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Separating $K^\pm$ from $\pi^\pm$ using In-Flight Decays to $\mu^\pm + \nu$

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Abstract

A method is presented for completely distinguishing between charged kaons and charged pions by using their charged muon (plus neutrino) decays (with neutrinos undetected) for meson laboratory momenta up to 1000 MeV/c. When either a charged kaon or a charged pion decays into a muon and a neutrino, momentum-energy (four-momentum) conservation will be used to provide unique "kinematic trajectories" for distinguishing kaon decays from pion decays when the change in three-momentum of the muon from that of either parent kaon or pion is measured (or simulated). In a magnetic field, observation of a tracked particle showing a "kink" and/or a change in helicity indicates the decay of the parent particle into a similarly-charged muon product. Unique kinematic separation between each parent kaon and parent pion is possible for each parent particle's momentum up to 1000 MeV/c. Curvature-radius of the helical path in a magnetic field is used to determine each charged particle's momentum, whether it be a kaon, a pion or a muon. A weak field is adequate for making this determination since momentum (curvature radius) need only be measured to an accuracy of about 10%. Monte Carlo calculations of the kinematic trajectories have been carried out for primary meson momenta between 0 and 1000 MeV/c and for a range of emission angles (or "kinks") between 0° and 180°. Monte Carlo results from these in-flight decay kinematic calculations show a complete separation is possible for pion decays from kaon decays for laboratory momenta up to 1000 MeV/c because these two classes of meson decays cluster into completely separated 2-D regions of difference-momentum $\otimes$ muon-angle space. The most difficult region for separating primary particles occurs for small-kink decays within less than 5°. Decay halflife and time dilation require an efficient time projection chamber to be fairly large, because kaons are strongly favored over pions at the higher laboratory momenta and for the smaller time projection chamber geometries.

Introduction

The present work provides the foundation for success for two distinct and different research efforts. (1) Mapping a Time Projection Chamber (TPC) for acceptance and efficiency as a function of position within the TPC will be seen as possible now using the present method of identifying charged pions from charged kaons within a large TPC (Sauli, 1987). (2) Measuring the strangeness production occurring in each central collision between two ultra-relativistic nuclei is made possible by counting the total number of charged kaons decaying within the TPC, as kaon production will be seen to provide a direct measure of strangeness production. This latter effort complements measurements of neutral kaon decay within a microTPC designed to be the component detector located closest to the collider vertex for ultra-relativistic nucleus-nucleus collisions (Braithwaite and Braithwaite, 1997).

The feasibility of detecting charged kaons was studied using the kink pattern and/or change in helicity-radius of a track (Howe et al., 1995) associated with each secondary muon formed in $K^\pm \rightarrow \mu^\pm + \nu$ decay. This kaon decay has a 63.51% branching ratio as opposed to and distinguished from secondary muons formed in the following pion decay:

$\pi^\pm \rightarrow \mu^\pm + \nu$, which has a 99.99% branching ratio (in neither case is the neutrino detected).

"Kinematic trajectories" for these decays cluster into completely separated 2-D regions of difference-momentum $\otimes$ muon-angle space, or $\Delta P \equiv |P_O - P_\mu| \cdot \text{sign}(P_O - P_\mu)$ versus θ_μ, showing kinematic separation is possible between charged kaon decays and charged pion decays. This complete kinematic separation is attributed to the much larger breakup momentum, 235.5 MeV/c in the center of momentum frame, available to each of the binary decay species (muon and neutrino) in the process of $K^\pm \rightarrow \mu^\pm + \nu$ decay. In contrast, a much smaller breakup momentum, 29.8 MeV/c in the center of momentum frame, is available to each of the binary decay species (muon and neutrino) in the process of $\pi^\pm \rightarrow \mu^\pm + \nu$ decay.

A fully-relativistic kinematics program (Braithwaite, 1972) was used to calculate each outgoing muon momentum arising from the spontaneous in-flight decay of either type of parent meson into a muon and a neutrino.

This study will demonstrate how easy it is to effect separation between the muon decay products coming from kaons and pions using kinematics alone, and thus it will establish the feasibility of using muon decays of charged pions and/or charged kaons in determining the acceptance

and efficiency of a large Time Projection Chamber (TPC) like the Main TPC of the STAR (Solenoidal Tracker) instrument at the Relativistic Heavy Ion Collider (Climer et al., 1996).

Pions dominate the charged particle production following a central Au on Au event at the Relativistic Heavy Ion Collider (RHIC). Kaons only occur between 5% and 10% as frequently, thus, any method proposing to extract the kaon decays must separate them completely from the pion decays if these decays are to be uniquely identifiable as coming from kaons rather than pions in a sea of background pions.

Materials and Methods

Above 500 MeV/c, charged kaons and charged pions interact with the gas in a large TPC to produce fairly similar ionization track densities, as a result track density is of little use in distinguishing kaon tracks from pion tracks. A limited but unique signature is possible for identifying kaons from pions if we examine the subset of kaons and pions that decay into muons before leaving the TPC.

In fact, since track densities for kaons, pions and muons are all quite similar within a TPC, kaons are only easily distinguished from pions at the point of spontaneous in-flight decay of each meson to a muon plus a neutrino. At the point of decay a "kink" occurs and the helicity of the track changes, as the laboratory momentum of the outgoing charged muon will be different from that of the parent meson. The meson particle-parentage may be determined by comparing the change in the track's helicity-radius (momentum) with the full spectrum of calculated kinematic trajectories of the muons produced in these decays. 99.99% of charged pions decay by $\pi^\pm \rightarrow \mu^\pm + \nu$; thus, before considering the detection of charged kaons from the kink pattern and the track helicity-change associated with each $K^\pm \rightarrow \mu^\pm + \nu$ decay (a 63.51% branching ratio), contributions from pion contamination must be shown to be negligible.

A fully-relativistic kinematics program (Braithwaite, 1972), originally written in FORTRAN, was modified to accommodate an EXCEL spread-sheet Monte Carlo calculation of the spontaneous in-flight decay of either type of parent meson into a muon and a neutrino. The "target" particle in an in-flight decay is non-existent, so both its rest mass and kinetic energy were taken as zero. This simplified the formalism somewhat, facilitating the calculation enough to make a spread-sheet approach practical. For each value of momentum for each meson species, laboratory-momentum branches (as applicable) were calculated for the outgoing muon from each decaying meson species.

Using the spread sheet method above, kinematic trajectories have been calculated for the in-flight decays of both pions and kaons for laboratory momenta up to 1000 MeV/c over the complete range of laboratory muon angles between 0° and 180°. 4000 Monte Carlo events were used to vary randomly the relativistic three-momentum for each pion and kaon between 0 and 1000 MeV/c. Equally spaced muon angles were chosen when calculating outgoing muon momentum associated with each parent kaon and parent pion.

The difference between the initial momentum of kaons or pions and the final momentum of the decaying muon is easy to determine experimentally (to better than 10%) using an externally-imposed (weak) magnetic field. To facilitate separation a graph of momentum difference versus laboratory angle was generated, giving predicted "kinematic trajectories" which are unique for each type of parent meson.

Results and Discussion

Figure 1 shows a distinct separation between "kinematic trajectories" for kaon decays from that for pion decays, except at muon angles of less than 5°. This graph shows that decaying pions may be separated uniquely from decaying kaons by comparing the momenta of initial and final charged particles at muon angles greater than 5°, where a "kink" in the charged-particle track has a chance of being noticeable.
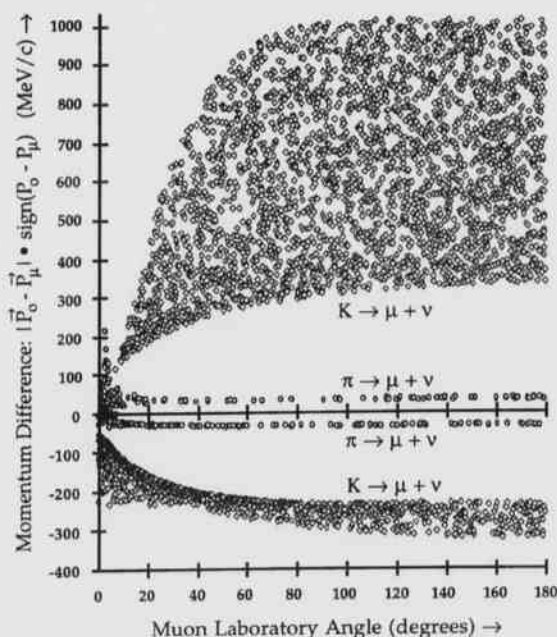

Fig. 1. "Kinematic trajectories" using the measureable $\Delta P \equiv |P_o - P_\mu| \cdot sign(P_o - P_\mu)$ show kaon decays cluster into completely separated 2-D regions of $\Delta P \otimes \theta_\mu$ space from pion decays. MC events for $\theta_\mu < 10°$ need further examination.

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To investigate the separation of muons from parent kaons versus muons from parent pions in the less well resolved angular region (of each forward-going muon) using "kinematic trajectories" alone, in-flight decay kinematics were examined (in a similar manner). 4000 Monte Carlo events were used to provide the laboratory three-momentum for each outgoing meson while restricting the muon laboratory angles to values between $0°$ and $15°$ (the less well resolved angular region). Figure 2 shows the results of focusing an additional 4000 Monte Carlo events into this forward angular region. Good separation between incident pions and kaons is seen for all laboratory momentum values for the parent mesons up to 1000 MeV/c.
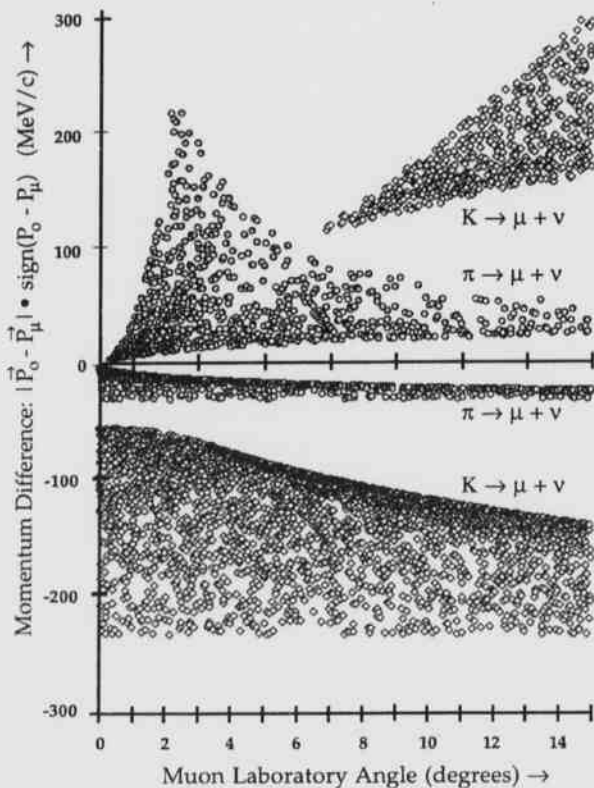

Fig. 2. 4000 Monte Carlo events between $0°$ and $15°$ show good separation of kaon decays from pion decays in this less well resolved angular region.

Much above 1000 MeV/c, the use of "kinematic trajectories" alone fails to effect separation between parent kaons from parent pions at the most forward angles. However, at muon-emission angles larger than $5°$, the separation between decaying kaons and pions remains complete. Also, it is worth noting that few kaons or pions are produced at

laboratory momenta above 1000 MeV/c. In addition, due to time dilation, those few pions produced above 1000 MeV/c will have their effective lifetimes (in the laboratory) increased dramatically compared to that of the kaons, therefore, pions (with laboratory momenta greater than 1000 MeV/c) will be considerably less likely to decay within the active volume of even a large TPC.

For example, at a laboratory momentum of 1000 MeV/c, a charged pion ($\tau = 26.03$ nanoseconds, or $c\tau = 7.804$ meters) will have a relativistic factor of $\gamma_\pi = 7.23$ (which is its time dilation factor). Thus in the laboratory the *effective* $c\tau = 56.42$ meters. If we take the geometry of the Main TPC of STAR (with an inner diameter of 2 meters and an outer diameter of 4 meters), the fraction of charged pions at 1000 MeV/c decaying within the Main TPC is $\exp(-1m/56.42m) - \exp(-2m/56.42m) = 0.0173$ or about 1 in 60.

In contrast, at a laboratory momentum of 1000 MeV/c, a charged kaon ($\tau = 12.37$ nanoseconds, or $c\tau = 3.7$ meters) will have a relativistic factor of $\gamma_K = 2.259$ (also its time dilation factor). Thus in the laboratory the effective $c\tau = 8.358$ meters. If we again take the geometry of the Main TPC of STAR, the fraction of charged kaons at 1000 MeV/c decaying within the Main TPC is $\exp(-1m/8.358m) - \exp(-2m/8.358m) = 0.100$ or about 10%. Thus, at this high momentum, kaons are favored over pions by about a factor of 6. Despite a smaller kaon branching ratio, time dilation brings up the ratio of kaon decays to pion decays within the Main TPC to between 20% and 40%, which is much closer to parity.

Now that a complete separation in particle-parentage is possible by associating a simulated or a measured meson decay with a unique "kinematic trajectory," the next step is the mapping of the TPC using either kaons or pions. Any realistic simulation of this TPC mapping requires a charged-particle transport program that takes into account interactions within the detector as well as motions of the particles within the relevant magnetic fields. The Monte Carlo program GEANT (1994) is capable of carrying out this particle-transport, and GEANT is available to members of the STAR Experiment at RHIC from the Center for European Nuclear Research in Geneva, Switzerland (CERN).

Now that mapping the acceptance and efficiency of STAR's Main TPC (with either kaons or pions) is seen to be possible, the second research effort, namely sampling kaon production, is seen to be possible as well. These two research efforts are now feasible, as it has been established that using "kinematic trajectories" alone it is possible to distinguish charged kaon decays from charged pion decays. The momentum changes need to be measured associated with the kink patterns in the charged-particle tracks and the associated change in the helicity-radius (momentum) of these tracks associated with the respective muon decays in

the reactions: $K^\pm \to \mu^\pm + \nu$ and $\pi^\pm \to \mu^\pm + \nu$.

Increased strange-quark production is one of the signatures that a Quark-Gluon Plasma was created in the aftermath of an ultra-relativistic nucleus-nucleus collision as predicted by the Standard Model (Harris and Müller, 1996). Thus the second research effort, namely sampling kaon production for comparison purposes between different primary collider events, is physically interesting for the substantial number of kaon events expected to occur for each primary ultra-relativistic nucleus-nucleus collision. Measuring an increase in singly-strange kaon production in the aftermath of each central Au-Au collision is tantamount to measuring an increase in strangeness production, one of the signatures of the onset of a Quark-Gluon Plasma.

Examining kinks and/or radius of curvature changes in a charged-particle track in order to determine into which pattern of in-flight decay kinematics the parent meson resolves itself allows the mapping of the acceptance and efficiency of the Main Time Projection Chamber of STAR using either meson species. Simulating the decays of either or both meson species is facilitated using the *generating* tables called *TAS Tables* which are derived from CERN's Monte Carlo program GEANT and provided to its users by the STAR Collaboration (Olson, 1993). These tables provide all the transport and kinematic information necessary for a TPC acceptance and efficiency study.

The output from these TAS Tables may be used to generate simulated pixel data for use in examining and critically testing the tracking algorithms (Howe, 1995) used to establish the charged-particle momenta, before and after the "kink." Whether obtained from real pixel data or from simulated pixel data, the momentum change and the angle change make possible the classification of each "kink" event into either a parent kaon or a parent pion using the present work.

As discussed earlier, the charged kaon lifetime is less than half the charged pion lifetime. Thus the kaon is more likely to decay within even a large TPC than is the pion. In addition, the charged kaon rest mass of 493.65 MeV/c^2 is substantially larger than the charged pion rest mass of 139.57 MeV/c^2, resulting in a substantially smaller time dilation for kaons than for pions at the same laboratory momentum (less than 1000 MeV/c).

Neglecting time dilation, a rough estimate of the number of kaons decaying within STAR's Main TPC is $\exp(-lm/3.7m) - \exp(-2m/3.7\,m)$ or about 1/5 of ($\sim 2/3$ of) the total number of charged kaons being produced, which is roughly 40-60 kaons per primary collider event. At a laboratory momentum of 1000 MeV/c, the time-dilation factor for charged kaons is $\gamma_K = 2.26$, less than 1/3 of the time-dilation factor for charged pions that is $\gamma_\pi = 7.23$ (see the earlier discussion). In addition to its smaller (rest-frame) lifetime, the smaller time dilation factor for the kaon additionally favors its decay over pion decay within the TPC, thus bringing the populations of decaying kaons and decaying pions within STAR's Main TPC into a more even balance.

TAS tables mentioned above are accessible to any user familiar with general purpose programming using event-based data-processing. Statistical accuracy in any Monte Carlo simulation of TPC acceptance and efficiency may be improved by aggregating the results of several primary 200*A GeV Gold-on-Gold collisions, in which each Gold nucleus has a kinetic energy of 19,600 GeV in the laboratory. Aggregating charged meson production from several primary Au-Au events increases the number of charged kaons (or pions) traveling through the TPC, improving the calibration accuracy. For normalization purposes, the *average* number of kaon (or pion) decays into muons within the TPC may determined for each primary event.

In summary, the present work provides the foundation for success for two distinct and different research efforts. Mapping a Time Projection Chamber (TPC) for acceptance and efficiency as a function of position within the TPC is possible now using the present method of identifying decaying charged pions from decaying charged kaons within a large TPC. Also, because the two classes of meson decays cluster into completely separated 2-D regions of difference-momentum $\otimes$ muon-angle space using the measurable $\Delta P \equiv |P_O - P_\mu| \cdot \mathrm{sign}(P_O - P_\mu)$ versus θ_μ, measuring strangeness production in each central collision between two ultra-relativistic nuclei is possible now by separating kaon decays (from pion decays) by identifying the appropriate "kinematic trajectory" for the decaying meson, then counting the total number of charged kaons decaying within the TPC. This method has merit as singly-strange kaon production is known to provide a direct measure of strangeness production. All other strange hadrons are produced in numbers too small to provide any hope of choosing one central collision over another by using them to measure strangeness production.

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