Exclusive Studies of Neutron and Charged Particle Emission in Collisions of ^{197}Au + ^{197}Au at 400 MeV/Nucleon

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We present data on collective flow of neutrons in collisions of ^{197}Au+^{197}Au at 400 MeV/nucleon. The azimuthal distribution about the beam axis is investigated with respect to the reaction plane as determined from light charged particles. The "squeezeout" of neutrons, perpendicular to the reaction plane, is observed for the first time. Quantitative agreement to a high level of accuracy is found between the behavior of neutrons and hydrogen ions.

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The determination of the equation of state (EOS) of nuclear matter is one of the central themes in experiments with relativistic heavy ions. It is hoped that such experiments will help determine the parameters of the EOS and provide data relevant to astrophysics which are not directly available from astronomical observation. An important feature of relativistic heavy-ion collisions is the collective behavior of nuclear matter at energies far above the Fermi energy. This has been clearly established experimentally and many aspects of collectivity (side splash, bounceoff, squeezeout) have been investigated [1-4]. However, all of the work of Refs. [1-4] was done with charged particles only. It is very intriguing to look at neutral particles—and neutrons in particular—which do not feel the long-range Coulomb force and might provide less disturbed information from the participant zone of a relativistic heavy-ion collision. Preliminary data have been reported on the in-plane transverse momentum p_t of neutrons as a function of rapidity y [5]. These data were obtained for the system ^{197}Au+^{197}Au at 150, 250, and 400 MeV/nucleon, and they showed an increase of the flow parameter, i.e., the slope of the p_t-y curve, with increasing projectile energy.

The determination of global quantities like the centrality of a collision or the reaction plane requires good solid angle coverage by an azimuthally symmetric detector with high granularity and good spatial as well as time resolution. For neutrons, it is not possible to meet within reasonable cost all of these requirements at the same time. However, if the global quantities are given by charged particles, they can be correlated with the properties of neutrons from a limited solid angle, and information on the neutrons' collective behavior is obtained. This report presents results on the collective flow of neutrons in collisions of ^{197}Au+^{197}Au at 400 MeV/nucleon. The data were taken in a joint experiment of the Large Area Neutron Detector (LAND) with the FOPI spectrometer performed at the heavy-ion synchrotron SIS of the GSI, Darmstadt. The experimental setup is shown schematically in Fig. 1 and detailed descriptions of the two detector systems are given in Refs. [6,7]. In the FOPI spectrometer (phase I), velocity vectors and charge numbers of charged particles are determined in the forward hemisphere of the c.m. system, and from these quantities the

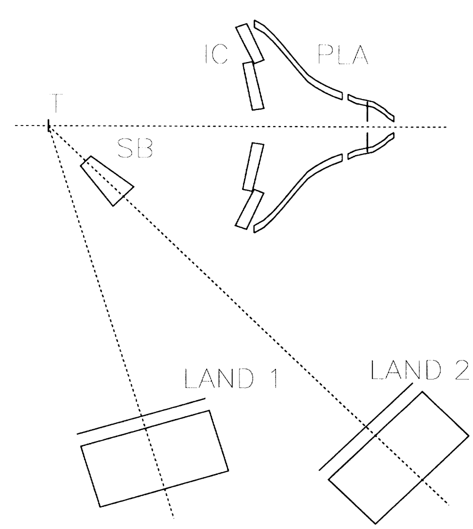

FIG. 1. Setup of the joint experiment of LAND and the FOPI spectrometer (phase I). The latter detects charged particles at $1° \leq \theta_{lab} \leq 30°$ with full coverage of the azimuthal angle. PLA indicates the internal and external plastic wall of scintillators; IC indicates a shell of ionization chambers for detection of heavy, slow clusters. For details, see Ref. [7]. The two halves of LAND are positioned at $\theta_{lab}=45° \pm 8°$ and $\theta_{lab}=73° \pm 12°$, respectively. The figure gives as an example the setup for a shadow bar (SB) measurement with LAND 2.

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centrality and the reaction plane can be derived event by event. The LAND is a time-of-flight spectrometer which has been optimized for the detection of high-energy neutrons: large efficiency ($\geq 80\%$ for $E_n \geq 400$ MeV), excellent spatial and time resolution ($\Delta x = 7$ cm and $\Delta t = 550$ ps FWHM), and good resolving power for many-particle events up to multiplicities of about 5 particles per event. For the experiment described here, the LAND was split into two subsystems with half the depth of the complete detector, covering a larger solid angle (1.9% of 4π) at the expense of somewhat lower efficiency. One subsystem was positioned at 73° (LAND 1), the other one at 45° (LAND 2) with respect to the beam axis. The distances to the target were 5 and 7 m, and the two halves covered about $\pm 12°$ and $\pm 8°$ in polar and azimuthal angle, respectively. In front of each subsystem, a plane of plastic scintillator strips was placed which permitted the identification of charged particles by energy loss versus time of flight with spatial and time resolution comparable to that of the neutron detector.

The two subsystems of the LAND consisted of five planes with twenty paddles each featuring a multilayered structure of passive iron converter and active scintillator material. The scintillation light is read out at both ends of each paddle. Mean timing provides the time of flight, the time difference yields the position, and the geometric mean of the energy signals gives the deposited energy. In the following, each set of two valid time and two valid energy signals from one paddle will be called a "hit."

The interaction of any particle within LAND results in electromagnetic and/or hadronic showers. Light is directly produced when charged particles hit the plastic scintillators, whereas neutrons are detected indirectly by means of their showers of secondary charged particles. Since secondary neutrons may travel through several paddles without light production, their showers are not necessarily contiguous. Consequently, complex hit patterns may occur in the neutron detector. The primary task in the evaluation of LAND data is to group all secondary hits produced by one particle into a shower, and to identify the particles using the specific properties of their showers. Hits are assigned to the same shower if they fulfill certain conditions on geometry, time relation, and kinematics.

Particle identification begins with the fastest particles possible, γ rays, which are easily identified by their velocity. Because of the short radiation length of $\simeq 2.5$ cm, γ-induced showers start within the first plane of LAND. If the measured velocity is equal to the velocity of light within twice the resolution, a hit is assigned to a γ ray. Subsequent hits in neighboring paddles are assigned to the same shower, if their relative velocity is within the resolution equal to the speed of light and their lateral distance within the Molière radius.

The Z identification of charged particles is provided by the plastic scintillator strips as described above. A hit in the neutron detector behind, occurring at a later time and at the same position, is taken as a starting point of a shower. The deposited energy in the shower is used to discriminate hydrogen isotopes against pions in the high-velocity domain ($v \geq 0.86c$).

All remaining hits in LAND which cannot be associated with a shower produced by a charged particle or a γ ray are then assigned to neutron-induced showers. The algorithm is based on Monte Carlo simulations of neutron interactions with LAND using the code HETC [8]. When the algorithm for particle identification was applied to the data from ^{197}Au$+^{197}$Au at 400 MeV/nucleon, all parameters describing shower characteristics were varied by as much as a factor of 2 in order to evaluate systematic errors, yet changes in the results were only of the order of a few percent. This is mostly due to the low multiplicity of particles hitting the detector under the present experimental circumstances.

When performing neutron studies, it is necessary to investigate the background which originates from scattering of neutrons from all massive objects within the experimental area and off the concrete walls. To this end, iron shadow bars were inserted between the target and each subsystem 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 which was found to be about 30% for the neutrons in LAND 2 and 10% for the neutrons in LAND 1. For the hydrogen ions, the background was 5% in LAND 2 and negligible in LAND 1, and for helium the background was negligible altogether.

We investigated the azimuthal distributions of neutrons and hydrogen ions in LAND with respect to the reaction plane under various conditions on the centrality of the collision. Both the centrality and the reaction plane of each event were derived from the charged particles in the plastic wall of the FOPI spectrometer: (i) The centrality was determined by the ratio of "transverse" to "longitudinal" energy. For each event, $E_\perp = \sum(p_\perp^2/2m)$ and $E_\parallel = \sum(p_\parallel^2/2m)$ were calculated, and the highest values of $E_{\rm rat} = E_\perp/E_\parallel$ were assumed to select the most central collisions. The data were grouped into five bins of this "energy ratio," with bin names E1 through E5. E5 indicates the highest energy ratios, i.e., the most central collisions corresponding to impact parameters of up to ≈ 3 fm. It has been demonstrated that $E_{\rm rat}$ provides a better cut on central collisions than the participant multiplicity used in earlier work [9]. (ii) 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. The top part of Fig. 2 shows the azimuthal distributions of

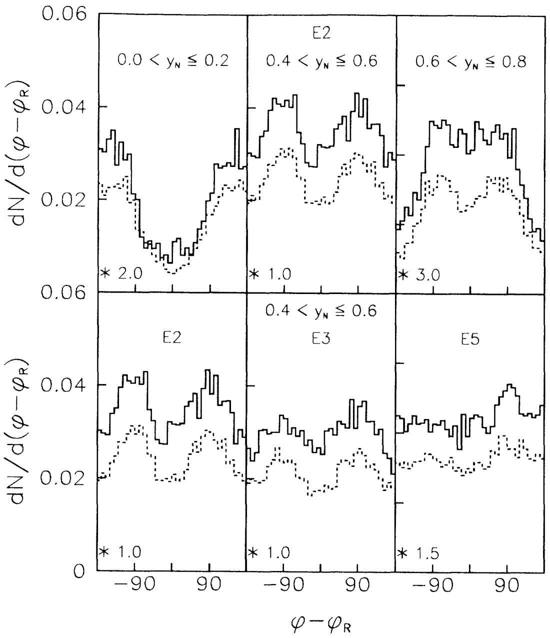

FIG. 2. Top row: Azimuthal distributions of neutrons (solid) and hydrogen ions (dashed) relative to the reaction plane in three bins of normalized rapidity: $0.0 < y_N = y/y_{\rm proj}^{\rm lab} \leq 0.2$, $0.4 < y_N \leq 0.6$, and $0.6 < y_N \leq 0.8$. The reaction plane was determined by the charged particles measured in the FOPI spectrometer. Yields are normalized to the number of central event triggers. The spectra were accumulated on the condition of intermediate centrality (E2). Bottom row: Azimuthal distributions of neutrons (solid) and hydrogen ions (dashed) relative to the reaction plane in three energy-ratio bins, E2, E3, and E5, with E5 indicating the highest energy ratio. The spectra were accumulated on the condition of intermediate rapidity ($0.4 < y_N \leq 0.6$). All of the spectra have been multiplied by the indicated factors in order to adjust the different yields to a common scale.

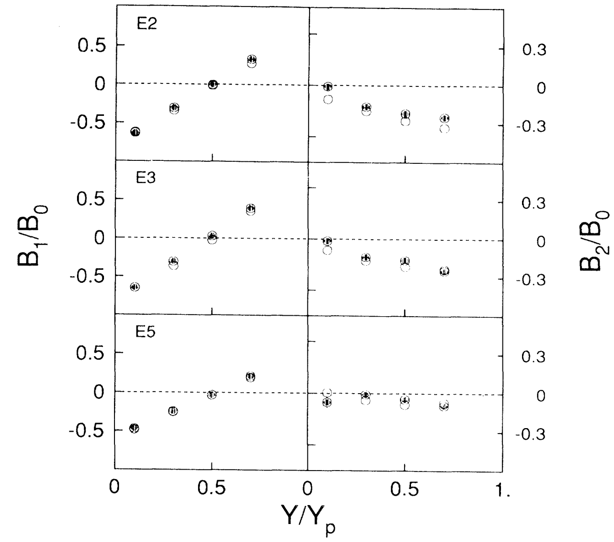

FIG. 3. Results of a fit of Legendre polynomials to the azimuthal distributions shown in Fig. 2 as a function of normalized rapidity. Left column: Normalized coefficient B_1/B_0 of the first-order polynomial in the three energy-ratio bins E2, E3, and E5. Coefficients obtained for neutrons are represented by filled circles and coefficients for hydrogen ions by open circles. The statistical errors are less than the size of the symbols. Right column: Normalized coefficient B_2/B_0 of the second-order polynomial in the three energy-ratio bins E2, E3, and E5.

neutrons and hydrogen ions in LAND for different regions of particle rapidities, with the rapidities being normalized to the projectile rapidity; i.e., $y_N = y/y_{\rm proj}^{\rm lab} = 0.5$ denotes midrapidity. The data are selected for intermediate centrality (E2). From the forward hemisphere, we present the azimuthal distribution in the rapidity bin $0.6 < y_N \leq 0.8$, which is the highest rapidity bin covered with reasonable statistics due to the angular cut at $\theta_{\rm lab} = 30°$. In that rapidity bin, tendency for alignment at $\Delta\varphi = \varphi_R - \varphi = 0°$ can be noticed; i.e., the particles are emitted preferentially in the reaction plane and on the same side of the beam as the total transverse momentum vector which determines φ_R. In the region of target rapidity ($0.0 < y_N \leq 0.2$), the $\Delta\varphi$ distribution is enhanced in the region of $\pm 180°$; i.e., the particles are also emitted in the reaction plane, but their momenta are opposite to those of the particles in the projectile region. In the bin at midrapidity, the particles are emitted preferentially at $\Delta\varphi = \pm 90°$ which indicates emission perpendicular to the reaction plane, i.e., "squeezeout." It can be seen that the squeezeout of neutrons closely follows that of the hydrogen ions.

The bottom part of Fig. 2 depicts the dependence of the squeezeout in the midrapidity region on centrality: The azimuthal anisotropy is strongest at intermediate centrality, and it disappears as the impact parameter decreases. Again the behavior of neutrons and hydrogen ions is very similar.

In order to obtain a more quantitative comparison between neutrons and hydrogen ions, their azimuthal distributions were fitted with Legendre polynomials $dN/d\Delta\varphi = B_0 + B_1 P_1(x) + B_2 P_2(x)$ with $x = \cos(\Delta\varphi)$. The resulting expansion coefficients are shown in Fig. 3 as a function of rapidity for neutrons and hydrogen ions, normalized with respect to B_0 to facilitate comparisons. The first-order coefficient (left column) reflects the correlation of the particles in the reaction plane as discussed above. The second-order term (right column), on the other hand, reflects the magnitude of squeezeout, i.e., the emission of particles out of the reaction plane. This coefficient vanishes in the region of target rapidity and becomes nonzero in the midrapidity region, and it tends to zero with decreasing impact parameter. Most of the coefficients of neutrons and hydrogen ions are within the error bars the same. We would like to point out that this result is only obtained when the background is properly taken into account, or else differences are found which typically amount to 30% and in extreme cases to a factor of 2.

A similar analysis of azimuthal distributions of neutrons was recently performed by Madey and co-workers [10]. Their results cannot directly be compared to ours, since the data were obtained at smaller laboratory angles ($\theta_{\rm lab} \leq 38°$) in a different rapidity region ($0.85 < y_N \leq 1.10$). With these differences in mind, one can compare their maximum azimuthal anisotropy at $\theta_{\rm lab} \approx 35°$ to ours at $y_N \approx 0.6$, and one finds that the anisotropies are consistent.

To summarize, we have performed a joint experiment of the Large Area Neutron Detector (LAND) with the FOPI spectrometer. One of its objectives was the investigation of the collective behavior of the neutrons without the need of 4π detection. The feasibility of this approach has been demonstrated by the first observation of the so-called squeezeout for neutrons and its comparison to that of hydrogen ions. We deliberately refrained from comparing our data to model calculations, since the presentation of experimental data on collective observables of neutrons is the primary goal of this contribution. We have found that, within the statistical limitations of the data presented here, there are no significant differences in the squeezeout of neutrons and hydrogen ions in ^{197}Au + ^{197}Au at 400 MeV/nucleon. However, many other aspects of the neutrons' dynamical behavior remain to be investigated, like their perpendicular momentum spectra, their production cross sections in different regions of phase space as compared to hydrogen isotopes, or their correlation with polar flow angles.

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