Strangeness production has long been proposed as a diagnostic tool for understanding the dynamics of relativistic heavy ion collisions. In this presentation we review the traditional picture of strangeness enhancement as a signature for quark-gluon plasma formation. We then review, in order, some experimental data on strange particle production in $e^+e^-$, $pp$, $p\bar{p}$, proton-nucleus and nucleus-nucleus collisions. This is not a comprehensive review, but rather an emphasis of a few significant points. Any clear interpretation of strange particle yields measured in heavy ion reactions is impossible without a physical understanding of the production mechanisms in elementary particle collisions.

1 Introduction

Hadronization of parton jets and multi-partonic systems is not directly calculable using Quantum Chromodynamics (QCD). This non-perturbative physics can only currently be described with phenomenological models that have been developed over the last 30 years. There are many such models including string fragmentation models, quark coalescence models, and statistical models. For the purposes of this presentation, we will use the statistical model as a baseline for comparing different colliding systems in terms of strangeness production. This is not meant to advocate one schematic description of hadronization over another.

Calculations assuming thermal and chemical equilibrium in hadron gas fireballs assume a universal hadronization mechanism and find a parton-hadron transition at a temperature of $T \approx 170$ MeV. The agreement between experimentally observed hadron yields in electron-positron jet fragmentation and in proton-(anti)proton reactions is reasonable. However, it is observed that particles carrying strange quarks are not in complete chemical equilibrium. There appears to be an additional suppression as expressed below:

$$\lambda_s = \frac{s\bar{s}}{2(u\bar{u} + d\bar{d})}$$  \hspace{1cm} (1)

There appears to be a deficit of strange hadrons that is common in inclusive proton-proton, proton-antiproton, $e^+e^-$ collisions as shown in Figure 1.

It was this observed suppression that led to the postulation that one could
Figure 1. $\lambda_s$ as a function of $\sqrt{s}$ for various colliding systems

bring the strange hadrons into chemical equilibrium via pre-hadronization partonic interactions or post-hadronization re-scattering. However, the time scale for total strangeness ($\Lambda, K$) equilibration via hadronic re-scattering is 10-100 fm/c, while for strange antibaryons ($\bar{\Lambda}, \bar{\Xi}, \bar{\Omega}$) take more than 1000 fm/c. It is interesting to note that some recent calculations differ substantially from the above rate calculations.

The strangeness equilibration time in a deconfined system of a quark-gluon plasma is substantially shorter, of order 3-6 fm/c. This is due to contributions from gluon-gluon fusion to $s\bar{s}$ pairs. This time is well within the expected heavy ion collision lifetime of 10-15 fm/c before particles are free streaming. It is comparable to the time in heavy ion collisions that one might naively expect a deconfined region to exist before it cools to the point of hadronization.
2 Proton-Proton

Often the assumption is made that there is no quark-gluon plasma formed in proton induced reactions. This raises the question of the definition of the quark-gluon plasma. One answer is that it is an extended region of space with strong color fields characterized by a large density of deconfined partons and restoration of approximate chiral symmetry. Although the parton density achieved in elementary particle collisions is quite large, the volume is not, and one can argue whether it represents a well-defined thermodynamic state.

In fact, Bjorken speculated that in the “interiors of large fireballs produced in very high-energy pp collisions, vacuum states of the strong interaction are produced with anomalous chiral order parameters.” He applied a schematic picture referred to as the Baked Alaska in describing pp collisions, and the MINIMAX experiment at Fermilab searched for disoriented chiral condensates. Although MINIMAX yielded a null result, this picture is not ruled out.

Experiment E735 at the Fermilab Tevatron studied pp collisions to look for quark-gluon plasma signatures. Both E735 and UA1 and others observed a substantially larger source volume in high multiplicity pp (p̅p) events via two particle correlations measurements. They also observed transverse momentum spectra that have a mass ordering that some described via hydrodynamic flow. E735, UA1 and the AFS experiment at the ISR observed a substantial enhancement of strange particle production as a function of the total particle multiplicity. These observations led some to speculate that a quark-gluon plasma was being formed. However, these effects can also be explained consistently by a picture of event bias from the multiplicity selection on events with hard processes, in particular gluon jets. Thus, one needs to take care in comparing non-inclusive pp data.

It is also interesting that statistical models often use the grand canonical ensemble. One can use the GCE even when the energy and other quantum numbers are conserved. The temperature and chemical potentials simply reflect the characteristics of the system. However one must be careful in the interpretation in particular of fluctuations quantities. If the volume of the system is large GCE is appropriate; however, for small volumes you must conserve quantum numbers (for example strangeness) in every event. Thus the canonical ensemble is relevant. In the CE, strangeness is suppressed in very small volume reactions and reaches the GCE limit only for large volume. It would be interesting to see if this can be tested in pp events with different HBT radii. There may be technical difficulties in dealing with autocorrelations with HBT radii and other collision characteristics.
3 Proton-Nucleus

Inclusive $pA$ reactions have only a few binary $NN$ collisions, and are thus not so different than $pp$. However, measuring recoil nucleons in $pA$ reactions allows one to select events where the probability of many binary collisions is large. This type of analysis is now being done by experiment E910 at the BNL-AGS and NA49 at the CERN-SPS.

E910 observes that the $K^+$ and $Λ$ production increases rapidly as a function of the number of collisions suffered by the proton and then appears to level off with no increase in production after $\approx 4$ collisions as shown in Figure 2. The data do not appear to scale with the number of participating nucleons (as is often used as a baseline for comparison in AA collisions). E910 has pointed out that the difference between the $Λ$ production data and participant scaling appears to increase linearly with the number of binary collisions up to three collisions. Three step valence quark stripping mechanisms and baryon junction models have been suggested to explain the data. The $Ξ$ is also measured and shows an even stronger enhancement relative to participant scaling that the singly strange hadrons. Also, most of the additional production is at target rapidity. Thus, measurements only at mid-rapidity are missing most of the increased production. $K^-$ production increases with $N_{coll}$, but after 4-5 collisions it sharply decreases. This decrease is potentially explained in that when the proton strikes the center of the nucleus ($N_{coll} > 5$), there is a high probability for processes such as $K^- + N \rightarrow π + Λ$ to effectively absorb the $K^-$.  

NA49 also observes a similar enhancement for all strange particles, in particular the the doubly strange baryons. NA49 and WA97 observe that the $Ξ$ yields increase faster than would be expected from simple participant scaling. Understanding the physical mechanism for the strangeness enhancement at both AGS and SPS energies is a theoretical challenge.

4 Nucleus-Nucleus

Heavy ion collisions at the AGS show an increase in the $K^+ / π^+$ ratio as a function of centrality or the number of participating nucleons, and thus total strangeness is enhanced. Most hadron yields can be described by a statistical equilibrium model within systematic errors, and one can see in Figure 1 the value for $λ_s$. At the lowest energies run at the AGS ($p_{beam} = 2 GeV$), strangeness production is near threshold and the yield drops drastically as expected.

Experiment E917 measures a ratio $\frac{Λ}{π} = 3.6^{+4.7}_{-1.8}$, which confirms an earlier
Figure 2. Measured Λ multiplicity as a function of the average number of binary collisions $\nu$.

indirect measure by experiments E864 and E878. This large enhancement of strange antibaryons is above the statistical equilibrium level and may result from some balance of enhanced production of $\Xi$ and annihilation losses for the $\bar{\Xi}$. Unfortunately there is no measurement of $\bar{\Xi}$. This is an excellent possible future measurement at the Japanese Hadron Facility (JHF) or an energy upgraded GSI.

Many experiments at the CERN-SPS also observe enhancement of strangeness in many channels. In particular, WA97 and NA49 observe a very large increase in the production of $\Xi$, $\Omega$, and $\Xi$, $\Omega$. The enhancement of participant scaling increases with increasing strangeness content $E_{\Lambda} < E_{\Xi} < E_{\Omega}$. This is the same trend seen in $pA$. The statistical models give good agreement with a temperature of 170 MeV, in agreement with that obtained from high energy $pp$, $p\bar{p}$ and $e^+e^-$. The press release from CERN on the discovery of the quark-gluon plasma states that, “Since the hadron abundances appear to be frozen in at the point of hadron formation, this enhancement signals a new and faster strangeness-producing process before or during hadronization, involving intense re-scattering among quarks and gluons.” It seems that this conclusion is made without full consideration of data at lower energy and in $pA$ reactions.

At RHIC there is already preliminary data from all four experiments
on strange and non-strange hadron yields. They also give a reasonable fit by a statistical model assuming equilibration of strangeness with $T = 170$ MeV. The enhancement of strangeness appears remarkably similar at the AGS, CERN-SPS and RHIC. I predict that LHC will see similar results.

5 Conclusions

Almost everywhere we look we observe enhancement of strange particle production. This effect is magnified as we go from proton-proton to proton-nucleus to nucleus-nucleus collisions. Many in the field assume this implies that strangeness production cannot be a signal of quark-gluon plasma formation. I believe this conclusion is premature. We must understand the global hadronization process from a region of vacuum with strong color fields in order to make progress. Future data at RHIC in $pp$, $pA$ and $AA$ are eagerly awaited.

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