ENERGY DEPENDENCE OF COLLECTIVE FLOW OF NEUTRONS AND CHARGED PARTICLES IN $^{197}\text{Au} + ^{197}\text{Au}$ COLLISIONS

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INTRODUCTION

Collective flow of nuclear matter is one important aspect of the research performed at heavy ion accelerator laboratories. The phenomenon was predicted on the basis of hydrodynamical calculations [1], and experimental evidence was first presented for the systems $^{93}\text{Nb} + ^{93}\text{Nb}$ and $^{197}\text{Au} + ^{197}\text{Au}$ in the projectile energy range between 150 and 1050 MeV/u [2]. The comparison to microscopic calculations shows that nuclear matter is compressed to about two to three times the ground state density and that a substantial fraction of the kinetic energy in the entrance channel is converted into compressional energy [3]. In these calculations, the relation between density and compressional energy depends on the parameterization of the nucleon-nucleon interaction. The values of its parameters will hopefully be restricted by a comparison of the calculations to experimental data, and thus one can obtain information on the

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nucleon-nucleon interaction within the nuclear medium which is not accessible from other sources.

This problem has until now mainly been attacked with data for charged particles. Such data are basically incomplete since the information on the neutrons is missing, and it is not a priori clear to what extent collective observables are modified by the long-range Coulomb interaction. It is therefore essential to compare neutrons and protons experimentally. At first sight, this seems to require the construction of a 4π -spectrometer for neutrons which is not feasible within reasonable cost. However, if the global observables of an event – like impact parameter or azimuthal angle of the reaction plane – are provided by a 4π -spectrometer for charged particles, the spectrometer may be combined with a neutron detector of limited solid angle, and the combination will still deliver triple differential cross sections $d^3\sigma/dydp_t d(\Delta\varphi)$ [y : rapidity, p_t : transverse momentum, $\Delta\varphi$: azimuthal angle with respect to the reaction plane]. Thus the full information is obtained which is equivalent to a measurement in the complete solid angle.

Preliminary data from such an experiment have been reported earlier [4, 5]. The neutron data were analyzed in terms of $\langle p_t \rangle$ in the reaction plane and azimuthal distributions about the beam axis. However, no analogous data for charged particles were taken, and hence the comparison to previous experiments is difficult. That difficulty is overcome by the combination of the FOPI-spectrometer [6] with the **Large Area Neutron Detector** LAND [7]: The FOPI-spectrometer (phase I) covers the forward hemisphere of the cm-system for symmetric systems at energies above ≈ 150 MeV/u and provides the impact parameter vector. LAND determines the momentum vectors of the neutrons and light charged particles in a limited solid angle. They are thus detected in the same region of phase space, and their properties can be compared without any inter- or extrapolation, and without systematic errors due to different acceptances. The combination with FOPI allows for the exclusive investigation with respect to the impact parameter vector.

Our contribution focusses on one particular aspect of collective flow of nuclear matter: the so-called "squeeze-out", i.e. the preferential emission of mid-rapidity particles perpendicular to the reaction plane. The data were taken for the system $^{197}\text{Au} + ^{197}\text{Au}$ at 400, 600 and 800 MeV/u. We will cover two topics, the comparison of neutrons and protons, and the bombarding energy dependence of the neutrons' squeeze-out.

EXPERIMENTAL SET-UP AND RESULTS

The experimental set-up is shown schematically in fig. 1, and detailed descriptions of the two detector systems are given in refs. [6, 7]. Results from this experiment at a bombarding energy of 400 MeV/u have been published in [8]. The analysis at two higher energies, 600 and 800 MeV/u, was strictly analogous. Two global observables of each event, the azimuthal angle of the reaction plane and the impact parameter, were obtained from the charged particles in the plastic wall of the FOPI spectrometer: (i) The azimuthal angle φ_R of the reaction plane was taken from the total transverse momentum of the charged particles in the forward hemisphere. A flow tensor analysis was not performed, therefore all azimuthal angles are measured about the beam axis. Contrary to most other experiments, the problem of autocorrelations did not arise, since the particles to be correlated with the reaction plane – those detected in LAND – were not involved in the determination of φ_R . (ii) The impact parameter was determined by the ratio of 'transverse' to 'longitudinal' energy. For each event, $E_\perp = \sum \frac{p_\perp^2}{2m}$ and

Figure 1: Set-up of the joint experiment of LAND and the FOPI-spectrometer (phase I). The latter detects charged particles at $1^\circ \leq \theta_{lab} \leq 30^\circ$ with full coverage of the azimuthal angle. PLA indicates the internal and external plastic wall of scintillators, IC indicates a shell of ionization chambers for detection of heavy, slow clusters. For details, see ref. 6. The two halves of LAND are positioned at $\theta_{lab} = 45^\circ \pm 8^\circ$ and $\theta_{lab} = 73^\circ \pm 12^\circ$, respectively. The figure gives as example the set-up for a shadow bar (SB) measurement with LAND 2.

$E_{||} = \Sigma_{2m} p_{||}^2$ were calculated. The data were grouped into five bins of the 'energy ratio' $E_{rat} = E_{\perp}/E_{||}$ with bin names E1 through E5, with E5 indicating the highest energy ratio. The transformation of E_{rat} into absolute values of the impact parameter had to be done by means of model calculations. Since the data are to be compared to quantum molecular dynamics calculations (see below), the same model was chosen for the impact parameter transformation. Figure 2 shows the result for one particular version, the so-called 'soft equation of state' with momentum-dependent interactions. As intuitively expected, the highest values of E_{rat} are found to select the most central collisions. The correlation between E_{rat} and impact parameter depends only weakly on the QMD version used.

Since neutrons have a long range, their spectra contain background which originates from scattering from all massive objects within the experimental area and off the concrete walls. To investigate this effect, iron shadow bars were inserted between the target and each sub-system of LAND separately, in such a way that the neutron detectors were shielded from particles coming directly from the target. During the analysis, all spectra were accumulated twice, once from runs without shadow bars and once from runs with the respective shadow bar in place. The spectra were then subtracted in order to eliminate the background. Table 1 shows the integral values in the two halves of LAND at the three projectile energies investigated. It is important to note that the background is event-correlated, i.e. some of the neutrons originate from the target, but reach the detector indirectly after scattering.

Figure 2: Relation between E_{rat} and impact parameter from QMD calculations

E_{proj}	LAND 1	LAND 2
400	10%	30%
600	12%	31%
800	14%	33%

Table 1: Neutron background in the two halves of the LAND detector

SQUEEZE-OUT OF NEUTRONS AND PROTONS

The squeeze-out effect is depicted in fig. 3 which shows typical data from the system $^{197}\text{Au} + ^{197}\text{Au}$ at 600 MeV/u. The figure shows azimuthal distributions about the beam axis of mid-rapidity neutrons (top) and hydrogen ions (bottom) for different impact parameter ranges which were selected by E_{rat} . Only particles with rapidities $0.4 \leq y/y_{proj} < 0.6$ are considered throughout the remainder of this contribution. The maxima of the count rate at $\Delta\varphi = \varphi - \varphi_R = \pm 90^\circ$ indicate the preferential emission perpendicular to the reaction plane. The anisotropy is very large at impact parameters which correspond to the radius of target and projectile, and it decreases with decreasing b as the system becomes more and more azimuthally symmetric.

From a qualitative inspection of fig. 3 it is already obvious that the behaviour of neutrons and hydrogen ions is very similar. However, collective flow effects are known to increase with the mass of the particle considered, and therefore a separation of the hydrogen isotopes is essential. A scintillator wall in front of LAND yields the charge number of a particle from the correlation of energy loss with time of flight, whereas the mass number is obtained from calorimetric information from the neutron detector itself. Fig. 4 shows – for particles with $Z = 1$ – the ratio of the deposited energy and the kinetic energy per mass, which is given by the Lorentz factor $\gamma - 1$. One clearly sees a sharp peak at 0.13 GeV, a second peak at about twice that value, and a broad shoulder around $E_{dep}/(\gamma - 1) \approx 0.4$ GeV. It is obvious that the calorimetric resolution

Figure 3: Azimuthal distributions of neutrons (top) and hydrogen ions (bottom) at impact parameters of $b=6.9\pm3.1$ fm (left), $b=4.2\pm1.8$ fm (middle), and $b=2.8\pm1.3$ fm (right).

is insufficient to separate the H isotopes event by event. However, we confirmed the correspondence of the peaks to the H isotopes by fitting the spectrum with three asymmetric peaks. Their positions and widths were fixed relative to each other at values of $1 : 2 : 3$ and $1 : \sqrt{2} : \sqrt{3}$, respectively, and the asymmetry was described by only one parameter common to all three components. The resulting fit, which has only six free parameters, provides a good description of the spectrum as shown in the left part of fig. 4. Hence a cut on $E_{dep}/(\gamma-1)$ can be used to enrich p, d, and t in the azimuthal distributions and to get a feeling for the size of the signal as a function of mass. After applying very conservative cuts (right part of fig. 4), the azimuthal distributions were fitted with Legendre polynomials $\frac{dN}{d\Delta\varphi} = B_0 + B_1 \cdot P_1(x) + B_2 \cdot P_2(x)$ with $x = \cos(\Delta\varphi)$. The coefficient B_2 describes the squeeze-out effect. Its values for mid-rapidity particles are shown in fig. 5. The results for neutrons and 'protons' are within the error bars the same, and the heavier isotopes show a larger anisotropy which is consistent with the earlier finding that collective effects show up more clearly in the data of heavier particles [9]. In addition, our results show that at relativistic energies collective observables are not affected by the Coulomb force despite its long range.

ENERGY DEPENDENCE OF NEUTRON SQUEEZE-OUT

We now turn to the dependence of the squeeze-out signal on the bombarding energy. This investigation is done for the neutrons only, since in that instance we do not need to worry about isotope effects which are known to be substantial (see above). The effect is summarized in fig. 6 which shows the squeeze-out ratio $R_N = \{N(+90^\circ) + N(-90^\circ)\} / \{N(0^\circ) + N(180^\circ)\}$ as a function of the neutrons' perpendicular momentum. At the highest transverse momenta very high anisotropies are reached, higher than ever observed for baryons before. Fig. 6 (left part) shows that at all bombarding energies

Figure 4: Enrichment of hydrogen ions by means of the energy deposited in the LAND detector. For details, see text.

Figure 5: Coefficients of 2^{nd} -order Legendre polynomials for neutrons (circles) and particles in the p-cut of fig. 4 (squares), in the d-cut (diamonds), and in the t-cut (asterisks).

Figure 6: Squeeze-out ratio for neutrons as a function of perpendicular momentum at $E_{proj}=400$ MeV/u (circles), 600 MeV/u (squares), and 800 MeV/u (diamonds). An E_{rat} -cut was applied which selects impact parameters of about 7 ± 3 fm.

Figure 7: Squeeze-out ratio for neutrons as a function of bombarding energy. An E_{rat} -cut was applied which selects impact parameters of about 7 ± 3 fm. The left part shows R_N for neutrons with $p_t=390$ MeV/c (circles), $p_t=470$ MeV/c (squares), and $p_t=550$ MeV/c (diamonds) in bins of 80 MeV/c. The right part shows R_N for neutrons with $p_t=0.9 \cdot p_{proj}$, $p_t=1.1 \cdot p_{proj}$, and $p_t=1.3 \cdot p_{proj}$, respectively.

the maximum values of R_N are the same, but they are reached at different transverse momenta: With increasing energy, the squeeze-out signal is shifted to increasingly higher p_t . The effect becomes even more striking if the transverse momentum of the neutrons is not measured in absolute numbers, but in fractions of the projectile momentum: The dependence of R_N on p_t leads to a universal curve, independent of bombarding energy, as shown in the right part of fig. 6. We are thus led to a new interpretation of the excitation function: The latter has been shown to decrease with energy, if no cuts on p_t are applied (fig. 12 from [10]). This situation corresponds to an acceptance cut on p_t in absolute values, and the result is reproduced if more detailed cuts are applied (left part of fig. 7). However, if the cut on p_t is implemented in units of projectile momentum, the excitation function of R_N becomes flat (right part of fig. 7).

These findings remind one of the scaling laws of non-viscous fluid dynamics. We need to point out, however, that the effect is clearly observed in a fairly narrow impact parameter range where the squeeze-out signal is large, but the signature gets less clear if we go to smaller b , although indications of the effect remain.

COMPARISON TO THEORY

In an attempt to interpret our data quantitatively, we compared them to microscopic calculations in the framework of quantum molecular dynamics (QMD) [11]. Since we are discussing the behaviour of neutrons, we chose the recently developed version of IQMD [12] which keeps track of isotopic spin. We restricted ourselves to two versions which both contain momentum dependent interactions, but use different compressibilities of infinite nuclear matter ('hard' and 'soft' equation of state). The

Figure 8: Squeeze-out ratio for neutrons as a function of perpendicular momentum at $E_{proj}=400$ MeV/u (top) and 600 MeV/u (bottom). An E_{rat} -cut was applied which selects impact parameters of about 7 ± 3 fm. Circles: experimental data, squares: QMD results with hard EOS, triangles: QMD results with soft EOS.

results of the calculations were filtered event-wise by the acceptance of the LAND- and FOPI-detectors, and then treated exactly like data: E_{rat} was used to cut on the impact parameter, the total transverse momentum was used to re-determine the reaction plane, and azimuthal distributions of neutrons were analyzed strictly analogous to the experimental data. The result of the comparison is shown in fig. 8: At 400 MeV/u, both versions of IQMD fit the data very nicely, however, at 600 MeV, the calculations are not able to reproduce the p_t -dependency of the squeeze-out signal. The experimental values are rising with p_t , whereas the calculated values show the opposite behaviour. As of this writing, the reason is unclear, and detailed investigations of the model are under way.

Until now, we have been dealing with squeeze-out which is related to collective flow perpendicular to the reaction plane. We have shown that in a certain impact parameter range, the squeeze-out signal scales with projectile momentum. Naturally, the question arises whether a similar behaviour can be found in other observables pertaining to collective effects. In particular, it is interesting to look at the 'flow parameter' F , i.e. the slope of the $\langle p_t \rangle$ - y curve at $y=y_{cm}$. $\langle p_t \rangle$ is the transverse momentum in the reaction plane, averaged over the particles of the event. At a given bombarding energy, F goes through a maximum if plotted versus impact parameter. A preliminary excitation function of the maximum F_{max} for the system $^{197}\text{Au} + ^{197}\text{Au}$ has been presented by the EOS collaboration [13]. It is rising continuously if $\langle p_t \rangle$ is measured in absolute values, whereas scaling of $\langle p_t \rangle$ with p_{proj} yields a value of $\approx 30\%$ independent of energy (see fig. 9). Thus the flow of $\langle p_t \rangle$ in the reaction plane exhibits the same scaling behaviour as the flow out of the reaction plane. This kind of scaling has been investigated earlier for the in-plane flow ([14]) in the frame work of hydrodynamical models, but our observation of this phenomenon for the out-of-plane flow calls for more quantitative calculations.

Figure 9: Maximum flow parameter versus bombarding energy for the system $^{197}\text{Au} + ^{197}\text{Au}$. For details, see text.

SUMMARY

In summary, we have presented a detailed investigation of the squeeze-out effect for the $^{197}\text{Au} + ^{197}\text{Au}$ system in the energy range $400 \text{ MeV/u} \leq E_{proj} \leq 800 \text{ MeV/u}$. We have shown that the effect is the same for neutrons and protons, which means that the Coulomb force – despite its long range – does not have a significant effect on the observables of collective flow. The size of the squeeze-out signal depends on the transverse momentum of the particles observed. The p_t -dependence scales with the momentum of the projectile such that a plot of R_N versus p_t/p_{proj} leads to a universal curve, at least for large impact parameters where the signal is large. This scaling behaviour for out-of-plane momentum flow is also found for in-plane momentum flow as measured by the slope of the $\langle p_t \rangle - y$ -curve at $y=y_{cm}$, and detailed comparisons to microscopic as well as macroscopic calculations seem necessary for an understanding of this effect.

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