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Sidewards collective flow of nuclear matter has been predicted by hydrodynamical calculations[1] to occur in nucleus-nucleus collisions at a few 10^2 MeV per nucleon. Such a behaviour was first observed experimentally in symmetric nucleus-nucleus collisions[2] by the Plastic Ball group at Berkeley. It should be emphasized that the experimental result (dN/d cosΘ distribution) gives no indication whether the flow occurs on the side of the projectile as predicted by the hydrodynamical calculations, or on the opposite side in an orbiting-like collective motion as was measured in low energy (few MeV per nucleon) nucleus-nucleus collisions some 15 years ago[3], and predicted also to occur below 100 MeV per nucleon[4], where there is experimental evidence[5] of a reversal of the flow direction at E/A≈50 MeV.

The existence of a sidewards flow enabled Danielewicz and Odyniec[6] to develop a method to determine the azimuth of the reaction plane, that is the symmetry plane which is conserved throughout the reaction. Also in this method, the azimuth is determined at ± 180°. They applied this method to demonstrate the existence of sidewards flow for symmetric systems of light nuclei where the dN/d cosΘ distribution was not sensitive enough to give a signal. We extended this method to asymmetric and very light symmetric systems, where the occurence of nuclear collective flow has been clearly stated[7].

In the Danielewicz method, a global transverse momentum vector **Q** is constructed by adding the weighted transverse momenta of all emitted particles. The weight is taken as positive for particles emitted in the forward hemisphere (in the centre of mass system) and negative for particles emitted in the backward hemisphere. Due to the collective flow, the particles have, on the average opposite-sign non-zero transverse momentum vector in the forward and backward hemispheres ; with the selected weights, all particles add up so that the **Q** vector points in the direction of the average transverse momentum in the forward hemisphere, and is located in the reaction (symmetry) plane.

We have used this method with the baryons emitted in the reaction, which are the signature for the collective flow of the nuclear matter. The weight used in determining the reaction plane direction is, for each baryon (charge Z_μ, mass m_μ), taken as $Z_\mu/m_\mu.(y_\mu - \langle y\rangle)$, where y_μ is the baryon rapidity and $\langle y\rangle$ the Z/m weighted average rapidity of all baryons of the event. In the reaction plane, the flow is characterized by a quantity F called flow parameter, which is the slope of the average in-plane transverse momentum $\langle p_x/m\rangle$ versus rapidity y at the rapidity y_0 for which $\langle p_x/m\rangle$ is zero (due to experimental inefficiency, y_0 may differ from $\langle y\rangle$) :

$$F = [\frac{d}{dy}.\langle p_x/m\rangle]_{y=y_0}$$

In what follows, the superscript ' will denote values obtained in the estimated reaction plane, while quantities without the superscript are corrected for systematic errors in the reaction plane reconstruction by the event by event fluctuations due to finite number effects[6].

It is worthwhile to investigate the behaviour of the pions, which are not present as real particles in the incoming beam and projectile nuclei but are produced in the collisions, and originate mainly in the deltas produced at the high density stage of the reaction[8,9]. The method of Danielewicz and Odyniec cannot be applied directly to the pions :

- the statistics for pion emission is much smaller than for baryons ;
- there is no a priori indication that there should be any collective behaviour of the pions.

However, the reaction plane determined from the baryons can be used as a reference for the pion triple differential cross-sections. It is then possible to make a similar transverse momentum analysis for the pions as is done for the baryons. In what follows, the results of this analysis will be presented and interpreted with the same language as for the baryons, in spite of the fact that the physical meaning of what is observed may be completely different for the pions and for the bayons. The flow parameter F will be defined as the slope of the $\langle p_x/m_\pi\rangle(y)$ dependence at the y_0 rapidity determined from the baryons.

Some streamer chamber[10] results of pion flow were already reported. We present here systematic investigation of pion production [11,12] in Ne and Ar induced reactions on various targets with the 4π detector Diogene[13] at the Saturne accelerator facility. The different projectile, target and beam energy combinations are given in table 1.

projectile	target	E/A (GeV)
Ne	NaF Nb Pb	.2 to 1 " "
Ar	Ca Nb Pb	.2 to .8 .2 to .6 .2, .4

Table 1 Projectile target energy combinations

The central chamber of the Diogene detector measures light charged particles (π^+, π^-, p, d, t, ^{3}He and ^{4}He) emitted between 20 and 132 degrees with energies above ≈15 MeV for pions and 25 A.MeV for baryons, thus selecting essentially the participants. The multiplicity is limited to ≈30 ; at higher multiplicities the inefficiency increases rapidly.

The aim of such experiments is to investigate the behaviour of dense (and hot) nuclear matter. The closest experimental approximation of dense nuclear matter can be achieved only in central collisions of relativistic heavy nuclei. It is thus advisable to try and get a quantitative estimate of the impact parameter. A method based on the anti-correlation between charged particle multiplicty and impact parameter has been developped[7] to calculate the average impact parameter associated with a class of events selected according to an interval of particle multiplicity.

The multiplicity of emitted pseudo-protons (free or bound protons) is strongly correlated to the number of participants, which, in a simple geometric picture increases uniformly as the impact parameter decreases. Model calculations support this assumption[14]. By identifying the integrated cross-section of having multiplicities larger than a given value to the integrated cross-section of having the impact parameter smaller that a given value, and normalizing these two cross-sections to the total and geometrical cross-sections respectively, one gets a one to one correspondance between average multiplicity and average impact parameter. Intra-Nuclear Cascade calculations[8] show that this relation is very reliable on the average (Fig. 1). Rather than using the absolute impact parameter value, we use a reduced impact parameter value b_r defined as :

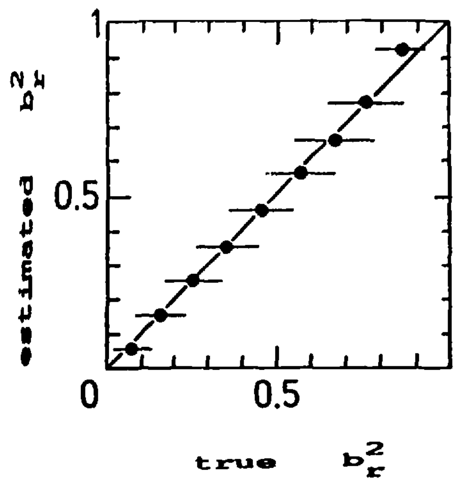

Fig.1 Squared reduced impact parameter in INC calculation for Ne + Pb at E/A = 800 MeV. The estimated value is plotted as a function of the true one.

$$b_r^2 = b^2 / (R_p + R_t)^2$$

where R_p and R_t are the projectile and target radii ($1.12\ A^{1/3}$). All the following results will be presented in selected bins of pseudo-proton multiplicities for which the average reduced impact parameter will be given. This will allow to compare various systems as a function of b_r.

The rapidity dependence of $\langle p_x/m \rangle$ is shown in Fig.2 for protons and π^+ emitted in central collisions (b_r^2=.18) of Ne on Pb at 800 MeV per nucleon. The protons exhibit the standard behaviour of positive average transverse momentum values at forward rapidities and negative values at backward rapidities. Their flow parameter value corresponds to 375 MeV per unit of rapidity. Contrary to the protons, the pions have always positive average in-plane transverse momentum values. They seem to be preferentially emitted in the direction of the projectile that is the light nucleus for this asymmetric system. This behaviour is not at all predicted by Intra-Nuclear-Cascade (INC) calculations as can be seen on the figure : within the error bars, the predicted value is compatible with zero. The experimental slope parameter for the pions yields 55 MeV per unit of rapidity.

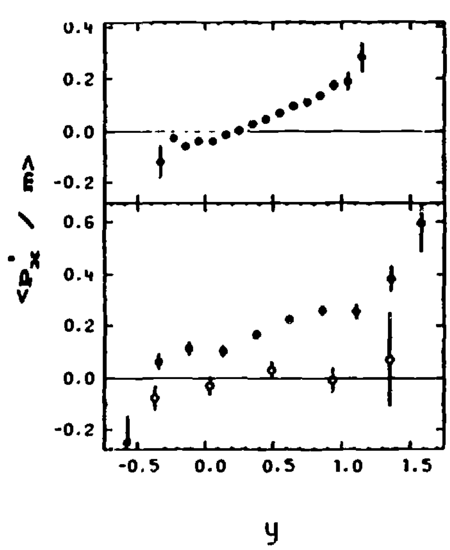

Fig.2 Average in-plane transverse momentum vs. rapidity for protons (top) and π^+ (bottom) from central Ne + Pb collisions at E/A = 800 MeV. The open circles (bottom figure) are INC results.

This behaviour has been systematically studied[11] versus beam energy, projectile and target size and collision centrality. Indeed, the average in-plane transverse momentum is always positive (or compatible with zero), and, as can be seen in Figures 3, 4 and 5, the flow parameter is small. The $\langle p_x/m\rangle(y)$ dependence can be simply characterized by two quantities : the flow parameter F, which is the slope of the curve (approximated by a straight line) and the mean value of $\langle p_x/m\rangle$, averaged over y, denoted as $\langle q_x\rangle$. The impact parameter dependence of these two quantities is plotted in Figures 3, 4 and 5.

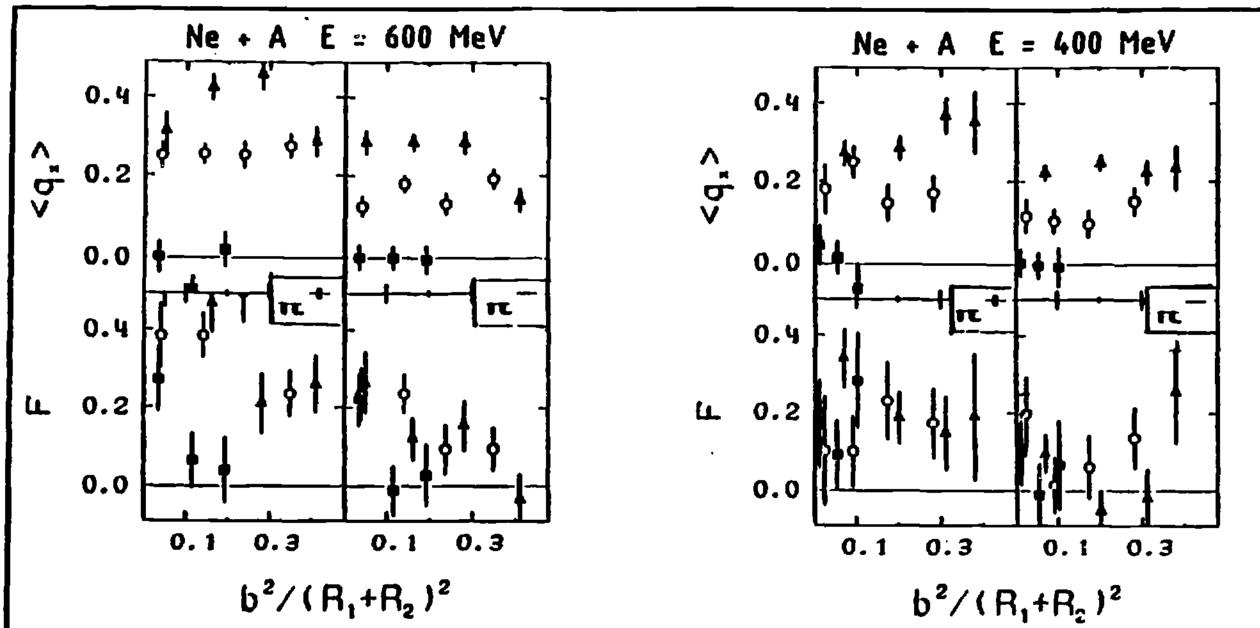

Fig.3 Pion flow characteristics (see text for the definition of each quantity) in Ne-nucleus collisions at 600 and 400 MeV per nucleon. The targets were Pb (full triangles), Nb (open circles) and NaF (squares).

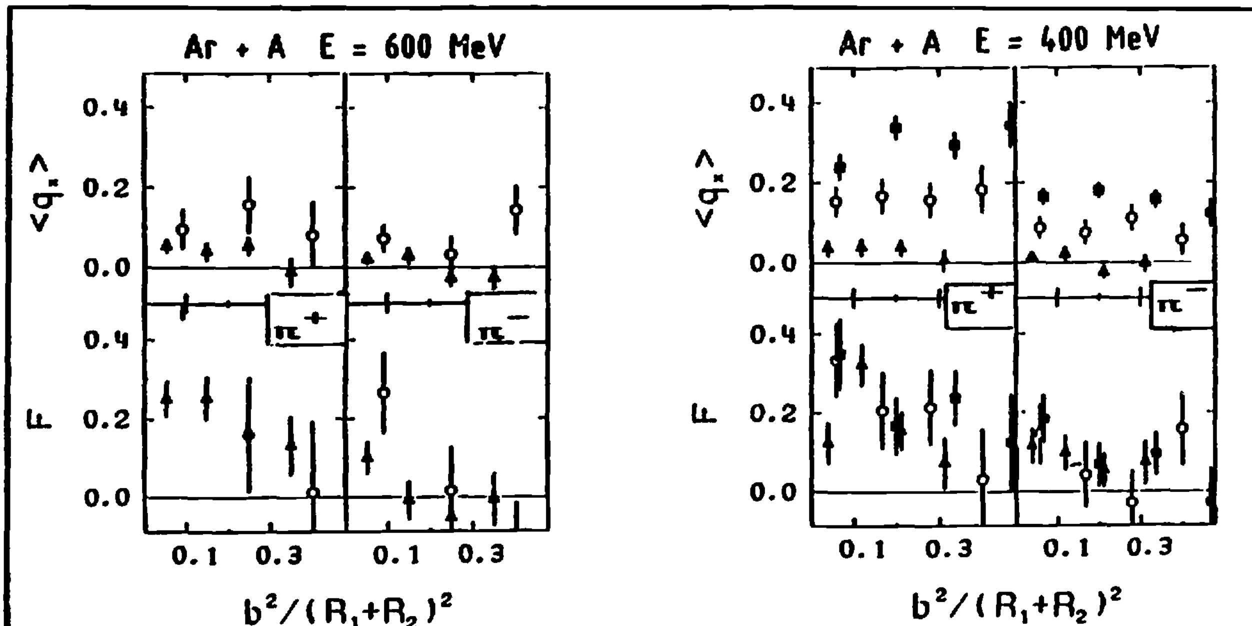

Fig.4 Pion flow characteristics (see text for the definition of each quantity) in Ar-nucleus collisions at 600 and 400 MeV per nucleon. The targets were Pb (full squares), Nb (open circles) and Ca (triangles).

The anisotropy of pion emission is very small for the two symmetric systems Ne+NaF and Ar+Ca for all impact parameters. For the Ne+NaF system, it is always compatible with zero, while a small non zero anisotropy is observed at small impact parameter in the Ar+Ca system. When the system gets more asymmetric, the anisotropy in the pion emission is increased ; the biggest effect is observed with the most asymmetric system (Ne+Pb). This anisotropy in the emission towards the projectile is always more pronounced for π^+ than for π^-. The impact parameter dependence of $\langle q_x \rangle$ shows no obvious systematic effect. The flow parameter F decreases for asymmetric systems at 600 and 800 MeV per nucleon, when the collision gets more peripheral. At 400 MeV per nucleon, no clear impact parameter dependence of F is observed whatever the projectile. Let us recall that the impact parameter dependence of F for the baryons is very small, with a shallow maximum at intermediate impact parameters[15].

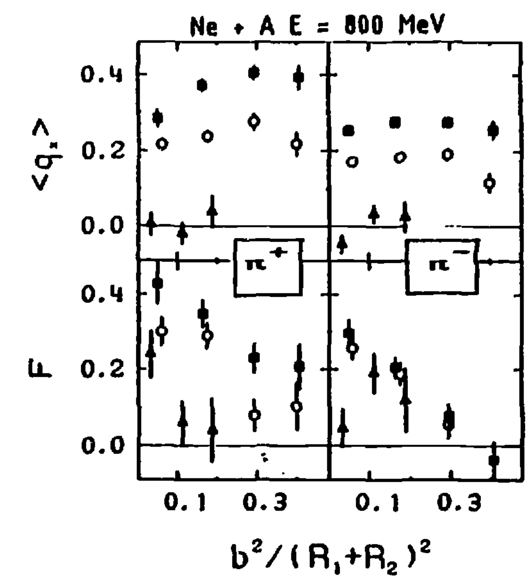

Fig.5 Pion flow characteristics (see text for the definition of each quantity) in Ne-nucleus collisions at 800 MeV per nucleon. The targets were Pb (full squares), Nb (open circles) and NaF (triangles).

Since pions are essentially produced through an intermediate delta resonance, one might think that the pion flow behaviour reflects the flow of the deltas, which in turn should be similar to the proton one. However, the pion flow characteristics is very different from the proton ones (Fig.2). Moreover, the Intra-Nuclear Cascade calculations which reproduce satisfactorily the proton flow[15,16], predict a zero flow for the pions. In the INC pion production occurs only through the delta resonance, and hence the effect of the delta flow on the pion behaviour should come out of the calculations. It seems thus very unprobable that the deltas could account for the observed effect.

The azimuthal anisotropy of pion emission increases with the asymmetry of the system : the heavier the target, as compared to the projectile, the larger the relative enhancement of the emission in the direction of the light projectile. This suggests the interpretation of this effect as the result of the pion absorption by the nuclear medium. The pions are produced in the participant region. Those pions that are emitted towards the projectile have much less material to go through in order to escape the interaction region than the pions that are emitted towards the target.

In order to study quantitatively this effect, let us concentrate on a selected region of impact parameter ($0 \le b_r^2 \le .25$ i.e. $\langle b_r \rangle = .33$) which is common to all measured systems. The $\langle q_x \rangle$ dependence versus mass asymmetry of the system is plotted in Fig.6. The $\langle q_x \rangle$ value is zero for symmetric systems, increases strongly with system asymmetry but depends very little on beam energy, which is again in favour of a pure geometrical effect. A very crude model has been developed to check this hypothesis. The pions are assumed to be all emitted at the centre of the participant region, and a fixed absorption mean free path λ of the pions in the nuclear matter, which is supposed to be independent of their energy. The pion azimuthal distribution is assumed to follow a functionnal like $dN/d\Phi = a_0 + a_1 \cos\Phi$ (as found in ref. 15). With these hypotheses, it is easy to calculate a ratio Ω :

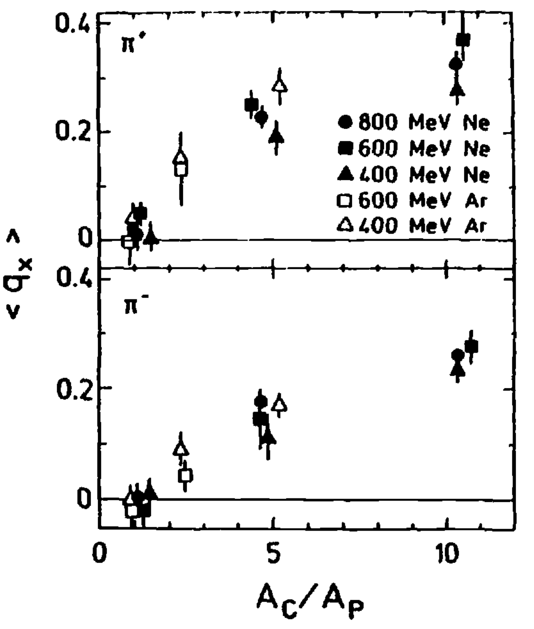

Fig.6 Pion average in-plane transverse momentum vs system asymmetry.

$$\Omega = \frac{\langle q_x \rangle}{\langle q_\perp \rangle} = \frac{1}{2}\ \mathrm{th}\ \left[\frac{\langle d_t \rangle - \langle d_p \rangle}{2\lambda}\right]$$

$\langle q_x \rangle$ and $\langle q_\perp \rangle$ are the experimental values. $\langle d_t \rangle$ and $\langle d_p \rangle$ are the average thickness of target and projectile respectively seen by the pions ; the corresponding values for the asymmetric systems are given in table 2.

System	$\langle d_t \rangle$	$\langle d_p \rangle$	$\langle d_t \rangle - \langle d_p \rangle$
Ar + Pb	8.56	3.97	4.58
Ar + Nb	6.35	4.36	1.99
Ne + Pb	8.53	3.04	5.49
Ne + Nb	6.51	3.19	3.32

Table 2 Average distances (fm) for the pions to escape nuclear matter, for $b_r = .33$.

The experimental ratio Ω is plotted versus mass asymmetry in Fig.7. The curves corresponding to the definition of Ω for $\lambda = 4$, 5 and 6 fm , obtained with the distances of table 2 are drawn in the figure. Within the error bars, all the experimental points lie in the interval 4 to 6 fm. These values should be compared with what can be deduced from pion absorption cross-sections[17]. These cross-sections can be estimated from pion production data in nucleon-nucleus reactions. Sparrow et al.[18] analyzed with a semi-classical model various experimental data[19] , assuming that the picn production is dominated by the delta resonance, and taking all cross-section values from experimental results of elementary processes, except for the pion absorption which is obtained by fitting the N+A → π+A reaction data. Their results are plotted in Fig.8.They are in agreement with the values of reference 17.

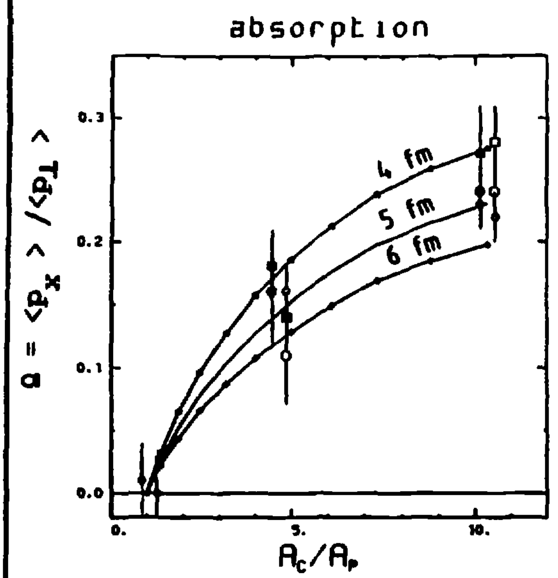

Fig.7 Experimental values of Q for π^+ (open symbols) and π^- (closed symbols).at 400 (cicles), 600 (squares) and 800 (losanges) MeV per nucleon. The curves are calculated for the indicated values of λ.

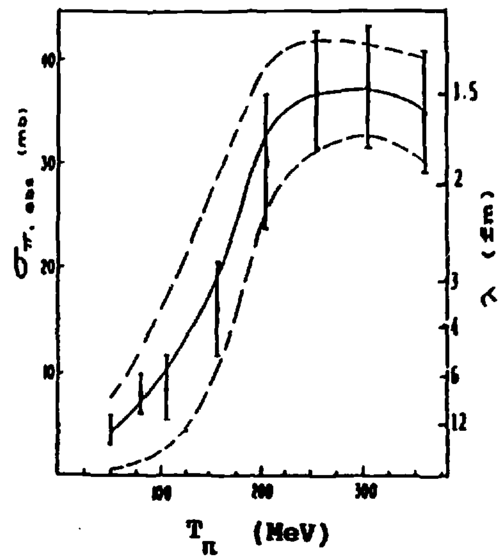

Fig.8 Pion-absorption cross-sections from ref. 17. The points are from p+Pb reactions. The average over all experiments is represented by the solid line. The dashed lines represent the uncertainties (σ). he cross-section has been converted in mean free path on the right scale.

In the model of Sparrow et al., the absorption cross-section is inversely proportional to the density. The mean free path varies thus from ≈1.5 fm to 12 fm for pion kinetic energies varying from 300 to 50 MeV at normal nuclear density. The estimated mean free path from our experimental results is in good agreement with these results.

C. Hartnack et al.[9] calculated with their Iso-QMD model that the pion flow was always positive for asymmetric systems. Since they use the same cross-section as in the INC, their interpretation was that the medium effects are responsible for the azimuthal anisotropy observed in pion emission. However, they could reproduce only half of the measured effect. In this paper, evidence has been given that pion absorption effects, which are known to be undersestimated in the INC[20], may be responsible for the measured anisotropy ; the target mass dependence comforts this assumption.

This has a remarkable consequence on the baryon flow : the transverse momentum method does not allow to distinguish between flow towards the light projectile or towards the heavy target. If the conclusion that the anisotropy of pion emission is due to the absorption then the pion flow must be towards the light nucleus. Since the reference direction for the flow is taken from the baryon data, it follows that the baryons, that flow in the same direction as the pions for forwards rapidities, have thus their collective flow towards the light projectile.

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