. 29). The data are not corrected for the error on the reaction plane determination and are therefore lower than the real values, whereas in calculations the reaction plane is perfectly known. From ref. 20.

The same insensitivity to $K$ is observed in BUU calculations for rather central collisions ($b <$ 0,5 $b_{grazing}$)[20,28]. For semi-peripheral collisions (not studied with other methods) a difference between soft and stiff EOS is obtained: Fig. 12. That seem to be the last hope for reaching the value of $K$ through flow measurements.

A similar effect is obtained in azimuthal anisotropy factors. Whereas the difference between soft and stiff EOS is less than 10% around 2.5 fm for Ar + Al at 45 MeV/u, it reaches 20% at 4.5 fm[27]).

### V.2. Sensitivity to the nucleon-nucleon cross section in medium

In ref. 17 and 20, a variation of $\sigma_{NN}$ of 20% leads to a shift of the balance energy of 10 MeV/u. This shift is large enough to determine the value of $\sigma_{NN}$ from a comparison to measured flow excitation functions. Calculated azimuthal anisotropies exhibit sensitivity to $\sigma_{NN}$. For Ar on Al at 45 MeV/u, an increase in $\sigma_{NN}$ from 33 to 55 mb diminishes $a_2/a_0$ by 25%[27]).

## VI. Comparisons of experimental data and theoretical predictions

### VI.1. How to perform such comparisons?

The first difficulty is the determination of the flow value from the variation of $< P_x/A >$ versus Y (see Fig. 5). Since there can be some leeway in determining the slope at mid-rapidity, it is useful to compare, at least for some cases, the full calculated $< P_x/A >$ variation to the experimental one. That has been made in ref. 17. The second difficulty comes from the fact that the experimental data ($< P_x/A >$ curve and flow parameter) are affected by an error on the reaction plane determination. Simulated events were used to study this problem[16].

These indeterminations must be introduced in the theoretical calculations. Firstly, one should assume that *all* particles and clusters are perfectly measured, and one uses the real reaction plane. One gets the

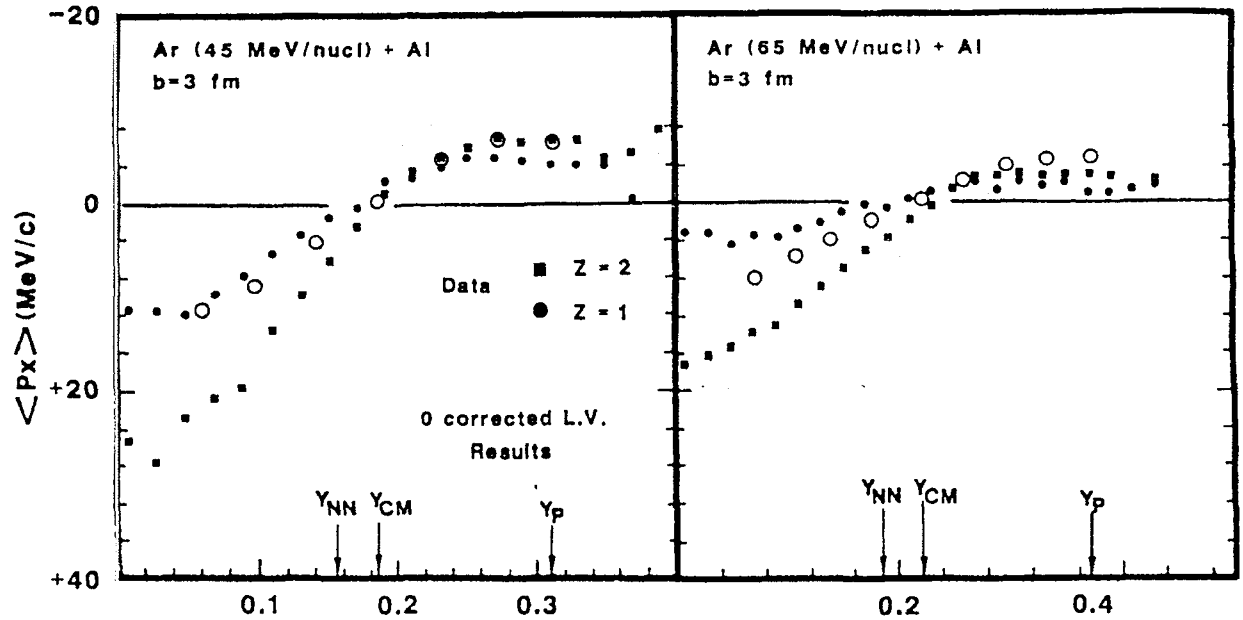


Figure 12: Mean transverse momentum in the reaction plane $< p_x > /A$ as a function of the longitudinal rapidity. The filled squares and circles show the experimental results for Z = 1, Z = 2 fragments. Open circles show theoretical results (**LVUU**) corrected for the reaction plane indetermination and the detector acceptance. From ref. 17.

theoretical $< p_x > /A$ variation. Secondly, one forgets that the reaction plane is known and find it with the same method as in the experiment. This second $< P_x/A >$ variation is (much) less steeper than the real one. Thirdly, a software filter is introduced which reproduces all detector limitations (thresholds, dead areas, finite size of detectors, momentum resolution ...) and the analysis is repeated. If this filtered variation of $< P_x/A >$ has a much smaller slope at mid-rapidity than the second one, then one should be careful before reaching any conclusion.

An example of such a comparison is shown in Fig. 12. Since the shapes of the experimental and calculated curves are similar, flow parameter values can be extracted in the same way and meaningfully compared.

Similarly, the error on the reaction plane must be introduced in azimuthal anisotropy calculations. It has been made in BUU calculations shown in Fig. 10[27].

### VI.2. Mass dependence of the inversion energy

The advantage of the inversion energy is that the theoretical values do not need to be filtered. **LVUU** calculations indicate an approximate $A^{-1/3}$ variation of the inversion energy for symmetric systems at the same relative impact parameter value[17]. This mass dependence can be seen as due to the competition between the mean field effect which is proportional to the surface (i.e. $A^{2/3}$) and the number of nucleon-nucleon collisions, which is proportional to the participant volume (i.e. A). An explanation based on hydrodynamics is given in ref. 17. The important point is that the experimental data agree with the calculations: Fig. 13. This agreement means that the importance of nucleon-nucleon collisions relative to mean field is properly accounted for by these **LVUU** calculations. Balance energies lower (higher) than the experimental data would mean that the role of nucleon-nucleon collisions is too large (too weak) in these calculations.

Such an agreement does not mean that the model and parameters are fully correct, but this agreement is a first condition to be fulfilled before undertaking more detailed comparisons on flow and anisotropy values on a very braod range of energies and several systems.

### VI.3. Choice of the effective nuclear force

Above the inversion energy, a local force with a stiff EOS give the same flow value as the Gogny force, whereas a soft EOS give lower flow values[17]. We have no experimental data to compare above the inversion energy, but we have data below.

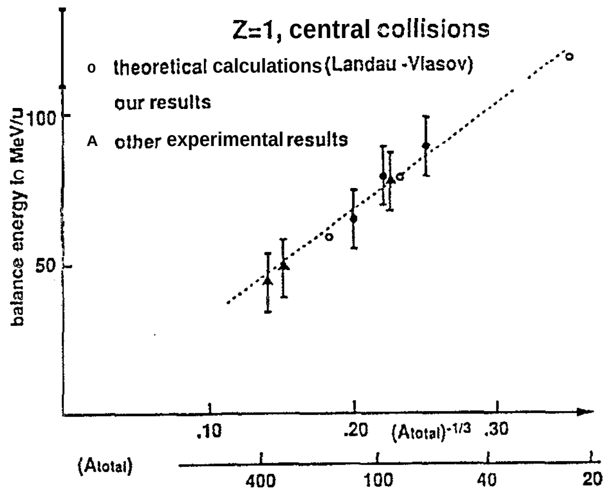


Figure 13: Balance energy versus the total mass of the system. Theoretical points are from ref. 17, experimental data from other experiments are from ref. 12, 15.

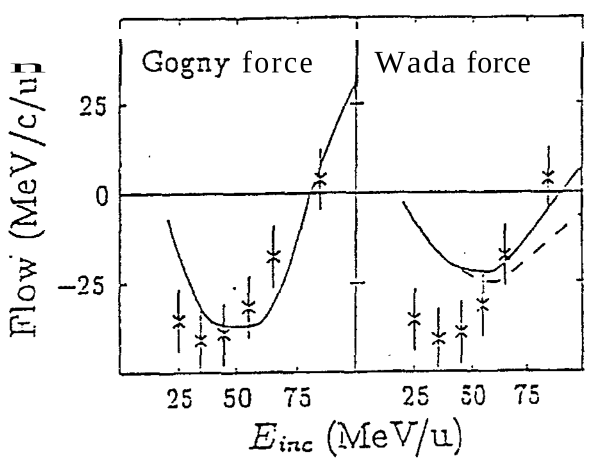


Figure 14: In-plane flow parameter in $^{40}$Ar + $^{27}$Al reactions at b = 3 fm. The solid and dashed lines represent the QMD results with $\sigma_{NN}$ = 40, 20 mb, respectively. The experimental data[9] are corrected for the error on the reaction plane determination[16] and assumed to be negative. The point at 85 MeV/u is shown as positive, but it can be negative as well. From ref. 19.

Fig. 14 shows the results obtained either with a Gogny force or with a local force (Wada force) which gives a stiff EOS[19]. In both cases, the effect of the repulsive density dependence reduces the (negative) flow value when the incident energy increases. In addition, the momentum dependence of the mean field in the Gogny force produces a larger variation with the incident energy, in agreement with experimental data. As also concluded in ref. 17, a local force cannot consistently be used in the whole energy range. Only a realistic effective interaction such as the Gogny force should be used.

### VI.4. Nucleon-nucleon cross section in medium

The same data were compared to LVUU calculations, again with the Gogny force D1 - G1, where the nucleon-nucleon cross section in medium is varied by ±20%[17]. Let us note that, in this case, $\sigma_{NN}$ is an in-medium corrected cross-section which amounts to roughly 80% of the free nucleon-nucleon cross section. The data are in agreement with this value, or with a slightly lower value.

Such a comparison has been made also with BUU calculations : Fig. 11 for b = 5 fm. Comparisons at b = 1.6 fm and 3 fm are given in ref. 20. The inversion energy is in agreement with sNN in medium $\sim 25-45$ mb. The calculated values, however, are lower than or equal to the raw data. When the error in the reaction plane is taken into account, the disagreement will get larger.

### VI.5. Stiff or soft EOS ?

We recall that when a momentum-dependent force is used, the experimental data below the inversion energy (negative flow) are correctly reproduced. The Gogny force corresponds to a soft EOS ($K$ = 228 MeV). Can it be modified to shift the incompressibility modulus $K$ to a much higher value without losing its ability to fulfil its original requirements ? This might not be impossible, but until it is done the flow data around the inversion energy do not need a $K$ value different from $\sim$ 220 MeV[17].

As said above, BUU calculations[20] exhibit some sensitivity to the EOS in semi-peripheral reactions, i.e. in low density interaction regions. But they do not reproduce the experimental data (Fig. 11) and it is not clear whether more complete calculations will retain this sensitivity to the EOS.

The comparison with azimuthal anisotropy ratios tends to favor a stiff EOS[27], but more detailed studies should be made.

## VII. Conclusions

A complete set of in-plane flow parameter values has been obtained for 3 systems, as a function of incident energy (mostly for negative flow), impact parameter and charge of the emitted fragment. Larger flow values are observed for heavier fragments. This is qualitatively attributed to the larger thermal energy per nucleon of lighter fragments[24], however a quantitative calculation is needed. Coulomb effects also play a role[17]. Another pending problem is the possible variation of the balance energy with the mass of the emitted fragment.

Detailed information has also been gained for the azimuthal distribution and $< P_t >$ azimuthal variation of mid-rapidity products. An in-plane enhancement ("rotation like behaviour") is observed for the light system $^{36}Ar + ^{27}Al$ at all energies studied here, i.e. up to 95 MeV/u and at the lower energies for the medium-mass system $^{64}Zn + ^{58}Ni$, whereas this system exhibits an out-of-plane enhancement ("squeeze-out") at higher energies (up to 79 MeV/u). The variation of this anisotropy with impact parameter is in agreement with a competition between in-plane enhancement due to the mean field and shadow effects (decreasing at high b values, stronger for higher energies and/or masses).

As to the in medium nucleon-nucleon cross section and the equation of state, comprehensive comparisons with theoretical calculations have yet to be made. In making such comparisons, one must take into account the error on the reaction plane due to finite number effects and to the detector acceptance. For the moment, a value of $K = 200$ MeV (soft EOS) can reproduce the data, but studies of azimuthal anisotropies should be pursued before excluding a stiff EOS. The possibility of obtaining quantitative information is still an open question. Comparisons show that momentum dependent interaction forces must be used. The observed balance energies are reproduced by LVUU calculations. It is necessary to compare values of the flow parameter (in MeV/c per nucleon) over a broad range of incident energies, at several impact parameter values and for several systems.

## References

1. P. Danielewicz and G. Odynie, Phys.Lett. **157B**, 146 (1985). Danielewicz, H. Strobele, G. Odyniec, D. Bangert, R. Bock, R. Brockmann, J. W. Harris, H. G. Pugh, W. Rauch, R. E. Renfordt, A. Sandoval, D. Schall, L. S. Schroeder and R. Stock, Phys.Rev. **C38**, 120 (1988).
2. K. G. Doss, H. A. Gustafsson, H. Gutbrod, J. W. Harris, B. V. Jacak, K. H. Kampert, B. Kolb, A. M. Poskanzer, H. G. Ritter, H. R. Schmidt, L. Teitelbaum, M. Tincknell, S. Weiss and H. Weiman, Phys. Rev. Lett. 59, 2720 (1987).
3. G. F. Bertsch, W. G. Lynch and M. B. Tsang, Phys. Lett. B 189, 384 (1987).
4. F. Sébille, V. De La Mota, B. Remaud and P. Schuck, Preprint LPN Nantes (1990); Proc. Riken IN2P3 Symposium, Obernai (1990) edited by H. Ishihara (World Scientific, Singapore, 1990).
5. G. Bizard, A. Drouet, F. Lefebvres, J. P. Patry, B. Tamain, F. Guibault and C. Le Brun, Nucl. Inst. & Meth. **A244**, **483** (1986).
6. A. Péghaire, B. Zwieglinski, E. Rosato, G. M. Jin, J. Kasagi, H. Doubre, J. Péter, Y. Cassagnou, R. Legrain, F. Guibault and C. Le Brun, Nucl. Inst. & Meth. **A299**, 365 (1990).
7. J. Péter, D. Cussol, G. Bizard, R. Brou, M. Louvel, J. P. Patry, R. Regimbart, J. C. Steckmeyer, J. P. Sullivan, B. Tamain, E. Crema, H. Doubre, K. Hagel, G. M. Jin, A. Péghaire, F. Saint Laurent, Y. Cassagnou, R. Legrain, C. Le Brun, E. Rosato, R. MacGrath, S. C. Jeong, S. M. Lee, Y. Nagashima, T. Nakagawa, M. Ogihara, J. Kasagi and T. Motobayashi, Nucl. Phys. **A519**, 611 (1990).
8. J. Gosset, O. Valette, J. P. Alard, J. Augerat, R. Babinet, N. Bastid, F. Brochard, N. De Marco, P. Dupieux, Z. Fodor, L. Fraysse, P. Gododetzky, M. C. Lemaire, D. L'Hôte, B. Lucas, J. Marroncle, G. Montarou, M. J. Parizet, J. Poitou, C. Racca,

A. Rahmani, W. Schimmerling and Y. Terrien, Phys. Rev. Lett. 62, 1251 (1989); J. Gosset, M. Demoulins, R. Babinet, C. Cavata, H. Fanet, D. L'Hôte, B. Lucas, J. Poitou, O. Valette, M. C. Lemaire, J. P. Alard, J. Augerat, N. Bastid, P. Charmensat, P. Dupieux, L. Fraysse, J. Marroncle, G. Montarou, M. J. Parizet, D. Qassoud, A. Rahmani, F. Brochard, P. Gorodetzky and C. Racca, Phys. Lett. B 247, (1990).

9. J. P. Sullivan, J. Péter, D. Cussol, G. Bizard, R. Brou, M. Louvel, J. P. Patry, R. Regimbart, J. C. Steckmeyer, B. Tamain, E. Crema, H. Doubre, K. Hagel, G. M. Jin, A. Péghaire, F. Saint Laurent, Y. Cassagnou, R. Lebrun, E. Rosato, R. MacGrath, S. C. Jeong, S. M. Lee, Y. Nagashima, T. Nakagawa, M. Ogihara, J. Kasagi and T. Motobayashi, Phys. Lett. **249B**, 8 (1990).
10. J. M. Harris, B. V. Jacak, K. H. Kampert, G. Claesson, K. G. R. Doss, R. Fergusson, A. I. Gavron, H. A. Gustafsson, H. Gutbrod, B. Kolb, F. Lefebvres, A. M. Poskanzer, H. G. Ritter, H. R. Schmidt, L. Teitelbaum, M. Tincknell, S. Weiss, H. Wieman and J. Wilhelmy, Nucl.Phys. **A471**, 241c (1987).
11. M. Demoulins, thesis, Université de Paris-Sud (1989) unpublished.
12. D. Krofcheck, W. Bauer, G. M. Crawley, C. Djajali, S. Howden, C. A. Ogilvie, A. Vander Molen, G. D. Westfall, W. K. Wilson, R. S. Tickle, and C. Gale, Phys. Rev. Lett. 63, 2028 (1989).
13. C. A. Ogilvie, W. Bauer, D. A. Cebra, J. Clayton, S. Howden, J. Karn, A. Nadasen, A. Vander Molen, G. D. Westfall, W. K. Wilson and J. S. Winfield, Phys. Rev. C42, R10 (1990).
14. W. K. Wilson, D. A. Cebra, S. Howden, J. Karn, D. Krofcheck, R. Lacey, T. Li, A. Nadasen, T. Reposeur, A. Vander Molen, C. A. Ogilvie, G. D. Westfall and J. S. Winfield, Phys. Rev. C43, 2696 (1991).
15. W. K. Wilson, W. Benenson, D. A. Cebra, J. Clayton, S. Ilowden, J. Karn, T. Li, C. A. Ogilvie, A. Vander Molen, G. D. Westfall, J. S. Winfield, B. Young and A. Nadassen, Phys. Rev. **C41**, R1181 (1990).
16. J. P. Sullivan and J. Péter, Nucl. Phys. A 540, 275 (1992).
17. V. De La Mota, F. Sébille, M. Farine, B. Remaud and P. Schuck, preprint LPN Nantes (1991) and Proc. XXIX Meeting on Nuclear Physics, Bormio (1991), edited by I.Iori, V. De La Mota, F. Sébille, M. Farine, B. Remaud and P. Schuck, Phys. Rev. C46, 677 (1992).
18. S. Leray, C. Ngô, M. E. Spena, B. Remaud and F. Sébille, Nucl. Phys. **A511**, 414 (1990).
19. A. Ohnishi, T. Maruyama and H. Horiuchi, Comm. at Nucleus-Nucleus Collisions IV, Kanazawa (1991).
20. H. M. Xu, preprint Texas A & M, College Station, 90-20 (1991), submitted to Phys. Rev. Lett.
21. M. Demoulins, D. L'Hôte, J. P. Alard, J. Augerat, R. Babinet, N. Bastid, F. Brochard, C. Cavata, N. de Marco, P. Dupieux, H. Fanet, Z. Fodor, L. Fraysse, P. Gorodetzky, J. Gosset, T. Hayashino, M. C. Lemaire, A. Le Merdy, B. Lucas, J. Marroncle, G. Montarou, M. J. Parizet, J. Poitou, C. Racca, W. Schimmerling, Y. Terrien and O. Valette, Phys. Lett. **B241**, (1990).
22. J. Gosset, M. Demoulins, D. L'Hôte, O. Valette, J. P. Alard, J. Augerat, R. Babinet, N. Bastid, F. Brochard, C. Cavata, P. Charmensat, N. de Marco, P. Dupieux, H. Fanet, Z. Fodor, L. Fraysse, P. Gorodetzky, M. C. Lemaire, B. Lucas, J. Marroncle, G. Montarou, M. J. Parizet, J. Poitou, D. Qassoud, C. Racca, A. Rahmani, W. Schimmerling and Y. Terrien, Peniscola 1989, the Nuclear Equation of State, A; edited by W. Greiner and H. Stocker, (Plenum, New York, 1989).
23. W. Q. Shen, J. Péter, G. Bizard, R. Brou, D. Cussol, M. Louvel, J. P. Patry, R. Regimbart, J. C. Steckmeyer, J. P. Sullivan, B. Tamain, E. Crema, H. Doubre, K. Hagel, G. M. Gin, A. Péghaire, F. Saint Laurent, Y. Cassagnou, R. Legrain, C. Lebrun, E. Rosato, R. Mac Grath, S. C. Jeong, S. M. Lee, Y. Nagashima, T. Nakagawa, M. Ogihara, J. Kasagi and T. Motobayashi, Nucl. Phys. A 551, 333 (1993).

24. H. H. Gutbrod, K. H. Kampert, B. W. Kolb, A. M. Poskanzer, H. G. Ritter and H. R. Schmidt, Phys. Lett. B 216, 267 (1989).
25. R. Bougault, F. Delaunay, A. Genoux-Lubain, C. Le Brun, J. F. Lecolley, F. Lefèbvres, M. Louvel and J. C. Steckmeyer, J. C. Adloff, B. Bilwes, R. Bilwes, M. Glaser, G. Rudolf, F. Scheibling, L. Stuttge and J. L. Ferrero, Proc. Int. School of Physics Enrico Fermi, Varenna (1990) CXII, p. 353.
26. W. K. Wilson, R. Lacey, C. A. Ogilvie and G. D. Westfall Phys. Rev. C 45, 738 (1992).
27. Y. G. Ma, W. Q. Shen, J. Feng and Y. Q. Ma, Z. Phys. A 344 469 (1993) and preprint INR Shanghaï, 1992
28. H. M. Xu, Phys. Rev. C46, R389 (1992).
29. J. C. Angélique, A. Péghaire, G. Bizard, G. Auger, A. Buta, C. Cabot, Y. Cassagnou, E. Crema, D. Cussol, Y. El Masri, Ph. Eudes, M. Gonin, K. Hagel, Z. Y. He, A. Kerambrun, C. Lebrun, R. Legrain, J. P. Patry, J. Péter, R. Popescu, R. Regimbart, E. Rosato, F. Saint-Laurent, J. C. Steckmeyer, B. Tamain, E. Vient and R. Wada, LPC Caen 93-01, to appear in Proc. XXXI meeting on Nuclear Physics, Bormio (1993).
30. V. de la Mota, F. Sébille, B. Rémaud and P. Schuck, Z. Phys. A 343, 417 (1992).