1. Collective Behaviour of Particles

Preface

In the nineteen-seventies a series of experiments at the Lawrence Berkeley Laboratory (LBL) opened a new field of research into the reaction dynamics of heavy-ion collisions. The results of those investigations with close connection to the present thesis are charged-particle flow [Gus84a] and squeeze-out of charged particles [Gut89a]. In the early nineties experiments in the energy domain well above the kinematical limit for pion production were performed at the Gesellschaft für Schwerionenforschung (GSI, Darmstadt). “Mesonic squeeze-out” was found by two independent experimental setups [Ven93, Bri93] at this laboratory. Model calculations of Bass et al. [Bas93c] indicate that rescattering and absorption on spectator matter are responsible for the depletion of the pion distributions in the reaction plane. From this finding it is interesting to look for similar effects for baryons. Therefore, this thesis investigates the connection between collective nuclear flow and shadowing effects by spectator matter.

1.1 Relativistic Heavy-Ion Reactions

During the mid-seventies a first series of experiments with relativistic heavy ions took place at the Berkeley accelerator complex. These made use of relativistic heavy-ion beams from the BevaLac which resulted from the coupling of the synchrotron Bevatron (from 1955) to the Super Heavy-Ion Linear Accelerator (SuperHILAC). By injecting a heavy-ion beam into the Bevatron nuclei could be accelerated to nearly the speed of light ($\beta \leq 0.95; \approx 2 \text{ GeV}/\text{u}$). The experimental setups used were the Plastic Ball [Bad82, Gut89b] and the Streamer Chamber [Str83, San83, Bib83, Kea88, Jia92].

The aim of the early experiments with relativistic heavy-ions was mainly the study of the equation of state of nuclear matter (figure 1.1) [Gre89, Sto86, Stö86]. The equation of state expresses the internal energy of the system as a function of density $\rho$. The total center-of-mass energy per baryon ($E_{\text{cm}}$) is divided into a thermal ($E_{\text{th}}$) and a compressional component ($E_c$). The function $E_c(\rho)$ is defined as the compressional energy at zero temperature and is commonly referred to as the nuclear Equation Of State (EOS). Whereas previously only the ground state of nuclear matter could be studied ($\rho/\rho_0 = 1$), with the upcoming relativistic
1.1. Relativistic Heavy-Ion Reactions

![Diagram of the Equation of State (EOS)]

**Figure 1.1**: The Equation of State (EOS) expresses the internal energy of nuclear matter as a function of density $\rho$. The ground state density $\rho_0$ of nuclear matter corresponds to the minimum of the EOS. $E_{th}$ is the thermal excitation energy per baryon and $E_c$ is the compressional energy per baryon [Kam89].

heavy-ion accelerators the main challenge became the investigation of the EOS at higher densities and higher compressional energies of nuclear matter.

In the mid-eighties the following important topics of relativistic heavy-ion physics were studied by LBL setups: thermalization [Gus84b], cluster production [Gut83] and collective flow [Gus84a], important for this thesis. In the beginning of the nineties several collaborations especially at the GSI investigated charged-particle emission in relativistic heavy-ion reactions [Abb93, Bri93, Bri96, Her93, Kie91, Met93, Mis94, Spe94]. In particular FOPI published several articles on studies of intermediate-mass fragments in Au + Au collisions mainly done at 150 GeV/u [Ala92, Kam93, Jeo94].

The most interesting “Composite-fragment flow” results of the Plastic Ball are recalled in section 1.3. An insight into these results is a prerequisite for the understanding of the forthcoming extended descriptions of collective behaviour of particles.
1.2 Azimuthal Asymmetries in Pion Distributions

The main motivation for the present study originates from the investigation of pion distributions at 1 GeV/u from the Au + Au reaction by Venema [Ven94] for the TAPS collaboration and by the Kaon-Spectrometer (KaoS) collaboration [Bri93]. KaoS published angular distributions for charged pions which show azimuthal asymmetries. The TAPS results on neutral pions, shown in figure 1.2, display an enhancement of neutral pions perpendicular to the reaction plane (azimuthal asymmetry). Expressions like reaction plane and azimuthal angle are explained in the following section. We first deal with the motivation for the research on the collective behaviour of charged particles. The “squeeze-out”-like \( \pi^0 \) distributions, shown in figure 1.2, imply an influence of hadronic matter on these distributions. Various model calculations [Bas93c, Bau91, Gle88, Hah88a, Hah88b, Har94, Li91a, Li91b, Li91c, Li93] investigated pion spectra. Following reference [Bas93c] “mesonic squeeze-out” is caused by absorption and rescattering. The aim of the present thesis is to study the behaviour of charged particles\(^1\) in the same reaction: will we observe the undisturbed collective flow of baryons in the azimuthal angular distributions, or will we be able to infer the influence of cold nuclear matter? If observed, the latter would confirm the pion results of reference [Ven94].

1.3 Dynamical Aspects of Heavy-Ion Collisions

The experiments at the Lawrence Berkeley Laboratory revealed that relativistic heavy-ion collisions are strongly influenced by collective behaviour of the interacting particles in the reaction volume. The reaction zone is primarily defined by the overlap volume of the colliding nuclei. An important geometrical parameter of the reaction mechanism is the impact-parameter vector which points from the center of the one nucleus to the other at closest approach for a linear trajectory. Moreover, this vector and the beam direction span a plane, the so-called reaction plane. Consequently, the centers of the nuclei are situated in the reaction plane. Figure 1.3 (1) illustrates the definition of the reaction plane.

The term rapidity will first be explained before discussing dynamical aspects of heavy-ion collisions in more detail. The rapidity of the particles in the labo-
ratory frame is defined as follows [Gut90]

\[ Y = \frac{1}{2} \ln \left( \frac{1 + \beta_\parallel}{1 - \beta_\parallel} \right). \]  

(1.1)

Here, \( \beta_\parallel \) stands for the longitudinal (parallel to the beam axis) component of the particle velocity \( v/c \). The Lorentz invariance of the rapidity is the advantage of this additive quantity. Midrapidity \( (y_{cm}) \) is the value for the rapidity of the center of mass of the reaction system. It corresponds to a value \( Y = 0.677 \) at 1 GeV/u for a symmetric collision as used for the present study (Au + Au). For this type of collisions a scaling to midrapidity is convenient

\[ Y_{CM} = Y - y_{cm}. \]  

(1.2)

Equation 1.2 defines the “center-of-mass rapidity”. In this thesis mainly rapidity is used in terms of relative rapidity

\[ Y_{REL} = \frac{Y_{CM}}{y_{cm}} = \frac{Y - y_{cm}}{y_{cm}}. \]  

(1.3)
Figure 1.3: Sketch of collective particle behaviour in heavy-ion collisions. 1) Projectile and target with impact parameter $b \neq 0$ spanning the reaction plane. 2) Squeeze-out of particles perpendicular to the reaction plane. 3) Charged-particle flow of the participants as well as bounce-off of the spectators in the reaction plane. The flow direction is given by the big arrows. The spectator remnants are directed into angles varying around the flow direction (bounce-off). [Gut91].

Midrapidity $y_{cm}$ results in the values $Y_{CM} = 0$ and $Y_{REL} = 0$. The target rapidity $y_T$ is found at $Y = 0$, $Y_{CM} = -0.677$ and $Y_{REL} = -1$. Similarly we obtain the values for the projectile rapidity $y_P Y = 1.354$, $Y_{CM} = +0.677$ and $Y_{REL} = +1$. For symmetric collisions the advantage of the scaled (equation 1.2) and the relative (equation 1.3) rapidities is obvious.

Dynamical aspects of heavy-ion collisions are classified by their orientation with respect to the reaction plane. Collective effects like transverse particle "flow" [Gus84a] in the reaction plane and "squeeze-out" [Gut89a] of nuclear matter perpendicular to this plane have been observed. These effects are depicted in figure 1.3 and are described in the following paragraphs.

The charged-particle flow [Gus84a] as the first sort of collective behaviour of
nuclear matter, discussed in the context of this thesis, is illustrated by the following scenario. In the initial stage of the heavy-ion collision the two nuclei can be represented by two independent fermi spheres (figure 1.3 (1)). The nuclei hit each other. As a consequence of the compression in the overlap volume of the colliding nuclei a high-density region develops. When the high-density region is built up the nucleons in the reaction zone get pushed sidewards by nucleon-nucleon collisions (kinetic pressure) and repulsion of the density-dependent potential. These nucleons flow away sidewards from the participant region under the so-called flow angle (figure 1.3 (3)). Therefore, this specific flow is also referred to as sideward flow. The flow angle gives information on the repulsive forces in the high-density zone of the reaction. Measurements of the flow angle were first published by the Plastic Ball group [Gus84a]. The analysis of transverse-momentum flow done by Kampert [Kam86] is presented in figure 1.4. Here, the mean transverse momentum in the reaction plane as a function of rapidity describes the flow for Au + Au reactions at an incident beam energy of 200 MeV/u. This kind of measurement averages over all particles and is insensitive to the azimuthal-angle information. In figure 1.4 is shown the average ratio of momenta in the reaction plane divided by the momenta which are azimuthally averaged. Furthermore, it is worthwhile to note the fact of bending of the curve towards higher rapidity values, depicted in figure 1.4. This can be interpreted as an influence of the spectator matter. The strength of the flow can be visualized by the azimuthal distributions of the particles emitted relative to the reaction plane, which is determined per event. The flow strength is depicted in figure 1.5 for the same reaction [Gut89b]. The steepness of the curves corresponds to the flow strength. The idea of studying flow by azimuthal distributions is adopted in this thesis for a more detailed analysis. The azimuthal distributions reveal more details of the collective behavior of the particles than the data based on the mean transverse momenta.

In figure 1.3 (2) another dynamical effect, the “bounce-off”, as well as the flow of charged particles are sketched. The pictorial description of the heavy-ion-collision scenario will be evoked again to give a good insight into this phenomenon. After projectile and target nucleons hit each other, the participants (nucleons in the reaction zone) flow sidewards. The spectators, initially oriented next to the participating regions but outside the overlap- and therefore reaction-zone, suffer a collective deflection. The mean additional momentum the spectator fragments get is reflected in the bounce-off angle, which is smaller than the flow angle. Both effects, the bounce-off of the spectators as well as the transverse flow of the participants are situated in the reaction plane.

We finally discuss a head-on collision with the impact parameter \( b = 0 \). In that case the collective particle flow would appear as a radially symmetric disc around the beam axis. Hydrodynamic calculations showed this emission pattern [Sch74]. At \( b \neq 0 \) the symmetric disc gets divided into the known collective particle flow
Figure 1.4: Transverse-momentum flow observed by the Plastic Ball. The average fraction of the transverse momentum in the reaction plane is shown for different fragments as function of rapidity for Au + Au reactions at 200 MeV/u [Gut89b].

in the reaction plane (main contribution; figure 1.3 (3)) and perpendicular to the reaction plane the “squeeze-out” of particles [Gut89a] (as a remnant of the symmetric \( b = 0 \) disc; figure 1.3 (2)). This is the consequence of the asymmetry \( b \neq 0 \) in the entrance channel. This description reflects one of the possible scenarios for the interpretation of the squeeze-out effect of baryons.

For pions one encounters a different situation [Bas93c] due to enhanced absorption on target and projectile spectator matter in the reaction plane. In contrast, the absorption is the smallest perpendicular to the reaction plane. Here, no spectator matter obstructs the pions. This allows “mesonic squeeze-out” perpendicular to the reaction plane as an additional particle-emission pattern.

Charged-particle flow is analysed quantitatively by the azimuthal distribution of particles relative to the reaction plane. Squeeze-out of baryons, as well as of mesons, is shown by this type of spectra, too (for charged particles: figure 1.6) [Gut89b].

1.4 Collective Motion and Shadowing

The absorption of particles on target and projectile spectator matter in the reaction plane was mentioned before as a possible interpretation for the effect of “mesonic squeeze-out” observed in nuclear reactions. This idea of spectator mat-
1.4. Collective Motion and Shadowing

Figure 1.5: Flow observed in azimuthal distributions of particles relative to the reaction plane (Au + Au, 200 MeV/u). On the left the flow is shown for peripheral events (MUL2) and on the right for semi-central events (MUL4). From top to bottom distributions are plotted for particles with charge $Z = 1, 2, 3$ and 6. The data are selected for two different rapidity intervals $0.32 < Y \leq 0.42(\star)$ and $0.52 < Y \leq 0.62(\times)$ [Gut89b].

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Figure 1.6: Azimuthal distributions of baryons relative to the reaction plane. Left: backward-, center: mid- and right: forward-rapidity regions. The center plot shows the squeeze-out which manifest itself by a peak at $90^\circ$. $90^\circ$ stands for out of plane emission. The left and the right panel show the effect of flow. (Au + Au, 400 MeV/u) [Gut89b].

anism which allows to form composites out of nucleons, e.g., combination of a proton and a neutron to a deuteron. Coalescence is described in more detail in chapter 2. Figure 1.7 shows a spatial representation of participant shadowing by spectator matter. Also sketched are the top and various side views on the reaction plane with special attention to the shadowing effect.

In figure 1.8 the transition from pure coordinate space (figure 1.7) to phase space is introduced by a representation of shadowing by spectator matter. The phase space is spanned by the rapidity of fragments and their momenta. As long as participants and spectators move with velocities of the same order (in figure 1.8: crossing of flow axis (participants) and bounce-off axis for spectators) interactions of particles from the reaction zone with fragments from the cold periphery become possible. This is valid before the final state of the reaction is reached. Furthermore, in figure 1.8 the vector $\vec{Q}$ is introduced. $\vec{Q}$ is the sum of the transverse momenta of all particles. In chapter 4 the orientation of the reaction plane is measured by means of analyzing $\vec{Q}$. 
Figure 1.7: Sketch of shadowing by spectator matter. A) top view of the reaction plane and the nuclei; the spectator matter is indicated by hatched areas. B) spatial presentation. C) side view of the colliding nuclei and the reaction plane in impact-parameter direction. D) front view of the colliding nuclei and the reaction plane in beam direction.
1.5 The Instrument

The investigation of collective behaviour of light charged particles makes exclusive measurements necessary. Impact-parameter selections and the analysis of sections of azimuthal angles are the main techniques used here.

The detector system which was employed for the present charged-particle studies was designed to measure photons mainly for pion reconstruction by invariant-mass analysis. For the development of this detector in 1987 an international collaboration of nuclear physics research groups was founded. Physicists from GSI and the two German Universities of Gießen and Münster joined in the so-called “High-Energy-Photon Collaboration” to design and exploit the Two-Arm Photon Spectrometer (TAPS) \(^2\) [Tap87]. The collaboration was joined at an early stage by the institute Grand Accélérateur National d’Ions Lourds (GANIL at Caen) and the Kernfysisch Versneller Instituut (KVI at Groningen). In 1990 TAPS was finished in time to measure with the first heavy-ion beams from the GSI heavy-ion synchrotron SIS \(^3\). In addition to the investigation of photon and neutral-meson production in heavy-ion reactions in the 1 GeV/u energy domain, TAPS provides the possibility to measure charged particles and thus to yield important information on their rapidity distributions and transverse momenta at backward rapidity.

\(^2\)Later the name of the instrument was also used as collaboration name (see section D for the collaboration list at the time of the experiment).

\(^3\)SIS = Schwerionen Synchrotron.
At GSI, nuclear physics in the energy regime of relativistic heavy-ion collisions \( (E/mc^2 \approx 1) \) uses the linac machine UNILAC as a pre-accelerator for the heavy-ion synchrotron SIS. UNILAC stands for UNIversal Linear ACcelerator. This accelerator has the capacity to accelerate nearly all existing elements up to energies of 18 MeV/u. The UNILAC-SIS combination can push these up to 2 GeV/u and accelerates projectiles up to the mass of uranium. Furthermore, the GSI facility offers some features which are necessary for a heavy-ion experiment if selective particle triggers are used. These features are a sufficient high particle current density and a good energy resolution.

### 1.6 Outline of this Thesis

After this introductory chapter the tools to handle the physics of this thesis are discussed in chapter 2. In this chapter various theoretical models needed for the interpretation of the experimental data are discussed. These include the Isospin Quantum Molecular Dynamics (IQMD) code [Har92, Har93], the Dubna-Cascade Model (DCM) [Gud78, Gud79, Ton83] and the Perpendicular Emitting Thermal Source parameter model (PETS) [Kug95].

A comprehensive review of the detectors, the setup and the experiment are the subjects of chapter 3. In particular emphasis is laid on the description of the two independently designed and operated detector systems TAPS and the Forward Wall of the FOur PI (FOPI \(^4\))-collaboration at GSI. For the first time in July 1991 a Au beam of 1 GeV/u from the SIS accelerator was used for a combined experiment of TAPS with the Forward Wall. This thesis describes this experiment and discusses the related analysis. The joint setup of TAPS with the Forward Wall allows a selection of neutral meson [Ven94] and charged-particle spectra. The Forward Wall is used in this thesis for event characterization while it is possible with TAPS to identify the charged particles and to measure their energy spectra as a function of the azimuthal angle.

In chapter 4 the conversion from the raw data to physical observables is described. This starts with the data calibration for both detector systems, TAPS and the Forward Wall. After that the data have to undergo necessary corrections. TAPS data are corrected for reaction losses and Forward Wall data for hit-acceptance inefficiencies. Finally, the physically meaningful variables can be extracted. The important capability of the Forward Wall is the reaction-plane determination. The reaction plane is determined from the azimuthal asymmetry of the charged-particle distributions. For TAPS the charged-particle identification and isotope separation are discussed extensively. At the end of chapter 4 the

\(^4\): 4\(\pi\) depicts the coverage of the whole 4\(\pi\) sphere in phase II of the project.
procedure to combine the two independently designed analysis program packages is given. In the thesis of Venema [Ven94] a more straight-forward method for the impact-parameter determination by means of information obtained from the Forward Wall is applied. In chapter 4 this method is compared to the one adopted here for the charged-particle analysis. The current reaction-plane analysis makes use of the full information of the Forward Wall.

The collective behaviour of light charged particles in the reaction of Au + Au at 1 GeV/u is studied in this thesis. The photon and meson production mechanisms in the same reaction have been studied in earlier works [Sch93, Ven94, Ber94, Sch94, Ven93]. In chapter 5 the particle separation with TAPS is discussed. A good separation of particles is important for this work. Another important aspect is the phase-space coverage of the applied detector systems.

The collective behaviour of charged particles is studied via charged-particle flow, ratios of charged-particle numbers and sideward energy flow. Azimuthal distributions of light charged particles from relativistic heavy-ion collisions have been determined. Collective behaviour of hydrogen and helium isotopes manifests itself as azimuthal anisotropy. From the magnitude of this anisotropy a flow strength parameter is derived. The anisotropy is further studied by analyzing the ratios of the azimuthal distributions for different fragment isotopes. From these ratio distributions the mean charged-particle ratios are determined.

Angular sections from the azimuthal distributions are chosen to investigate the behaviour of hydrogen isotopes. This analysis reveals the influence of shadowing by spectator matter (chapters 5 and 6).

In chapter 6 the interpretation of the experimental results is made by comparison to model calculations. The comparison of particle spectra, like kinetic energy, allows to judge whether the proper nucleon-nucleon dynamics and cross sections are implemented in microscopic model calculations. After that, flow strength parameters can be derived from azimuthal distributions of light charged-particle isotopes. The analysis of baryon distributions selected in or perpendicular to the reaction plane is sensitive to the collective particle-emission pattern known as "collective particle flow" (section 1.3). Restrictions on extraction of entropy from particle ratios [Dos85, Dos88] are discussed, based on these distributions. One of the main issues addressed in this thesis is the interpretation of sideward energy flow spectra due to shadowing by spectator matter. For that purpose the experimental data are compared to results of the model calculations introduced in chapter 2. The adoption of detector acceptance filters to the models is discussed in this context.