Observation of Enhanced Subthreshold K^+ Production in Central Collisions between Heavy Nuclei

D. Miśkowiec, W. Ahner, R. Barth, M. Cieślak, M. Dębowski, E. Grosse, W. Henning,* P. Koczoń, R. Schicker, E. Schwab, and P. Senger
Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany

P. Baltes, Ch. Müntz, H. Oeschler, S. Sartorius, Ch. Sturm, and A. Wagner
Technische Hochschule Darmstadt, D-64289 Darmstadt, Germany

P. Beckerle, Ch. Bormann, D. Brill, Y. Shin, J. Stein, R. Stock, and H. Ströbele
Johann Wolfgang Goethe Universität, D-60486 Frankfurt, Germany

B. Kohlmeyer, H. Pöppl, F. Pühlhofer, J. Speer, and K. Völkel
Philipps Universität, D-35037 Marburg, Germany

W. Waluś
Jagiellonian University, PL-30-059 Kraków, Poland
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In the very heavy collision system ^{197}Au+^{197}Au the K^+ production process was studied as a function of impact parameter at 1 GeV/nucleon, a beam energy well below the free N-N threshold. The K^+ multiplicity increases more than linearly with the number of participant nucleons and the K^+/π^+ ratio rises significantly when going from peripheral to central collisions. The measured K^+ double differential cross section is enhanced by a factor of 6 compared to microscopic transport calculations if secondary processes ($\Delta N \to K\Lambda N$ and $\Delta\Delta \to K\Lambda N$) are ignored.

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Relativistic nucleus-nucleus collisions are a unique tool to study the properties of nuclear matter away from its ground state. In the course of a nearly central collision the nuclei interpenetrate and a significant part of the initial kinetic energy is converted not only into chaotic motion and compressional energy, but also into intrinsic excitation of the nucleons. At bombarding energies around 1 GeV/nucleon a substantial number of Δ and N^* resonances is produced forming, together with the nucleons, a transient phase of hot and dense hadronic matter. These resonances are the predominant source of pions providing information on the microscopic reaction mechanism [1-7]. In addition, these excited baryons may serve as an energy reservoir for subthreshold particle production. The rate of collisions involving resonances is increasing rapidly with the density in the reaction zone, as two subsequent interactions are required. According to microscopic transport calculations densities of 2-3 times normal nuclear matter density are reached in nuclear collisions at 1 GeV/nucleon bombarding energy [8]. This energy is below the K^+ meson production threshold of 1.58 GeV for free N-N collisions. Subthreshold kaon production depends strongly on the available energy and is considered to be a probe of nuclear matter properties at increased density. Compared to K^- or η mesons, the K^+ have a considerably longer mean free path in the nuclear medium and hence can leave without substantial final-state interactions.

Pioneering experiments on strangeness production in nuclear collisions have been performed at the Bevalac at LBL [9-11]. Inclusive K^+ and Λ^0 production cross sections have been measured, mostly at beam energies above the free N-N threshold. In this Letter we report on the first measurement of K^+ mesons in nucleus-nucleus collisions at a subthreshold beam energy and as a function of the impact parameter. Also for the first time subthreshold K^+ production has been studied in a very heavy collision system.

The experiment was performed with the Kaon Spectrometer (KaoS) at the heavy ion synchrotron SIS of GSI. The magnetic spectrometer was designed to identify the kaons in the presence of a high background of protons and pions [12]. KaoS combines a compact geometry to minimize meson decay in flight, a large acceptance in solid angle ($\Omega \approx 30$ msr), and a broad momentum range ($p_{\max}/p_{\min} \approx 2$ up to $p_{\max} = 1.8$ GeV/c). A time-of-flight stop detector array, consisting of 50 plastic scintillator paddles, is positioned along the focal plane of the spectrograph. This arrangement allows for a very fast mass-selective trigger which is indispensable for the detection of rare particles in a heavy-ion experiment. A row of Cherenkov detectors with water and lucite radiators located behind the focal plane improves proton suppression [13]. A large-area multiwire chamber is used to suppress background particles.

Only in central collisions of heavy nuclei can one expect to create a hot and dense reaction zone large enough to allow for the observation of collective compressional effects. Thus an event characterization is needed to study meson production as a function of the event centrality

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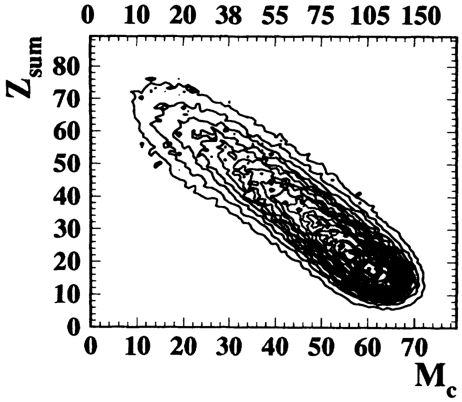

FIG. 1. Projectile spectator charge sum Z_{sum} for $0.5° < \Theta_{lab} < 11°$ measured with the small angle hodoscope versus participant charged particle multiplicity M_c measured at $12° < \Theta_{lab} < 48°$ with the large angle hodoscope. The data are from $^{197}Au + ^{197}Au$ collisions at 1.0 GeV/nucleon. Lower scale: M_c as measured; upper scale: M_c corrected for multiple hits.

which is determined by the number of participating nucleons. This information is extracted in our experiment from the charged particles detected by two plastic scintillator arrays. The large angle hodoscope consists of 96 modules positioned between 8 and 13 cm from the target. It measures the particle multiplicity in the polar angular range of $12° < \Theta_{lab} < 48°$; most of these particle are participating protons, i.e., protons originating from the collision zone. The small angle hodoscope is composed of 380 plastic scintillator modules and covers polar angles of $0.5° < \Theta_{lab} < 11°$. Particles emitted in this angular range are predominantly spectator fragments. This detector system is located 7 m downstream of the target and measures time of flight and the specific ionization to determine the nuclear charge. In addition the hodoscope provides information on the fragment polar and azimuthal emission angles and thus on the orientation of the reaction plane [12]. The performance of the two hodoscopes is demonstrated in Fig. 1 showing the correlation of the summed projectile spectator charge Z_{sum} with the participant charged particle multiplicity M_c. Z_{sum} is measured with the small angle hodoscope and includes all particles which have at least 70% of the projectile velocity. The lower and upper scales of Fig. 1 show M_c before and after correction for multiple hits, respectively. Central collisions are dominating this data set due to the spectrometer trigger.

We investigated proton and meson production in $^{197}Au + ^{197}Au$ collisions at a beam energy of 1.0 GeV/nucleon. A beam of 10^5 particles per spill of 4 s duration hit a target of 1.9 g/cm^2 metallic Au. Protons, pions, and kaons were measured within a polar angular range of $40° < \Theta_{lab} < 48°$. The corresponding acceptances in units of normalized rapidity are $0.2 < y/y_{proj} < 0.5$ for protons, $0.5 < y/y_{proj} < 0.7$ for pions, and $0.3 < y/y_{proj} < 0.6$ for kaons.

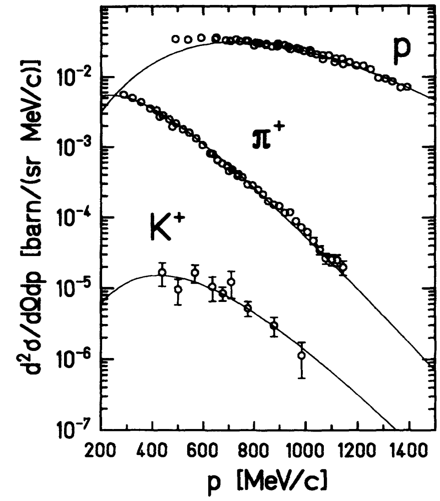

FIG. 2. Double differential cross sections for protons, positive pions, and kaons as a function of the laboratory momentum measured at $40° < \Theta_{lab} < 48°$ in $^{197}Au + ^{197}Au$ collisions at 1.0 GeV/nucleon. The data are compared to Maxwell-Boltzmann distributions (see text).

Figure 2 shows the double differential cross sections $d^2\sigma/dp\,d\Omega$ for protons, pions, and kaons as measured in the laboratory system. The error bars reflect counting statistics only. The absolute cross sections for protons and pions have an additional systematic error of 15% due to uncertainties of beam normalization (10%), the efficiencies of the detector (5%), and of the trajectory reconstruction method (10%). The systematic error of the kaon yield is 21% due to an additional uncertainty in the efficiency of the kaon identification (15%). The spectrometer acceptances and the trajectory reconstruction for the different particles and momenta have been studied by simulations using the GEANT3 code which also allows one to correct for the particle decay in flight [14].

The spectra in Fig. 2 are compared to Maxwell-Boltzmann distributions $d^2\sigma/p^2dp\,d\Omega \propto \exp(-E/T)$ calculated in the N-N center-of-mass frame and transformed to the laboratory system (solid lines). For the K^+ spectrum the slope parameter T was found to be 67 ± 5 MeV. The pion spectrum is fitted with an overall slope parameter of 68 ± 3 MeV, although a better description is achieved with a superposition of two distributions [15]. The proton spectrum deviates from a Maxwell-Boltzmann distribution in the low momentum part; this effect is attributed to the contribution from target spectators. The total K^+ cross section is determined by extrapolating and integrating the double differential cross section $d^2\sigma/dp\,d\Omega$ over momentum and solid angle. Under the assumption of isotropic emission in the N-N system this would result in a K^+ cross section of $\sigma_{K^+} = 41 \pm 11$ mb.

In order to examine more closely the particle production mechanisms we have studied the π^+ and K^+ multiplicities as a function of the number of participating nucleons. The events were sorted into four groups according to the charged particle multiplicity M_c as measured with the large angle hodoscope. The corresponding meson multiplicity per center-of-mass solid angle $dM_m(M_c)/d\Omega_{\rm c.m.}$ is determined by

$$dM_m(M_c)/d\Omega_{\rm c.m.} = (d^2\sigma_m/dM_c d\Omega_{\rm c.m.})/(d\sigma_R/dM_c) \quad (1)$$

with $d^2\sigma_m/dM_c d\Omega_{\rm c.m.}$ the meson (pion or kaon) production cross section per event group and per center-of-mass solid angle. This cross section is determined from the measured double differential cross section $d^2\sigma/dp\,d\Omega$ by integration over the meson momentum and by transformation into the center-of-mass frame. The reaction cross section $d\sigma_R/dM_c$ is measured with the large angle hodoscope and a minimum bias trigger. The variable M_c is related to the number of participating nucleons $A_{\rm part}$:

$$A_{\rm part}(M_c) = A/Z \times 2 \times [Z - Z_{\rm sum}(M_c)] \quad (2)$$

with A and Z the mass and charge of a gold nucleus. The "spectator" charge $Z_{\rm sum}(M_c)$ is taken from Fig. 1 after correction for acceptance and for the contamination of participant particles.

Figure 3 (upper part) shows the π^+ and K^+ multiplicities per unit solid angle $dM_m/d\Omega_{\rm c.m.}$ as a function of the number of participant nucleons. The data points are given at $\Theta_{\rm c.m.} \approx 90°$, i.e., at midrapidity. Total meson multiplicities can be derived by assuming angular distributions. For pions they are known to be forward and backward peaked: the nonisotropic to the isotropic fraction of pions emitted in Ar+KCl reactions at 1.8 GeV/nucleon is 28% for peripheral and 16% for central collisions [1]. Integration over the full solid angle taking into account these values yields π^+ multiplicities which are larger by factors of 1.28 and 1.16 for small and large $A_{\rm part}$, respectively, as compared to those obtained for isotropic emission. The result, that the pion multiplicity depends nearly linearly on the participant number, is therefore influenced very little by the assumed emission pattern. Such a linear dependence was also found in ^{139}La + ^{139}La collisions at 800 MeV/nucleon [16].

In contrast, the K^+ multiplicity per solid angle increases more rapidly than linear as a function of the number of participants. Therefore, the K^+/π^+ ratio increases with the number of participant baryons in a nucleus-nucleus collision as shown in Fig. 3 (lower part). The corresponding impact parameter scale for Au+Au collisions is plotted below the $A_{\rm part}$ axis. The impact parameter is determined from the measured reaction cross section $d\sigma_R/dM_c$ assuming $d\sigma_R/db = 2\pi b$ and a monotonous relation between multiplicity M_c and impact parameter b. Figure 3 also includes the K^+/π^+ ratio which was measured with the same setup in Ne+NaF collisions at 1.0 GeV/nucleon [17]. This data point corroborates the low K^+/π^+ ratio ($\leq 10^{-3}$) observed in peripheral Au+Au collisions, i.e., for a small number of participants,

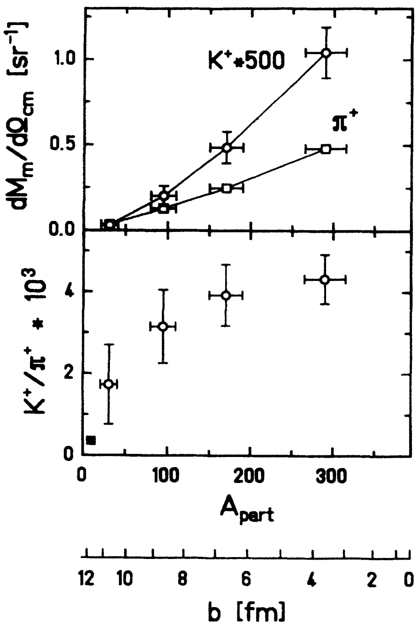

FIG. 3. Upper part: π^+ and K^+ multiplicity per center-of-mass solid angle at midrapidity as a function of the number of participating nucleons. The vertical and horizontal error bars reflect statistical and systematical uncertainties, respectively. The data are for ^{197}Au+^{197}Au collisions at 1.0 GeV/nucleon and $40° < \Theta_{\rm lab} < 48°$. Lower part: Multiplicity ratio K^+/π^+ at midrapidity for Au+Au (open circles) and for Ne-NaF collisions at the same beam energy (full square). For the determination of the impact parameter axis b see text.

where no higher order effects are expected. The increase observed for high $A_{\rm part}$ indicates secondary processes: with a resonance formed in the first step the probability to produce a kaon in the second step is largely enhanced at higher baryon densities.

Higher order processes in subthreshold particle production have been studied by microscopic transport models [18–21]. They indicate that baryonic resonances play a key role in the subthreshold production of particles like etas, kaons, and antiprotons. Such calculations, performed for Au+Au collisions at 1.0 GeV/nucleon, underpredict the K^+ yield by a factor of 6 when taking only N-N collisions and Fermi motion into account. Thus the models have to include secondary and higher order collisions such as $\Delta N \to K\Lambda N$ and $\Delta\Delta \to K\Lambda N$ in order to account for the high K^+ cross sections as reported here. It turns out that within the framework of the microscopic calculations the $\Delta N \to K\Lambda N$ channel is the dominant kaon production process in nucleus-nucleus reactions around 1.0 GeV/nucleon [20,21].

An interesting aspect of these calculations is that they predict an observable effect of the nuclear incompressibility on the K^+ yield. For a "soft" equation-of-state a higher baryon density is reached in a central nuclear collision. This results in a larger number of secondary processes and hence in a higher kaon yield. On the other hand the calculations indicate that an unambiguous determination of nuclear matter properties from the absolute K^+ cross section is not possible with the presently available information. The elementary kaon cross section close to threshold is not known well enough and no experimental information is available on the process $\Delta N \rightarrow K\Lambda N$ [22]. In addition, the kaon production depends on the in-medium nucleon-nucleon dynamics [19,23]: The inclusion of momentum-dependent interactions considerably reduces the calculated kaon yield. These uncertainties cancel to some extent when ratios of kaon yields are studied which are measured for different sizes of the collision system. Therefore, the increase of the K^+ multiplicity with decreasing impact parameter also reflects nuclear matter properties. Further detailed investigations are required, both experimentally and theoretically, in order to extract more quantitative information.

In summary, we have investigated the K^+ production as a function of impact parameter in the heavy collision system Au+Au at a bombarding energy of 1.0 GeV/nucleon, which is far below the K^+ production threshold for free N-N collisions. We find the K^+/π^+ ratio enhanced when the number of participant baryons increases. This is the first experimental evidence that subthreshold kaon production is dominated by two step processes which are favored by high nuclear densities reached in central nucleus-nucleus collisions.

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*Present address: Argonne National Laboratory, Argonne, IL 60439.

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