Review of Nuclear Reactions at the AGS

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Results from p+A and A+A collisions from the beam energies 2-18 AGeV/c are reviewed with emphasis on the properties of dense hadronic matter, and its implications for claims that a new state of matter has been formed at the SPS.

1. Introduction

The central goal of AGS heavy-ion program is the study of hadronic matter at several times normal nuclear density: how this matter is formed, and the characterization of its properties. The physics of dense matter is compelling in its own right. In addition we need to understand how the properties of dense matter affects QGP signatures, to help assess whether the QGP has been formed in heavy-ion collisions[1]. My goals for this talk are to review what we have learned about dense hadronic matter, to assess the open questions, and to sketch the possibilities for a future research program.

2. Mean-fields in Dense Matter

The mean free-path of a typical hadron in dense matter is $\lambda = 1/\rho \sigma$, hence at four times normal nuclear density, $\lambda \sim 0.5$ fm. This mean free-path is so short that successive collisions are unlikely to be independent processes. Attempts have been made to model n-body collisions[2] as well as off mass-shell propagation between collisions[3]. A simpler ansatz may be to incorporate the average effects of multiple soft interactions into an effective mean-field. This extends a long tradition in low-energy nuclear physics to higher densities. Within this mean-field, successive elastic and inelastic two-body collisions between hadrons take place, forming resonances and strings that subsequently decay.

One test of this mean-field ansatz is the measurement of the average transverse momentum in the reaction plane ($< p^x >$). Protons measured by E895[4] flow within the reaction plane, i.e. have opposite sign $< p^x >$ either side of mid-rapidity (Figure 1). Qualitatively the flow of protons is driven by pressure gradients in the reaction zone. Quantitatively the magnitude of the flow is not reproduced by calculations that consider only a cascade of two-body collisions. Much better agreement is obtained by including the additional deflection driven by gradients in the repulsive nuclear mean-field.

The proposed mean-field has a complicated dependence on density and momentum[5]. At low momenta the field is moderately repulsive at high-densities, then as the momentum of the particle increases, the field progressively becomes more repulsive. Such a momentum dependent mean-field was found to be necessary[6] to reproduce the measured $p_t$...
distributions of proton from Au+Au reactions at 11.7 AGeV/c (Figure 2)[7].

A sensitive check on the applicability of a mean-field at high densities is elliptic flow: the back-to-back azimuthal emission of particles. At low beam energies elliptic flow is oriented 90° with respect to the reaction plane, where the matter is ”squeezed” out from the top and bottom of the reaction zone. For squeezeout, the second-order moment $v_2$ has negative values. As the beam energy increases, the spectator matter moves rapidly away from the collision, which decreases the spectators’ effectiveness at blocking mid-rapidity emission. The beam energy dependence of elliptic flow is therefore sensitive to pressure gradients and the reaction time-scale[8]. The elliptic flow data from E895[9] and E877[10] (figure 2) change from being directed 90° to the reaction plane (negative moment $v_2$) to elliptic-flow within the reaction plane (positive moment $v_2$). This evolution, as well as the location of no elliptic flow near 4 AGeV, is quantitatively reproduced by a transport model that includes the repulsion due to a momentum dependent mean-field[6].

A future test of the mean-field dynamics will be whether transport models can reproduce the measured azimuthal dependence of pion correlations. Shown in Figure 3 are the extracted HBT parameters measured as a function of azimuthal angle from Au+Au reactions at 4 AGeV[11]. As an indication of the richness of the information in this data, consider the case when $\phi=0$, i.e. when the transverse momentum of the pair is parallel to the reaction plane. At $\phi=0$ the data indicate that $R_{out} < R_{side}$ consistent with the almond shape of the initial collision zone. It is however remarkable that this shape information is retained throughout the dynamics of the reaction to freezeout.

Figure 1. The measured $<p_x>$ for protons from Au+Au reactions as a function of beam energy from E895[4]. The dashed line is a cascade calculation and the solid line includes a repulsive mean-field.
Figure 2. The left panel shows the invariant yield of protons at mid-rapidity from Au+Au at 11.6AGeV/c\cite{7}, while the right panel shows the measured elliptic flow $v_2$ from Au+Au(open symbols). Both observables are well reproduced by transport calculation (RBUU 3.5) that include a momentum-dependent repulsive mean-field\cite{6}.

Figure 3. The extracted HBT parameters as a function of the azimuthal angle between the pair and the reaction plane for Au+Au at 4 AGeV\cite{11}. The lines are a global fit.
The major caveat in these tests of the high-density mean-field is whether the multiple elastic and inelastic collisions are under control in transport models. Recent data on proton distributions in p+A reactions provide insight into these scattering processes, and therefore act as a critical benchmark. The x-distributions \((x = p_z/p_{beam})\) of protons from p+Be reactions at 18 GeV/c\(^{[12]}\) are shown in figure 4. In reactions where the mean number of collisions \((\nu)\) is close to 1, the measured protons are broadly spread over a wide range of x-values. The measured proton x-distribution shifts backwards as the number of collisions increases, consistent with more momentum exchange in multiple collisions. This evolution provides a quantitative test of a transport model’s description of rescattering after the first collision.

![Figure 4](image)

Figure 4. The preliminary x-distribution of protons from p+Be reactions at 12 GeV/c\(^{[12]}\). Reactions with number of collisions \(\nu \sim 1\) have the largest yield at high x. The x-distributions steepen as \(\nu\) increases to \(\nu \sim 2.3\).

Another open question is whether mesons experience a mean-field in dense matter. Data on kaonic atoms\(^{[13]}\) suggest that K\(^-\) have attractive resonant interactions with baryons, whereas for K\(^+\) and K\(^0\) the interaction with baryons is predicted to be repulsive. The interactions kaons experience in dense matter can be incorporated into a mean-field or expressed as a change in the dispersion equation of a kaon propagating in dense matter\(^{[14]}\). The energy at zero momentum is the kaon’s effective mass, which for K\(^-\) is predicted to decrease at large densities\(^{[14]}\). The cleanest observation of the repulsive mean-field for K\(^0\) is the directed transverse momentum for K\(^0\)\(^{[15,16]}\) which is opposite that for the baryons (figure 5). The data are well reproduced by a transport model that include a vector and scalar mean-field that repels the K\(^0\) away from the baryons.
3. Rescattering in Dense Matter

The dense environment in a heavy-ion collision changes the yield of produced particles as compared to p+p reactions. As an example, the centrality dependence of particle production in Si+Au and Au+Au reactions, shows a strong increase in the kaon yield per participant nucleon from peripheral to central reactions. This is consistent with rescattering in central reactions being more effective at producing kaons. The yield of pions per participating nucleon changes more slowly.

These increases in particle production depend complexly on the number of rescattering collisions during a heavy-ion reaction and on the energetics and type of each rescattering. The balance between these factors changes as the beam energy is lowered. For example, the measured $K/\pi$ ratio (Figure 5) decreases as the beam energy is reduced. However, the decrease is not as rapid as the decrease in $K/\pi$ ratio from p+p reactions. This is most easily seen in the $K/\pi$ enhancement shown in figure 5. The enhancement is largest at the lower beam energies which indicates that rescattering becomes relatively more important as the beam energy decreases. At low energies, secondary collisions are close to the kaon production threshold, so the increased enhancement implies a large increase in the number of secondary collisions.

It is worth noting that moving in the other direction and increasing the beam energy, the $K/\pi$ enhancement smoothly decreases from AGS energies to the SPS at 40 and 160 AGeV/c. This is consistent with a smooth evolution of the reaction mechanism. Furthermore the maximum in the $K/\pi$ ratio in A+A reactions can be explained as a mathematical artifact caused by the convolution of a rising $K/\pi$ ratio from p+p reactions and a falling enhancement as the beam energy increases.
A sufficiently large rescattering rate will drive the dense matter towards thermal equilibrium. Thermal models have been very successful in reproducing particle ratios from A+A collisions\cite{20}. The fit parameters of these models, temperature and baryon chemical potential, map out a contour of constant energy density\cite{20} (figure\ 7). The third parameter in the model is the strangeness saturation factor ($\gamma_s$) which measures how close the system is to complete chemical equilibrium. As can be seen in Figure\ 7, $\gamma_s$ is approximately 0.7 in heavy-ion reactions at both AGS\cite{21} and SPS energies. This is larger than the $\gamma_s \sim 0.2$ extracted from p+p reactions\cite{20}, indicating that there are strong processes in heavy-ion collisions that drive the system towards full chemical equilibrium.

At SPS energies it has been suggested that the increase in strangeness production occurs in a new state of matter, possibly the QGP\cite{1}. At AGS energies it is widely considered that the rescattering of hadrons drives the system towards strangeness saturation. It is unsatisfactory to have two separate explanations for very similar experimental results and we need to be confident that hadronic rescattering cannot explain the strangeness production at the SPS. The difficulty is illustrated by two comparisons between hadronic cascade transport calculations and measured strangeness production that are shown in Figure\ 8. The Hadron String Dynamics (HSD) model\cite{5} underpredicts the AGS K$^+$/π$^+$ data, while the RQMD cascade model reproduces the K$^+$ yield at the highest AGS energy but increasingly overpredicts the data as the beam energy is reduced. Based on this trend, it is not surprising that RQMD underpredicts the strangeness yield at SPS energies\cite{22,21}. Given the broad and systematic failure of these models to describe strangeness production at any energy, it does not seem prudent to use their underprediction of strangeness to support the argument that the QGP was formed at SPS energies. We need to understand the failure of these models at 1-10 AGeV/c to help interpret the failure of these models at 160 AGeV/c.
Progress can be made using particle production results from p+A experiments. For example, the production of $\Lambda$ from p+Au reactions increases as a function of the number of collisions (figure 9). Folding this increase into a Glauber model, where each projectile nucleon suffers multiple interactions, accounts for approximately 70% of the measured $K^+$ in Si+Au and Au+Au reactions. The remaining increase may be driven by complex rescattering processes that involve more than exciting projectile nucleons.

Other results from p+A experiments can be used to gain more insight into the physics of rescattering. The measured $x$-distribution ($x = p_z/p_{beam}$) of pions from p+Be is shown in figure 9. Pions with a significant fraction of the incoming momentum, $x > 0.6$, have been previously described as the fragmentation of the leading quark-diquark system. However, the bulk of pions in pA reactions are emitted with $x < 0.3$. These pions could be modeled as a decay of a leading resonance, since if the decay pions are emitted at or near beam-rapidity, they will have a momentum fraction $x < 0.3$.

4. Outstanding Questions in Dense Matter

One of the puzzles in the AGS program is the large $\Lambda/\bar{p}$ ratio observed in both Si+Au and Au+Au reactions. In figure 10 the $\Lambda/\bar{p}$ ratio for central reactions rises significantly above the ratio in peripheral reactions, as measured by experiment E917 and inferred from a comparison of E864 and E878 $\bar{p}$ yields. One possible explanation is a difference in absorption between $\Lambda$ and $\bar{p}$. Models of $\bar{p}$ absorption can now be tested against the recent anti-flow measurements of $\bar{p}$ from E877. An alternate suggestion is that n-body collisions may increase the yield of anti-baryons.

Looking to the future, there are two new planned accelerator complexes that will reach heavy-ion beam energies of 25 AGeV. The Japan Hadron Facility was recently funded for
proton acceleration, and a new facility is proposed for GSI, Germany. The key physics opportunity at both will be to measure soft di-leptons of invariant mass near the $\rho/\omega$ peak. This directly addresses the question of whether hadrons change their properties in dense matter due to the possible change in vacuum condensate as the nuclear density increases. Other opportunities include detailed measurements of the centrality and beam-energy dependence of directed and elliptic flow to provide insight into multiple collisions and the physics of the mean-field at high densities. It will also be important to extend the excitation function of strangeness production and to accurately map out $\gamma_s$ versus $E_{beam}$.

On the more speculative side, it is an open question whether a method can be devised to select events that form a very cold, yet dense system, and explore the region of phase space near the conjectured color superconducting phase of matter\cite{29}. One possibility is to use the stochastic nature of heavy-ion reactions to produce event-by-event nuclear matter with different density and temperature. Dynamical transport models can be used to estimate how broad this variation is and whether there are event-by-event observables that preferentially select reactions that pass through a cool, dense region of phase space.

5. Conclusions

Many of the dynamical observables measured by the AGS experiments are well described by transport models that incorporate soft interactions into a repulsive, momentum dependent mean-field. The success list includes directed and elliptic flow, and proton $p_t$ spectra. In contrast, microscopic attempts to describe the yields of particle production and its beam energy dependence have been relatively unsuccessful. This could be resolved by first using the broad range of pA data to benchmark the detailed processes that occur when hadrons multiply scatter, then applying these lessons to the heavy-ion data.

The measurements of strangeness enhancement and extraction of strangeness chemical
Figure 9. Left panel shows the total yield (open symbols) of Λ from p+Au reactions at 18 AGeV/c (solid symbols are the yield within acceptance). The lines are various parameterizations of the production. The right panel shows the x-distribution of π⁻ production from p+Be at 12 GeV/c. The reactions with the largest number of collisions ν have the strongest yield at low-x.

...saturation suggest that there is a smooth evolution of reaction mechanism from 2-160 AGeV. At the same time there are substantial disagreements between data at the AGS and current hadronic transport models. Both facts imply that we need to improve our understanding of the baseline properties and dynamics of dense hadronic matter before strongly claiming the existence of a new state of matter at the SPS.

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Figure 10. The measured $\Lambda/p$ ratio as a function of centrality from Au+Au at 11.7 AGeV/c [26,27].

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