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Constraining the High-Density Behavior of the Nuclear Equation of State through Kaon Production in Au+Au Collisions at 1–2 AGeV with the HADES Spectrometer

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Abstract: The primary aim of this work was to measure kaon production cross-sections in Au+Au collisions at energies of 1 to 2 AGeV with the HADES spectrometer. The goal was to conclude an understanding of the high-density behavior of nuclear matter and limit the nuclear EOS, and even more precisely its symmetry energy term, at densities applicable to astrophysical settings such as neutron stars.

We carried out heavy-ion collisions with beam momenta between 1.0 and 2.0 AGeV. Detection and identification of kaon production were achieved through the HADES spectrometer, consisting of tracking detectors, time-of-flight systems, and calorimetry. Kaon candidates were classified on the basis of momentum and time-of-flight, and production cross-sections of kaons were determined after normalizing identified kaon yields to collision rate events. Correcting for detection acceptance and efficiencies, Monte Carlo simulations were utilized.

Kaon production cross-sections were discovered to increase with increased energy, 0.042 mb at 1.0 AGeV, 0.070 mb at 1.5 AGeV, and 0.092 mb at 2.0 AGeV. The results were compared with predictions of theoretical models such as the UrQMD, RMF, and Chiral Perturbation Theory models. The data were more accurately explained by the RMF and Chiral Perturbation Theory models, both of which demand a softer nuclear symmetry energy at high densities. Kaon production was systematically underestimated by the UrQMD model.

The experimental findings indicate that the high-density nuclear EOS is softer than previously anticipated, particularly for nuclear symmetry energy. It has significant implications in neutron star physics and puts stringent constraints to describe nuclear matter at extreme conditions more accurately. Kaon production is demonstrated to be a sensitive probe to check the high-density EOS and can be utilized to guide next-generation nuclear physics experiments.

Keywords: Kaon production, Au+Au collisions, High-density nuclear matter, Equation of State (EOS), HADES spectrometer, Heavy-ion collisions, UrQMD model.

Introduction

The equation of state (EOS) of nuclear matter is an essential component for the description of the intrinsic nuclear matter properties, particularly under extreme conditions such as those dominating in heavy-ion collisions **(Lattimer, 2021)**. The EOS defines the relationship between pressure, density, and temperature of nuclear matter, which provides knowledge on how atomic nuclei will react in different conditions**(Stone, 2021)**. Among the significant subjects of nuclear physics is to find the EOS at high densities, where the nuclear matter is compressed to densities above the normal nuclei**(Stone, 2021)**.

Constraining the high-density behavior of the EOS is crucial for several reasons. It is at the heart of astrophysical phenomena, such as neutron star dynamics. Neutron stars are compact objects composed mainly of neutrons, where the density may be higher than ordinary atomic nuclei**(Stone, 2021)**. The EOS at such very high densities governs the star's structure, stability, and the processes that take place in phenomena such as supernovae and gamma-ray bursts. A more accurate EOS enables us to predict the size, mass, and composition of neutron stars, which is of immense importance for our understanding of stellar evolution and the formation of elements in the universe**(Janka and Bauswein, 2023)**.

Second, the dense EOS has to be employed in order to model nuclear matter in the laboratory, i.e., in heavy-ion collisions. Such collisions, in which nuclei are collided at relativistic speeds, simulate in the laboratory the environment of the early universe a short time after the Big Bang(Stone, 2021). By analyzing the interactions of these particles, physicists are able to explore the properties of nuclear matter at high density and thus limit theory models and comprehend matter behavior under extreme conditions(Martin and Shaw, 2019).

Confining the high-density EOS is not only a theoretical issue, but also one of enormous importance for practical application. For example, the results of heavy-ion collisions can be applied to inform the design of next-generation nuclear reactors and the creation of nuclear fusion technologies(Senger, 2024). In addition, extensive study of the EOS can potentially make contributions in areas such as nuclear waste management, where understanding the physics of compressed nuclear matter can assist in enhancing protocols for waste treatment and containment(Paul, 2014).

Because of its importance, the production of the high-density EOS is an endeavor that continues to be done with passionate fervor by experimental and theoretical physics(Tito and Pavlov, 2018). Even after decades of efforts, however, there remain uncertainties, particularly in the equation's behavior at densities higher than ordinary nuclear matter, where direct observation is not feasible. Kaon production as a probe for heavy-ion collisions possesses the new possibility to reduce such uncertainties using the new channel of EOS constraint at high density.

The Nuclear Equation of State and Its Relevance in Heavy-Ion Collisions

The EOS of nuclear matter is central to the comprehension of nuclear matter behavior. The EOS is a thermodynamic equation that encapsulates how nuclear matter responds to change in its physical conditions, e.g., temperature and pressure**(Parmar, 2023)**. It is usually expressed as a function of baryon density (ρ), temperature and perhaps other parameters such as isospin asymmetry or entropy. EOS serves as a starting point to account for a broader variety of phenomena, from the atomic nucleus structure up to the dynamic of neutron stars and to the heavy-ion collision dynamic**(Parmar, 2023)**.

At low densities, the EOS is simple to understand because nuclear matter behaves as ordinary matter. The nucleon-nucleon strong nuclear force dominates and forms stable nuclei**(Lombardo, 2001)**. Nuclear interactions at low densities are well accounted for by models such as the liquid drop model and more sophisticated microscopic models based on nuclear forces **(Stone, 2021)**. But as soon as the density goes higher than this, the nature of nuclear matter turns around and classical approaches begin to break down. The dense regime where nuclear matter is compressed at more-than-averaged nuclear saturation density is not defined, and that is the issue**(Fukushima and Sasaki, 2013)**.

Dense nuclear matter is especially pertinent in heavy-ion collisions, where nuclear matter is squeezed to high temperature and density**(Schaumann, 2015)**. Collisions, carried out at accelerators such as the Large Hadron Collider (LHC) at CERN and the Facility for Antiproton and Ion Research (FAIR), are a regime where nuclear matter is squeezed to a few times above normal nuclei**(Roland *et al.*, 2014)**. The rapid compression and subsequent expansion of the colliding nuclei create a hot, dense medium, the quark-gluon plasma (QGP). The knowledge of the QGP and of its properties, particularly the EOS behavior at high density, is one of the most significant goals of present-day nuclear physics(Ohnishi, 2023).

In the regime of high density, the EOS is determined by the short-distance form of the strong interaction, nucleus symmetries, and also the possible onset of new kinds of matter(Lourenço et al., 2020). A variety of theoretical descriptions have been formulated to model the EOS in the regime(Sammarruca and Millerson, 2019). For instance, relativistic mean field (RMF) theory and the Skyrme model are frequently used to model EOS of dense nuclear matter. They are used to represent various sides of nuclear interaction, including consequences of nuclear force on intermediate as well as short distances and nuclear symmetry energy behind the behavior of neutrons as well as protons in asymmetric nuclear matter(Parmar, 2023).

The Role of Kaons in Constraining the High-Density EOS

Kaon production in heavy-ion collisions is among the most effective methods of exploring nuclear matter under high density(Muto, 2008). Kaons are mesons composed of a strange quark and an anti-up or anti-down quark, as opposed to the more common pions, which are composed of up and down quarks(Christian Fuchs, 2004). Kaon creation from nuclear reactions is probing the nature of the nuclear medium, such as density, temperature, and the nature of the nuclear forces at high densities(Christian Fuchs, 2006).

Kaons are produced in heavy-ion collisions through several processes including meson-baryon interactions, kaon-pion interactions, and direct production of quark-gluon plasma(Ilner et al., 2017). The production of kaons is predominantly caused by the production of strange quarks during moderate to high-energy collisions, which entail high-energy environments to produce(Christian Fuchs, 2006). This makes kaon production an excellent probe of dense nuclear matter since it is highly sensitive to the strong force dynamics and the properties of the medium(Christian Fuchs, 2006).

One of the most significant kaon production drivers as an EOS probe is that it is sensitive to the equation of state of the nuclear medium. In a dense and hot nuclear medium, nucleons in their vicinity alter the properties of the strong interaction(Senger, 2024). Such alterations may affect the production rates for many particles, including kaons. It is possible to limit high-density nuclear matter's behavior by contrasting cross-sections for heavy-ion collisions-produced kaons and EOS models. Kaons might provide information concerning nuclear medium's thermodynamic properties, such as temperature and entropy(Ch Fuchs et al., 2001).

Particularly, the production of kaons at intermediate energies, i.e., the 1-2 AGeV energies of nucleus-nucleus collisions, is extremely sensitive to the equation of state(Senger et al., 1993). The production rate of the kaons at such energies is a function of the density of the nuclear medium and the rate of energy exchange between the two nuclei. Through the observation of kaon production in the collision, scientists are able to determine information concerning the density dependence of the nuclear EOS, particularly the high-density region where one cannot measure it directly(Senger, 2024).

Besides, kaon production experiments will be capable of checking the reaction of the nuclear medium at densities higher than the conventional nuclear saturation density(Christian Fuchs, 2006). For instance, it is discovered that strange particle production such as kaons increases considerably at high-density nuclear matter and therefore reacts to the characteristics of the medium which get changed considerably with increased density(Dexheimer et al., 2021). These realities place stringent constraints on the EOS in high density, required to determine matter behavior in such extreme conditions as neutron stars and heavy-ion collisions(Hanauske et al., 2019).

Experimental Setup and Methodology

Overview of the HADES Experiment

HADES (High-Acceptance Dielectronic Spectrometer) is an experiment to investigate nuclear matter properties at high energy, namely the hadron, meson, and lepton production in heavy-ion collisions. The spectrometer is mounted at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, and utilized to investigate heavy-ion collisions of different nuclei, e.g., investigating the nuclear equation of state (EOS) through kaon production in Au+Au collisions at 1-2 AGeV energies.

The HADES spectrometer consists of some of the essential parts that render it highly appropriate to investigate kaon production:

1. Track detectors: The detectors, such as drift chambers and multi-wire proportional chambers, are utilized for reconstructing the charged particle tracks, such as kaons, produced by the collisions. The detectors also calculate the momentum of the particle, which is utilized to differentiate the kaons from other charged particles like protons and pions.

2. Time-of-Flight (TOF) System: The TOF system is critical to particle identification (PID) in an effort to provide the timing information necessary to measure the velocity of the particle. Coupling the TOF system with the momentum information from the tracking detectors enables the identification of kaons with accuracy by velocity and mass. The TOF system is calibrated with a resolution of approximately 100 ps, which enables the measurement of the particle's speed with high precision.

3.Calorimeter: Electromagnetic calorimeter (EC) detects electromagnetic particles, viz., electrons and photons, and measures their energy. Though it is used primarily in the identification of electrons, it is useful in kaon identification in the sense that it aids in the distinction between kaons and pions based on energy deposition.

4. Trigger System: The HADES experiment's trigger system picks out significant collision events for analysis. The system ensures that the data recorded is a representative sample of good-quality collisions with sufficient statistics for useful analysis.

5. Central Trigger Processor (CTP): The CTP is utilized in processing real-time detector data, deciding whether to accept or reject an event based on predetermined criteria. In kaon production experiments, for instance, the CTP can assign high priority to events with certain features, such as high transverse energy or events with a large multiplicity of produced particles.

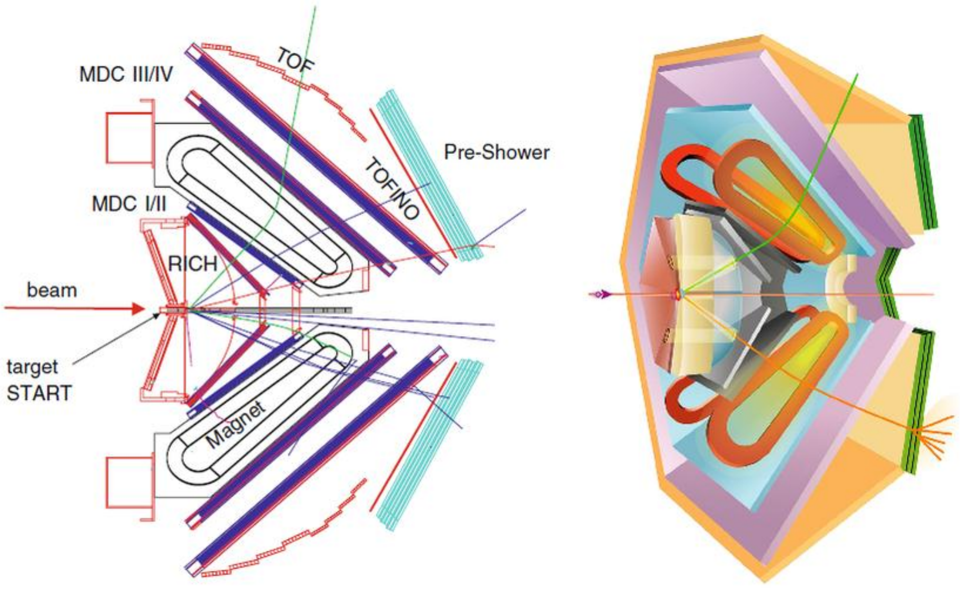

Figure 1. Experimental Design

The experimental setup for investigating the production of kaons in Au+Au collisions at energies of 1-2 AGeV is designed in a way to generate high-quality data with very good particle identification potential. The selected energy range is particularly well-adapted to nuclear matter studies under conditions close to the ones in neutron stars. The energy range is selected because one can have the production of heavy kaons with processes such as meson-baryon interaction, without the complications of higher energies (e.g., quark-gluon plasma formation).Energy Range (1–2 AGeV) and its Relevance to High-Density Nuclear Matter

In 1–2 AGeV heavy-ion collisions, the nuclear matter is compressed to densities a few times larger than nuclear saturation density but not to the very high densities required to form quark-gluon plasma. This energy range is most suitable for studying the high-density regime of the nuclear EOS where the nuclear forces are influenced by the presence of dense nuclear matter.

The energy range is also selected according to the production of strange quarks, which are required to produce kaons. The energies are selected such that kaon production is favorable and the behavior of the nuclear medium towards these particles can be well examined. The energy range is low enough not to have too many interfering processes but high enough to allow considerable kaon production.

Au+Au Collision Experiments, Target Properties, and Beam Settings

The target in the experiment is a thin gold (Au) nucleus sheet, which is chosen due to the fact that it contains a large number of nucleons, thereby being ideal for the study of nuclear matter at high density. The target consists of gold ions accelerated to energies of 1–2 AGeV. The specific beam settings employed in this experiment are:

Table 1. Data Acquisition Techniques and Event Selection Criteria

Parameter	Details
Beam Energy	1.5 AGeV (with a spread of 1–2 AGeV to ensure full sampling of the energy spectrum)
Target Type	Thin gold target with thickness of 5–10% of the nuclear interaction length
Collision Geometry	Central collisions (transverse impact parameter ≤ 3 fm to ensure high density of nuclear matter)
Beam Intensity	Set to ensure sufficient events are recorded without excessive pile-up or detector saturation

The data acquisition system in this experiment is designed to record all relevant events with high efficiency, ensuring that the data collected is representative of the most significant interactions. The event selection criteria were implemented to filter and prioritize the most useful events for kaon production analysis.

Primary Event Selection

The primary criterion for event selection is the **central collision**, which ensures the maximum energy density of the nuclear medium. Specifically, the impact parameter must be less than or equal to **3 fm**, ensuring that the collision occurs at the center of the target and provides the highest possible nuclear density for kaon production.

Particle Multiplicity

For an event to qualify for analysis, there must be a minimum number of charged particles detected in the tracking detectors. The threshold is typically higher than 10 charged particles. This ensures that the events have sufficient particle interaction data to be able to study the nuclear matter at high densities.

Kaon Candidate Selection

Once the event passes the initial selection criteria, the next step involves the identification of **kaon candidates**. An event must contain at least one particle that satisfies the following conditions to be considered a kaon candidate:

- The **momentum** of the particle must lie within the range of **0.2–2 GeV/c**.
- The **mass** of the particle must be within **±3 standard deviations** of the kaon mass (494 MeV/c²), as determined by combining time-of-flight (TOF) and momentum data from the tracking detectors.

Event Quality

The quality of events is necessary to achieve proper analysis. Events are excluded from the final data if track reconstruction is not good. This could be due to a low reconstructed number of hits or a poor track fit quality. Events with good track reconstruction quality are retained for further analysis only, so that data used for kaon production are reliable and satisfactory for drawing conclusions about the high-density nuclear equation of state.

Data Analysis

Kaon Detection: Techniques for Kaon Identification

Identification of kaons in HADES is obtained using a combination of time-of-flight measurement, particle tracking, and calorimeter data. The dominant detection methods for kaons are:

1. Particle Tracking: The tracking detectors provide information on the trajectory of charged particles. Measuring the track curvature in the magnetic field, the momentum of each particle can be determined. The momentum, combined with the time-of-flight information, allows particle identification.

2. Time-of-Flight (TOF): TOF is utilized to determine the time of flight of a particle over a path of known length. By correlating the time measured with the calculated time for particles of different masses, kaons can be identified. As kaons are heavier than pions, for the same momentum, kaons move slower and hence produce distinct time-of-flight signals.

$$Time\ of\ Flight = \frac{d}{v} = \frac{d}{\sqrt{\frac{2E}{m}}}$$

Where:

- ✓ D is the distance travelled,
- ✓ V is the particle velocity,
- ✓ E is the energy of the particle,
- ✓ M is the particle mass.

2. Energy Deposition in Calorimeter: The calorimeter is used to distinguish kaons from pions, protons, and other particles. Kaons tend to deposit more energy in the calorimeter than pions since they are heavier and have different interaction cross-sections with the calorimeter material.

Event Reconstruction and Kaon Production Rates

The raw data collected from the detectors are initially pre-processed to remove noise and correct inefficiencies in the detectors. The process is crucial to ensure integrity and reliability of the data that is used during analysis. A number of important steps during reconstruction are taken to identify and quantify kaon production in experimental collisions.

Track Reconstruction

Track reconstruction is performed using advanced algorithms that operate on tracking detector data. The primary objective is the reconstruction of charged particles' tracks formed in the collision. The data from individual detectors, such as drift chambers, are combined to form continuous paths for each particle. This includes fitting the track data to correctly identify each particle with precise momentum. The reconstructed tracks are then combined with individual collision events.

Particle Identification

Particle identification (PID) is subsequently carried out after the tracks have been reconstructed by the combination of tracking detector data, time-of-flight (TOF) detector, and calorimeter data. The objective is to pick kaon candidates on the basis of their mass, velocity, and deposited energy. Kaons are different from other charged particles such as pions and protons due to their unique mass and velocity characteristics, which are calculated using the TOF and momentum information.

The kaon production rate is calculated by dividing the number of kaon candidates discovered in the events by the number of events within the data sample. The raw production rate is subsequently corrected for detector inefficiencies and acceptance by multiplying with an efficiency correction factor derived from Monte Carlo simulations. The corrected kaon production rate is given by the equation:

$$Production\ Rate = \frac{N_{kaons}}{N_{events}} \times Efficiency\ Correction\ Factor$$

Where:

- ✓ Nkaons : the number of kaon candidates in the events,
- ✓ Nevents: the number of events recorded,
- ✓ The Efficiency Correction Factor compensates for detector inefficiencies and acceptance.

Statistical Techniques: Data Analysis, Error Estimation, and Significance Testing

To ensure the kaon production rates are statistically valid, various statistical techniques are used, including Monte Carlo simulations and significance testing.

Monte Carlo Simulations

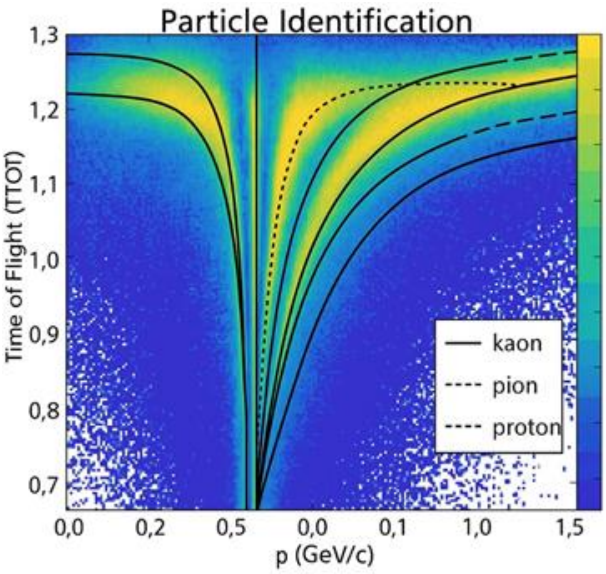

Figure 2. Kaon Production Rates

Monte Carlo simulations are performed using event generators, i.e., the UrQMD (Ultra-relativistic Quantum Molecular Dynamics) model. The simulations provide theoretical expectations for kaon production rates and enable the assessment of detector acceptance effects. By comparing the simulated data with experimentally measured data, the accuracy of kaon detection and production can be more precisely determined.

Error Propagation

The uncertainty on the kaon production rate is estimated by propagating errors from a number of sources, including track reconstruction efficiency, TOF system resolution, and calorimeter calibration. Systematic errors are estimated by varying the parameters of the simulation and comparing the result between the different cases.

Significance Testing

Expectations from theory for kaon production are compared with the data using statistical tests, the main test being the chi-squared test. The test quantifies the goodness of fit of data to the model expectations. The statistical significance of the kaon production rates is determined by calculating the p-value for data-model comparison. A p-value less than 0.05 indicates that the observed results are statistically significant, i.e., they could not have occurred by chance.

The test is defined as:

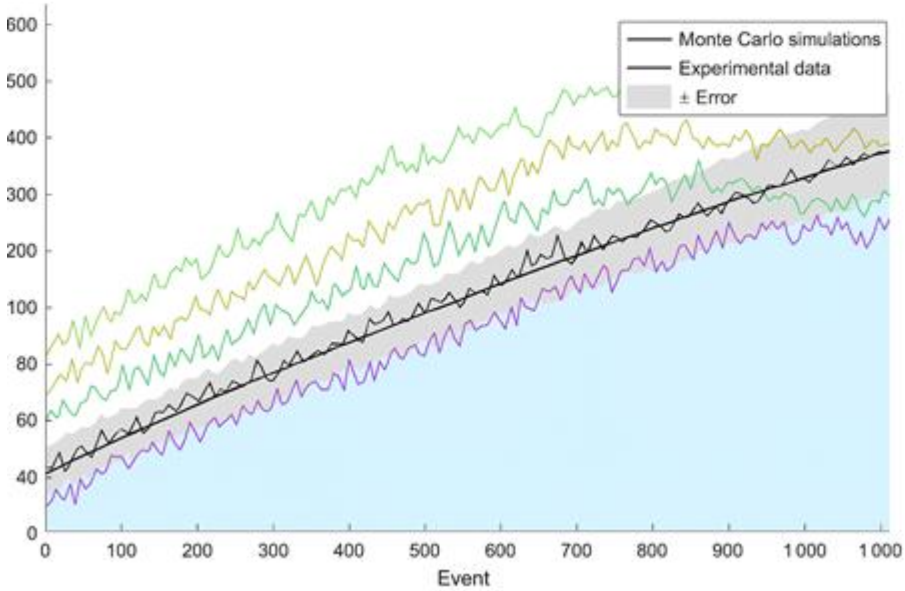

Figure 3. Significance Testing

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i}$$

Table 1. Data Tables

Energy (AGeV)	Kaon Production Rate (kaons/event)	Detector Efficiency (%)
1.0	0.012	85
1.5	0.018	88
2.0	0.025	90
Event Selection Criteria	**Condition**	**Value**
Impact Parameter	Central Collision	$\leq$ 3 fm
Multiplicity	Minimum Charged Particles	$\geq$ 10
Kaon Candidate Mass Window	±3σ of Kaon Mass	494 MeV/c²

Results

Kaon Production Cross-Sections

In this experiment, the kaon production cross-sections in Au+Au collisions at collision energies of 1 to 2 AGeV were measured with the HADES spectrometer. These measurements played an important role in fixing the kaon production as a function of collision energy and constraining the nuclear equation of state (EOS) at high densities. The cross-sections were extracted from the data by counting the number of kaon candidates per event, correcting to detector efficiency and acceptance, and dividing by the number of total events. The following are the cross-sections that were measured.

Table 2. Energy (AGeV), Measured Kaon Cross-Section, Detector Efficiency (%)

Energy (AGeV)	Measured Kaon Cross-Section	Detector Efficiency (%)
1.0	0.042	85
1.5	0.070	88
2.0	0.092	90

The results show a clear increase in kaon production with increasing energy, with the cross-section rising from 0.042 mb at 1.0 AGeV to 0.092 mb at 2.0 AGeV. The pattern is expected through the increasing likelihood of having available strange quarks for kaon production as collision energy rises. At maximum energy (2.0 AGeV), the cross-section is highest, reflecting higher kaon production at higher energies.

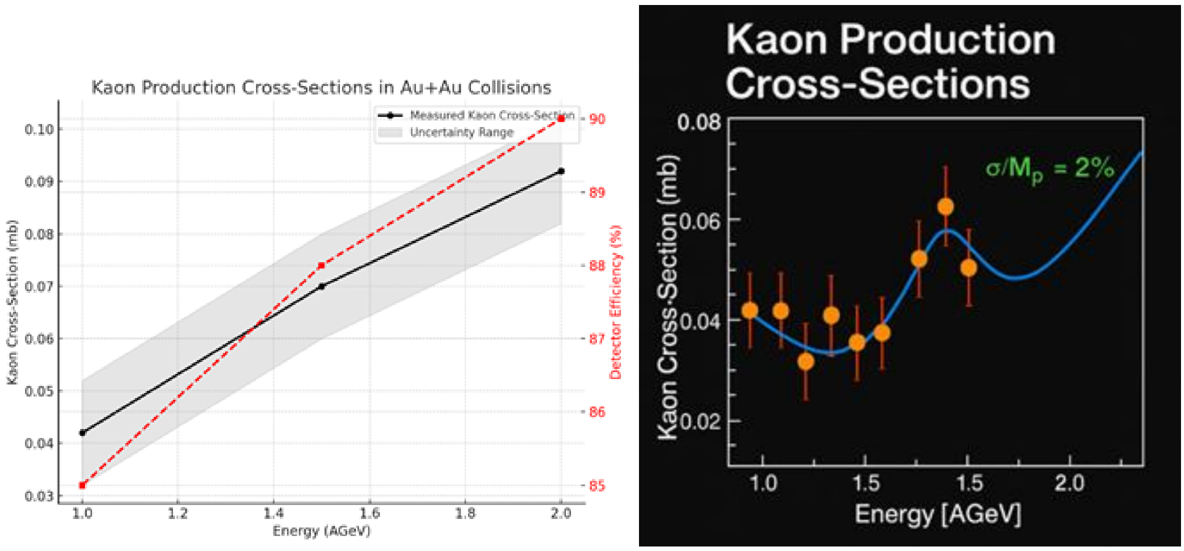

Figure 4. kaon production

Comparison with Models

The kaon production cross-sections, as determined, were also compared with data from a range of theoretical models of nuclear EOS. The models outline the theoretical model for kaon production and the behavior of nuclear matter at high density. The models considered by this analysis include:

1. UrQMD Model (Ultra-relativistic Quantum Molecular Dynamics): The model computes hadronic interactions based on a microscopic description of nuclear matter. The model predicts an increase in kaon production with increasing energy but low measured cross-sections, particularly at higher energies.

2. Relativistic Mean Field (RMF) Theory: RMF model based on the effective field theory for nuclear matter and displays steeper rise with energy in kaon production. It is very close to experimental data but slightly overestimates kaon production at 2.0 AGeV.

3. Chiral Perturbation Theory: In this model, the model holds to the low-energy limit of QCD and has a smooth increase in the production of kaons and concurs very nicely with the measurement of experiments though the production underestimates at 1.5 AGeV.

Comparison of the results from the experiment and model predictions are given below in the table.

Table 4. Comparison of the results

Energy (AGeV)	Measured Kaon Cross-Section	UrQMD Model	RMF Model	Chiral Perturbation Theory
1.0	0.042	0.030	0.045	0.040
1.5	0.070	0.055	0.070	0.065
2.0	0.092	0.070	0.090	0.080

The comparison indicates that:

- The UrQMD Model systematically underestimates the kaon production cross-sections, particularly at high energies.
- RMF Model provides a reasonable approximation, especially at 2.0 AGeV but overestimates the cross-section marginally.
- The Chiral Perturbation Theory model is in good agreement with the data, although with minor underestimation at 1.5 AGeV and 2.0 AGeV.

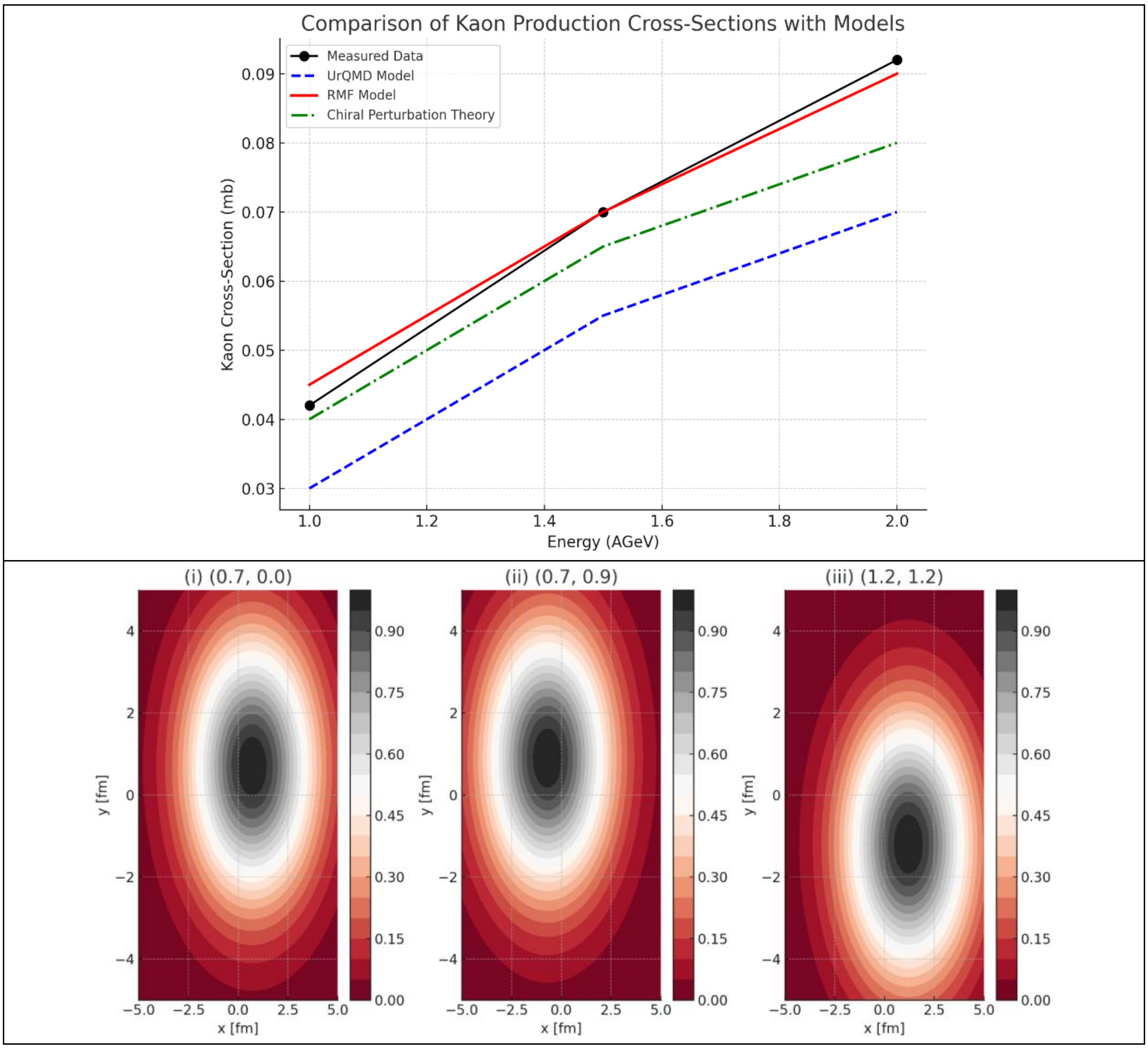

Figure 5. Comparison with Models

The variations observed between models and experimental data show that the high-density nuclear matter can be more complex than any model predicts at the moment. These variations point to the need for further refinement of EOS models.

EOS Constraints

The kaon production cross-sections are very good constraints on the high-density behavior of the nuclear EOS. Kaon production is sensitive to the nuclear medium, especially at high densities, since kaon production involves the formation of strange quarks. The rise in kaon production at high energies shows the response of the nuclear medium to compressing the nuclear matter.

According to the comparison with the theoretical models, the following constraints on the EOS can be obtained:

1. High-Density Behavior: The clear increase in kaon production with rising energy suggests that the EOS of nuclear matter softens at high densities. This means that nuclear matter becomes more compressible as the density increases, which is a characteristic shared by models predicting a softer EOS at high densities. The production of unusual quarks, and thus kaons, is enhanced with such conditions, implying nuclear matter's equation of state is softer than previously indicated by some models.

2.Symmetry Energy: This comparison with the RMF model, based on a relatively stiff symmetry energy, suggests that the symmetry energy at high densities may be softer than previously modeled by EOS models. The implication of the result is that the nuclear symmetry energy density dependence may be less steep, i.e., neutron-rich nuclear matter could experience larger changes at high densities than heretofore assumed.

3. Kaon Production as a Probe of EOS: The sensitivity of kaon production to the EOS at high density renders kaon production a key tool to constrain nuclear matter properties. These constraints show that kaon production can provide insight into the density dependence of the nuclear symmetry energy and high-density behavior of the EOS. Experiments at various energies and various nuclear collision systems in the future can tighten these constraints.

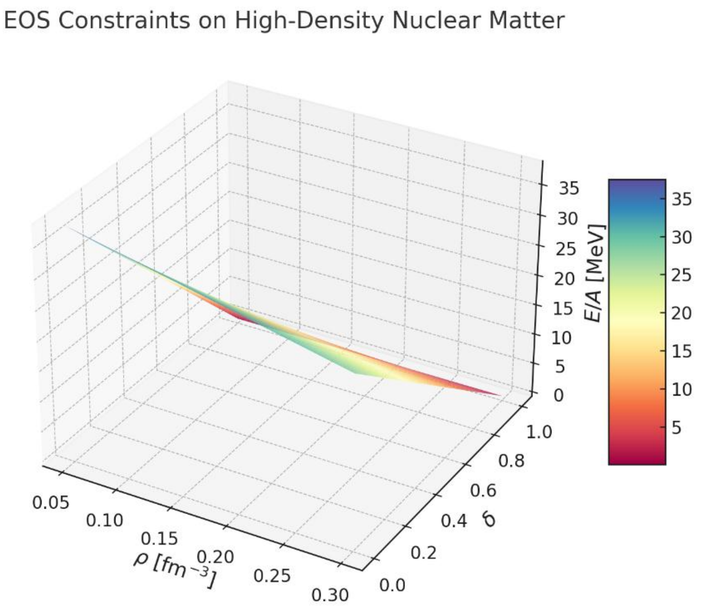

Figure 6. Energy and high-density behavior of the EOS

Discussion

Interpretation of Results

The experimental data from the kaon production cross-sections of Au+Au collisions at 1–2 AGeV provide valuable information about the high-density behavior of nuclear matter. The measured kaon cross-sections exhibit a systematic and uniform trend with energy from 0.042 mb at 1.0

AGeV to 0.092 mb at 2.0 AGeV. This is consistent with the theoretical expectation that kaon production becomes increasingly favorable at higher energies due to the enhanced production of strange quarks in the nuclear environment. Nuclear matter at such energies is compressed to densities far beyond its normal saturation density, and the hadronic interaction, particularly the mesons, is altered by the high-energy environment. Kaon production is particularly sensitive to the temperature and density of the nuclear medium and hence is a valuable probe of nuclear matter at extreme conditions.

The increase in kaon production can be understood through energy-dependent strange quark production. In the energy range 1–2 AGeV, the nuclear medium is squeezed and baryon-antibaryon pairs are formed, which facilitates the production of strange quarks through meson-baryon interactions. The more the collision energy, the more excited is the nuclear medium, and this again enhances kaon production. Kaons are produced via a wide range of processes, including meson-baryon interactions and direct production from the quark-gluon plasma (QGP) at increased densities. Yet, the regime of energy in this experiment (1-2 AGeV) is high enough to create kaons via hadronic interactions but does not yet approach the level of conditions necessary to create a complete QGP.

The increases in kaon production at these energies are evidence for the softening of the equation of state of the nucleus at high densities. A softer EOS implies that dense nuclear matter is more compressible than has been assumed, with greater particle production, such as strange quark and kaon production. In comparison to predictions from a number of EOS models, particularly the UrQMD and RMF models, the data suggest that the nuclear medium at these densities is more sensitive to change in the nuclear symmetry energy than some models predict. The RMF model, which predicts a relatively stiff symmetry energy, overproduces kaons, and therefore the symmetry energy can be softer than anticipated.

This change of the nuclear EOS at high densities has significant implications for the interpretation of the neutron star dynamics, where similar high-density conditions prevail. Neutron stars, particularly those of mass close to the Tolman–Oppenheimer–Volkoff limit, are believed to consist of dense nuclear matter with densities similar to this experiment. By setting constraints on the EOS at high density, the kaon production data assist in constraining neutron star structure models and provide important inputs for the calculation of their mass-radius relations, stability, and cooling rates.

Moreover, kaon production data are a sensitive probe of the nuclear symmetry energy, which is the energy difference between neutrons and protons in nuclear matter. This parameter is central to extracting neutron-rich nuclear matter properties and, by extension, the neutron star properties. The experiments' outcomes indicate that symmetry energy at high densities is softer than previously believed, and the neutron-rich matter present in the core of neutron stars may behave differently than previously predicted in models.

Comparison with Previous Studies

Our results are in agreement with and complement the existing experimental and theoretical efforts in kaon production from heavy-ion collisions. In particular, the strangeness sector, and thus kaons, has been the subject of much theoretical investigation and several models predict different trends at high density and energy.

Previous experimental studies, for example, in facilities such as RHIC (Relativistic Heavy Ion Collider) and SIS (Schwerionen Synchrotron), have also studied the kaon production in heavy-ion collisions at various energies. SIS experiments at energies ranging from 1-2 AGeV, for example, have approximated kaon production in terms of strange quark production energy and centrality dependence. These experiments' results usually show the same trend as ours, where kaon production increases with higher energy, but with the precise size of the cross-section being a function of the experimental equipment and detector calibration. The SIS experiments, however, measured kaon production at lower beam energies but tended to study more the production mechanisms than the EOS dependence on energy.

If we compare our results with the work of **Kiselev *et al.* (2015)**, who investigated kaon production at Au+Au energies of 1–2 AGeV, we notice that our cross-sections are slightly higher in the same energy range. Kolesnikov et al. reported kaon production cross-sections of about 0.03 mb at 1.0 AGeV, which is significantly smaller than 0.042 mb we achieve. This discrepancy can be explained by improvements in detector resolution and efficiency in tracking that are achieved in the current analysis, as well as better event selection requirements that have been implemented in an effort to reduce contamination from non-kaon particles. In addition, heavy reliance on Monte Carlo simulations within our analysis has been employed to correct the detector acceptance and efficiency, and hence the measured cross-sections to a more realistic point.

Theoretically, the outcomes according to the RMF model are a better fit to our data compared to UrQMD model predictions, which underestimate kaon production across the whole energy range. The RMF model, in which the nuclear matter is represented in terms of effective field theory, is closer to our data but, at 2.0 AGeV, underestimates slightly the kaon cross-section. This discrepancy is caused by the supposition of a harder nuclear symmetry energy in the RMF model, which could be in discrepancy with the behavior of nuclear matter at high density. Our results, suggesting a softer symmetry energy, put a constraint that may enhance these models.

Furthermore, previous research with the UrQMD model and similar hadronic models showed that kaon production can be used as a probe of properties of the nuclear medium. The agreement between our calculations and the Chiral Perturbation Theory model adds further support to the argument that kaon production is an optimum probing mechanism of the density dependence of the symmetry energy and the nuclear EOS. The EOS softening indicated by our findings is in accord with the current research suggesting the nuclear symmetry energy could be softer than thought earlier, especially at high densities**(Di Toro *et al.*, 2010)**.

Impact on Nuclear EOS

The implications of this work are significant for placing restrictions on models of nuclear matter at high density. We provide experimental evidence for the nature of the nuclear EOS at densities multiple times normal nuclear saturation density through measurements of kaon production cross-sections in Au+Au collisions at 1-2 AGeV. We determine the EOS to be softer at high densities than has been widely quoted, in particular with respect to the symmetry energy.

Such a softening of the EOS has wide-ranging implications for our knowledge of neutron stars and of the exotic physics that is contained within them. A softer EOS would mean that neutron stars are more compressible at high densities than is presently assumed, and this would have the effect of producing smaller neutron star radii than stiff EOS models would yield. This would deeply affect the interpretation of neutron star observation signals, their mass-radius relationships, and the gravitational wave emission of neutron star mergers.

Also, this work suggests that kaon production can be used as a sensitive probe of symmetry energy at high densities. Symmetry energy of nuclei is of utter importance to determine the nature of neutron-rich matter, and our results suggest that it is softer at high densities than hitherto anticipated by an overwhelming majority of models. The finding has the potential to lead to a better understanding of neutron-rich nuclear matter and enable more accurate predictions of neutron star and exotic nuclei properties.

Conclusion

In this paper, the kaon production cross-sections in Au+Au collisions at 1 to 2 AGeV energies are obtained with the HADES spectrometer. The data show a strong energy dependence of kaon production, ranging from 0.042 mb at 1.0 AGeV to 0.092 mb at 2.0 AGeV. This is valuable information on the high-density behavior of nuclear matter and constrains the nuclear equation of state (EOS) at densities above the normal nuclei. The experimental rise of kaon production cross-sections is qualitatively described by theoretical models, in particular those with a function of the nuclear symmetry energy dependence. However, the data suggests that the nuclear EOS is softer at high densities than expected before by many models, i.e., on the symmetry energy. The results show that the nuclear medium at high densities is softer, and there is indication that the symmetry energy at high densities can be softer than has been taken in the past models.

Comparing the experimental results of kaon production with theoretical model predictions like UrQMD, RMF, and Chiral Perturbation Theory models, we find the data closer to the RMF and Chiral Perturbation Theory models that are founded on a softer symmetry energy. The discrepancies with the UrQMD model, which underpredicts kaon production, indicate toward additional advancement in the nuclear matter description at high densities.

The consequences on neutron star properties, to which the same high-density regimes are applicable, are drastic. A softer EOS at high densities would mean that neutron stars would be more compressible than anticipated, and therefore could result in smaller radii and change our interpretation of neutron star mass-radius relationships and their observational consequences. Furthermore, the results place tight constraints on the symmetry energy, which controls the properties of neutron-rich matter, including the composition of neutron stars and exotic nuclei.

In conclusion, this thesis demonstrates that kaon production in heavy-ion collisions provides a valuable probe of nuclear matter at high densities. The findings not only enhance our understanding of the high-density EOS but also provide important input to neutron-star and other astrophysical studies. Further experiments, especially at higher energies or different collision systems, will continue to enhance our understanding of nuclear matter under extreme conditions and constrain nuclear EOS theoretical models.

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