ELSEVIER

9 December 1999

PHYSICS LETTERS B

Physics Letters B 469 (1999) 30–36

Elliptic emission of K^+ and π^+ in 158 $A \cdot$GeV Pb + Pb collisions

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PII: S0370-2693(99)01289-7

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Received 21 September 1999; received in revised form 25 October 1999; accepted 29 October 1999
Editor: L. Montanet

Abstract

An event-by-event analysis of the azimuthal angular correlation with respect to the reaction plane has been carried out for K^+ and π^+ emission near mid-rapidity in 158 $A \cdot$GeV Pb + Pb collisions. In semi-central collisions, K^+ mesons are found to be preferentially emitted out of the reaction plane, while π^+ mesons are emitted in the reaction plane. The results suggest that the kaon emission is influenced by in-medium potential effects in addition to collective flow effects.

1. Introduction

Relativistic heavy ion collisions provide a unique tool for the study of nuclear properties at high temperature and density. The study of collective motion in the final state of the produced hadrons is expected to provide information on both the dynamics of heavy-ion collisions and the equation of state [1]. The observation of collective behavior in the system provides a validation of a hydrodynamical description of the dynamics. Once a hydrodynamical interpretation is established the collective motion will result from pressure gradients in the matter, which will reflect the compressibility of the underlying equation of state. In the case of a phase transition from ordinary matter to quark-gluon plasma, it is expected that the compressibility should exhibit a softening due to the increased number of degrees of freedom [2].

A standard way to search for collective motion in the final state is to analyze the azimuthal distribution of particle emission with respect to the reaction plane in terms of a Fourier expansion. The first two coefficients in the Fourier decomposition are termed the directed and elliptic flow components. The importance of collective motion measurements has been emphasized by several authors [2–5] and measurements have been reported over a range of energies; directed and elliptic flow at $0.1 \sim 1$ $A \cdot$GeV [6–9], at 10 $A \cdot$GeV [10] and also at 158 $A \cdot$GeV [11,12]. One of the striking features of these results is the change of the elliptic flow direction from out-of-plane (squeeze-out) to in-plane in the region between 1 $A \cdot$GeV and 100 $A \cdot$GeV incident energy.

The azimuthal distribution of a particular particle species in the final state is also expected to be sensitive to the in-medium potential of the particle. Namely, it is interesting to study the distributions of K^+ and K^- mesons because the kaon-nucleon potential in nuclear matter is expected to be repulsive for K^+ but attractive for K^- mesons [13–15].

Recently, the elliptic emission of nucleons, pions, and K^+ mesons has been observed in the mid-rapidity region in $0.8 \sim 1$ $A \cdot$GeV ^{197}Au + ^{197}Au and ^{209}Bi + ^{209}Bi collisions [7–9]. The observed out-of-plane emission of K^+ mesons is claimed as a consequence of the repulsive K^+-nucleon potential. On the other hand, pions and nucleons also show out-of-plane emission at this energy, which is interpreted as dominantly due to the shadowing effect of the spectator nucleons [7,16,17].

At higher incident energies, particles produced near mid-rapidity are not expected to interact with the spectator matter due to the short crossing time of the collisions. Therefore, the in-medium potential effects might be more clearly visible at SPS energies [18]. In this letter we present the azimuthal distributions, relative to the reaction plane, of K^+ and π^+ mesons near mid-rapidity in 158 $A \cdot$GeV Pb + Pb collisions. This is the first observation of the elliptic emission of K^+ mesons at SPS energies.

2. Experimental setup

The data presented here were taken with a subset of the WA98 experiment detector system using the 158 $A \cdot$GeV ^{208}Pb beams of the CERN-SPS on a Pb target of 213 μm thickness. In the WA98 setup the incident Pb beam provides a trigger by a valid signal in a gas Cherenkov start counter with a timing resolution of 30 ps and no signal in a downstream veto counter with a 3 mm diameter hole. The minimum bias trigger and centrality of the collision is determined by the total transverse energy, E_T, measured with the mid-rapidity calorimeter (MIRAC) which covers the pseudo-rapidity range of $3.5 < \eta < 5.5$. The Plastic Ball detector has full azimuthal coverage in the pseudo-rapidity range of $-1.7 < \eta < 0.5$. It identifies pions, protons, deuterons, and tritons with kinetic energies of 50 to 250 MeV by simultaneous ΔE and E measurement using the mass and energy dependence of dE/dx [11]. The measurement of identified particles near mid-rapidity is performed using two tracking spectrometer arms with a large (1.6 m) aperture dipole magnet (GOLIATH) which provides 1.6 Tm bending power. The particle identification is based on a measurement of momentum and time-of-flight.

The present analysis has been performed on the full sample of WA98 positive charged particle tracking arm data. This data sample is limited due to the fact that the positive charged particle tracking arm was installed only for the final run period of WA98. The tracking arm has a momentum resolution of $\Delta p/p \simeq 0.97\% + 0.16\% p + 0.023\% p^2$ (p in GeV/c) and a time-of-flight resolution of $<$ 90 ps. The rapidity and transverse momentum (y, p_T) coverages of the Plastic Ball and the tracking arm are shown in Fig. 1. The (y, p_T) coverages for the

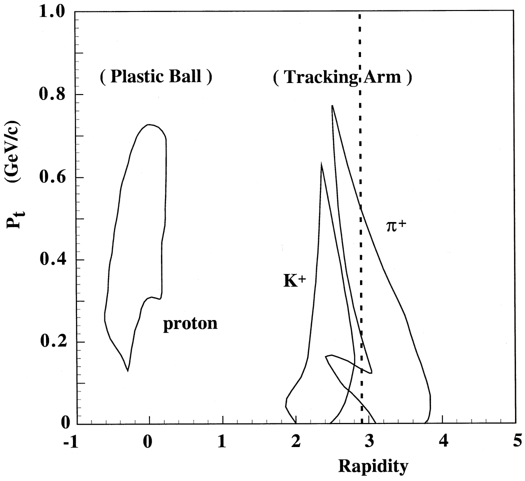

Fig. 1. The rapidity and transverse momentum (y, p_t) coverages of the Plastic Ball detector and the tracking arm. The midrapidity of the collisions is shown as dashed line.

Table 1
Results of the Fourier analysis of K^+ and π^+ mesons for semi-central 158 A·GeV Pb + Pb collisions. The values are integrated over the indicated y and p_T ranges. Positive v_1 corresponds to an emission in the same direction as nucleons. Observed negative value of v_1 for π^+ indicates so-called anti-flow of pions. Positive and negative v_2 corresponds to an in-plane and out-of-plane elliptic emission, respectively. The values are obtained numerically by evaluating $\langle\cos(\phi - \Phi_0)\rangle$ and $\langle\cos(2(\phi - \Phi_0))\rangle$, with corrections of the reaction plane resolution at each E_T bin. The errors include the statistical errors and the errors of the experimental resolution of the reaction plane determination

Particle	y	p_T (GeV/c)	v_1	v_2
K^+	2.2–2.8	0.05–0.60	-0.004 ± 0.031	-0.24 ± 0.14
π^+	2.4–3.4	0.05–0.80	-0.010 ± 0.006	0.047 ± 0.024

present analysis are listed in Table 1. Detailed information about the positive tracking arm [20] and the experiment can be found elsewhere [11,19].

3. Experimental results

The reaction plane is determined from the azimuthal direction of the total transverse momentum vector of fragments (p, d, and t) observed by the Plastic Ball detector [11]. The azimuthal angle of the reaction plane, Φ_0 in the laboratory is determined as

$$\Phi_0 = \tan^{-1}\left(\frac{\sum_{i=1}^{N} p_{Ti}\sin(\phi_i)}{\sum_{i=1}^{N} p_{Ti}\cos(\phi_i)}\right), \tag{1}$$

where the sum runs over all fragments. Here ϕ_i and p_{Ti} are the azimuthal angle in the laboratory and the transverse momentum of the i-th fragment, respectively. The multiplicity of protons in the Plastic Ball detector is around 8 in semi-central collisions and a minimum of three protons is required for this analysis. The Φ_0's accumulated for many events should be uniformly distributed if there is no detector bias. The observed Φ_0 distribution has a variation of less than 2% due to the detector biases such as dead channels and inefficiency. In the following analysis, we have corrected for this effect by weighting with the inverse of the yield although there is no significant difference in the results obtained with or without this correction.

The angular correlation between the azimuthal angle ϕ of K^+ and π^+ near mid-rapidity and the Φ_0 determined in the target rapidity region has been studied. Since the acceptance of π^+ crosses mid-rapidity, Φ_0 was rotated by 180° for particles in the region forward of mid-rapidity. Otherwise, the extracted value of the directed flow would be underestimated since it changes sign at mid-rapidity. Fig. 2 shows the azimuthal distributions of K^+ and π^+ mesons with respect to the reaction plane for semi-central ($50 < E_T < 250$ GeV in MIRAC) and central ($320 < E_T < 500$ GeV) Pb + Pb collisions. For π^+ mesons in semi-central collisions, the azimuthal distribution indicates weak maxima at $\phi - \Phi_0 = 0°$ and $\pm 180°$, which indicates an enhanced emission in the reaction plane. On the other hand, the K^+ azimuthal distribution in semi-central collisions exhibits maxima at $\phi - \Phi_0 = \pm 90°$ which demonstrates an enhanced emission out of the reaction plane. Although the statistics is limited, the results provide evidence that the K^+ emission axis is orthogonal to the in-plane emission axis of the π^+. In central collisions, as shown in Fig. 2, the azimuthal distributions for both particle types are nearly flat, as expected from the near azimuthal symmetry of the collision system at small impact parameter.

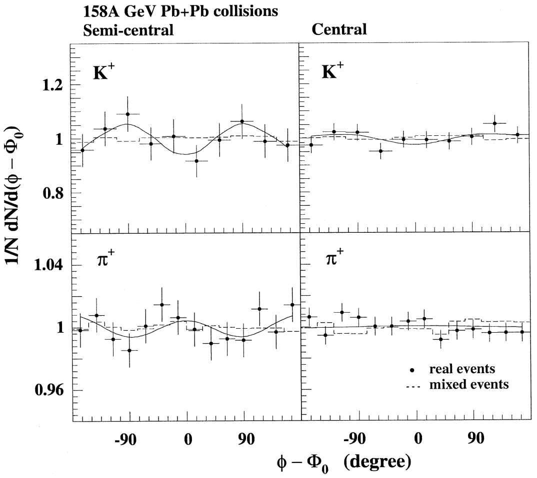

Fig. 2. The azimuthal distributions of K^+ and π^+ mesons with respect to the reaction plane for semi-central and central 158 A·GeV Pb + Pb collisions. Solid circles with error bars show the real events and dashed histograms show the results of the mixed events. The solid curves show the fits using Eq. (2). The (y, p_T) coverages for this analysis are listed in Table 1.

To test for detector effects, such as geometrical acceptance and detector efficiency, fake events were created using a mixed-event method which were then analyzed in the same manner as the real events. The mixed-event results are shown as histograms in Fig. 2. The azimuthal distributions for the mixed-events are flat which indicates that the observed anisotropies are not due to detector effects.

The strength of the azimuthal anisotropy is evaluated by means of a Fourier expansion [21,22]. The Fourier coefficients $v_n\,(n=1,2)$ can be extracted from the azimuthal distribution of identified particles with respect to Φ_0;

$$\frac{1}{N}\frac{dN}{d(\phi-\Phi_0)} = 1 + 2v'_1\cos(\phi-\Phi_0) + 2v'_2\cos\big(2(\phi-\Phi_0)\big), \tag{2}$$

where ϕ is the azimuthal angle of the particle in the laboratory frame. The Fourier coefficient v'_1 quantifies the directed flow, whereas v'_2 quantifies the elliptic flow. Positive v'_1 corresponds to an emission in the same direction as nucleons. (Please note that this definition is opposite to our previous reports [11].) The coefficient v'_2 is negative for an out-of-plane emission and positive for an in-plane emission.

The observed distributions are affected by the experimental resolution of the reaction plane determination. Since the measured Fourier coefficients are reduced by this effect, they should be corrected as [21–23]

$$v_n = \frac{v'_n}{\langle\cos(n\Delta\Phi)\rangle}, \quad (n=1,2), \tag{3}$$

where $\Delta\Phi$ is the deviation from the true reaction plane and $\langle\ \rangle$ indicates the mean value summed over all events. The reaction plane resolution is determined by randomly subdividing the full event into two equal size subevents and extracting $\langle\cos(\Delta\Phi)\rangle \approx \sqrt{2}\cdot\sqrt{\langle\cos(\Phi_a-\Phi_b)\rangle}$, where Φ_a and Φ_b are the azimuthal angles of the reaction plane of two equal size subevents. Using the more accurate interpolation formula of Ref. [22] one obtains $\langle\cos(\Delta\Phi)\rangle = 0.360 \pm 0.018$, $\langle\cos(2\Delta\Phi)\rangle = 0.084 \pm 0.005$ for semi-central collisions.

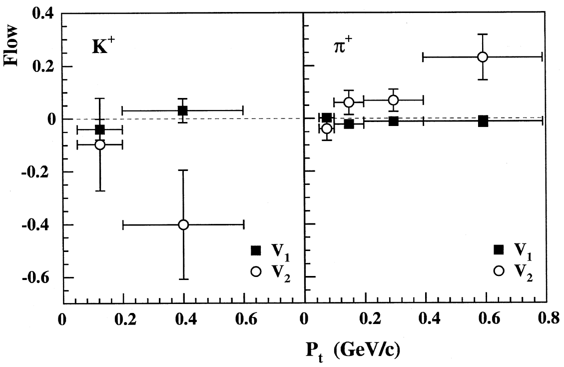

Fig. 3. The p_T dependence of the v_1 and v_2 values of K^+ and π^+ mesons for semi-central 158 $A\cdot$GeV Pb + Pb collisions. The rapidity coverages are listed in Table 1. The results are corrected for the experimental resolution of the reaction plane determination. Solid squares are used for v_1 and open circles for v_2.

The values of the Fourier coefficients $v_n(n=1,2)$ are obtained numerically by evaluating $\langle\cos(\phi-\Phi_0)\rangle$ and $\langle\cos(2(\phi-\Phi_0))\rangle$, respectively. The results for semi-central collisions are listed in Table 1 [1]. The values have been corrected for the reaction plane resolution according to Eq. (3) at each E_T bin. The value of v_1, indicating the strength of the directed flow, is negative for π^+, which corresponds to the direction opposite to the nucleons. This so called anti-flow of pions has been previously reported [11,12]. The value of v_1 for the K^+ meson is compatible with zero. The value of v_2 for the K^+ meson is negative with a 1.7σ separation from zero, while the value of v_2 for the π^+ mesons is positive with a 1.9σ separation from zero. Under the assumption of gaussian errors these results correspond to confidence levels of 95.7% and 97.5% for the assignment of the sign of v_2 for K^+ and π^+, respectively. Although the significance of the result is limited by statistics, one may conclude at the 93% confidence level that the elliptic emission planes for K^+ and π^+ are oriented orthogonally to one another. The systematic errors on the v_2 values due to the contamination from other particle species are estimated to be less than 8% for K^+ and 2% for π^+.

Fig. 3 shows the v_1 and v_2 values as a function of the transverse momentum p_T for K^+ and π^+ mesons in semi-central collisions. For the K^+ data

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[1] One can obtain the values of v_1 and v_2 from fitting the azimuthal distribution with Eq. (2). Within the errors, the fit values agree with those listed in Table 1.

only two bins are shown due to the limited statistics. The magnitude of v_2 for K^+ and π^+ mesons tends to increase with p_T, while the v_1 values remain close to zero for both particles.

4. Discussion

To compare the present results with other measurements the v_2 values for protons, pions, and kaons near mid-rapidity are plotted as a function of the beam energy in Fig. 4. For both protons and pions a transition from out-of-plane to in-plane emission occurs around 5-10 $A \cdot$GeV. At SPS energy, results from NA49 [12] have shown that protons and pions exhibit in-plane emission near mid-rapidity. Our π^+ data agree with the NA49 results within errors. Unlike the case for protons and pions, the present results indicates that K^+ mesons exhibit out-of-plane emission, which is similar to observations for 1 $A \cdot$GeV Au + Au collisions [8].

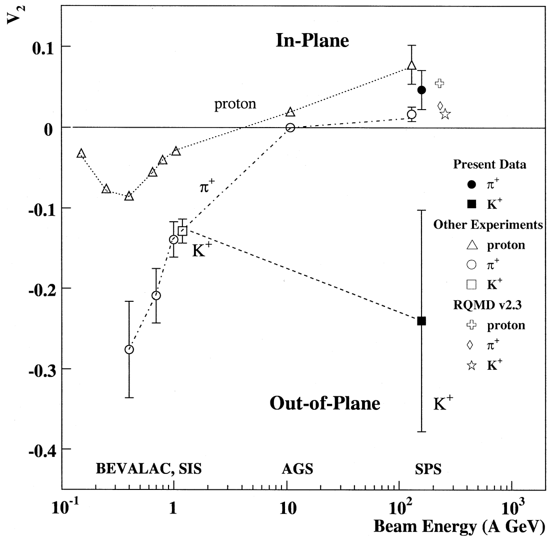

Fig. 4. Beam energy dependence of the v_2 value near mid-rapidity [6–8,10,12]. Solid symbols indicate the present data. Note that the region in (y, p_T) is different for each experiment. The RQMD (v2.3 cascade mode) calculations for proton, π^+ and K^+ in 158 $A \cdot$GeV Pb + Pb collisions are also shown for the impact parameter range $b =$ 6.5–12 fm with the filter of experimental acceptance. The data points are shifted horizontally where they overlap.

Results of RQMD model calculations (v2.3 cascade mode) [24] filtered with the experimental acceptance are also shown in Fig. 4. The RQMD results show in-plane emission for π^+, proton, and also for K^+. The RQMD calculation agrees with the measured results for π^+ and proton, but it fails to reproduce the out-of-plane elliptic emission of K^+. These results might suggest that a new ingredient to the calculation such as the in-medium potentials of the K^+ and K^- mesons is required [13–15]. A simple model calculation [25] in which K^+ mesons propagate through a static anisotropic distribution of nucleons with a repulsive K^+N potential demonstrates that a final out-of-plane elliptic emission pattern can emerge from an initially isotropic azimuthal distribution of K^+.

It is clear that if the azimuthal distribution of the pions reflects their preferential in-plane collective motion, then the out-of-plane K^+ azimuthal distribution would indicate that the kaons carry little direct information about the collective motion of the pion matter. The results therefore appear to question the assumption of a common collective flow velocity for pions and kaons.

5. Summary

In summary, we have measured the elliptic emission patterns of K^+ and π^+ mesons near mid-rapidity in 158 $A \cdot$GeV Pb + Pb collisions. In semi-central collisions, the K^+ mesons are found to be emitted preferentially perpendicular to the reaction plane, while π^+ mesons tend to be emitted in the reaction plane. The RQMD cascade calculation reproduces the v_2 values for π^+ and protons, but it fails to explain the out-of-plane emission of K^+ mesons. The results suggest that the kaon emission is influenced by in-medium potential effects in addition to collective flow effects.

Acknowledgements

We express our gratitude to the CERN accelerator division for the excellent performance of the SPS accelerator complex. We gratefully acknowledge the effort of all engineers, technicians, and support staff who have made possible the construction and operation of this experiment. We thank Dr. T. Maruyama for useful discussions.

This work is supported by the German BMBF and DFG, the US DOE, the Swedish NFR and FRN, the Dutch Stichting FOM, the Department of Atomic Energy, the Department of Science and Technology, and the University Grants Commission of the Government of India, the Indo-FRG Exchange Programme, the Stiftung für Deutsch-Polnische Zusammenarbeit, the Grant Agency of the Czech Republic under contract No. 202/95/0217, the PPE division of CERN, the Swiss National Fund, the INTAS under contract INTAS-97-0158, the Polish KBN under contract 2P03B16815, the Ministry of Science and Technologies of the Russian Federation, the Grant-in-Aid for Scientific Research (Specially Promoted Research & International Scientific Research) of the Ministry of Education, Science, Sports and Culture, JSPS Research Fellowships for Young Scientists and also by the University of Tsukuba Special Research Projects, and ORISE. ORNL is managed by Lockheed Martin Energy Research Corporation under contract DE-AC05-96OR22462 with the US Department of Energy. MIT is supported by the US Department of Energy under the cooperative agreement DE-FC02-94ER40818.

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