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DEUTERONS AND FLOW: AT INTERMEDIATE AGS ENERGIES

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ABSTRACT

A quantitative model, based on hadronic physics and Monte Carlo cascading is applied to heavy ion collisions at BNL-AGS and BEVALAC energies. The model was found to be in excellent agreement with particle spectra where data previously existed, for Si beams, and was able to successfully predict the spectra where data was initially absent, for Au beams. For Si+Au collisions baryon densities of three or four times the normal nuclear matter density (ρ_0) are seen in the theory, while for Au+Au collisions, matter at densities up to $10\,\rho_0$ is anticipated. The possibility that unusual states of matter may be created in the Au beams and potential signatures for its observation, in particular deuterons and collective flow, are considered.

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DISCLAIMER

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Abstract

A quantitative model, based on hadronic physics and Monte Carlo cascading is applied to heavy ion collisions at BNL-AGS and BEVALAC energies. The model was found to be in excellent agreement with particle spectra where data previously existed, for Si beams, and was able to successfully predict the spectra where data was initially absent, for Au beams. For $Si + Au$ collisions baryon densities of three or four times the normal nuclear matter density (ρ_0) are seen in the theory, while for $Au + Au$ collisions, matter at densities up to $10\rho_0$ is anticipated. The possibility that unusual states of matter may be created in the Au beams and potential signatures for its observation, in particular deuterons and collective flow, are considered.

1 INTRODUCTION

This meeting CRIS '96, the first in a fruitful series I hope, is to some extent devoted to a phase transition known to exist in infinite nuclear matter, but perhaps not easily created in collisions between finite nuclei. I refer to the liquid to gas tranformation that appears at some 2/3 normal nuclear saturation density in the infinite system. Present at CRIS '96, on the other hand, are a large number of users of the EOS [1] detector, now situated at the AGS and poised to examine another possible phase transition. The latter is the deconfining and/or chiral symmetry restoring transition apparently dictated by QCD in hadronic matter. EOS is to examine at Au+Au collisions at less than the full beam momentum $11.6 GeV/c$ employed in the earliest E866 [2] and E877 [3] experiments at BNL.

Theorists using the ARC simulation [4, 5, 6] have suggested that thermalisation is unlikely at this momentum but possible near $4 GeV/c$. The EOS collaboration [1] proposes to try $2 - 8 GeV/c$ and has preliminary data at 4. Declan Keane [7] has already reported on the latter. I will here discuss work, mainly of my younger colleagues, on deuteron yields [8], and of David Kahana and Yang Pang on sideways flow [9, 10], which may provide signals of unusual collective behaviour at the lower AGS energies. I will not provide details of ARC; David has talked about these to this audience on previous occasions. Also, you have already heard from Aichelin [11] and Faessler [12] on QMD, effectively therefore on RQMD [14, 15], and ARC is just like these without the Q or the M. In fact none of these codes is really quantum in nature. Stripped of mean fields they should reduce to a classical cascade with any quantum effects confined to the form of two body crossections employed.

I would like however to comment on remarks that I have heard in the last few days to the effect that the liquid-gas transition is more likely to be observed in the lab than the hadron-parton transition. Strictly speaking, no phase change can occur in a system of a finite number of particles. Notice I do not just say "finite system", ie a system interpreted as having a surface but still with a very large number of constituents. In collisions of finite nuclei, however, one can still employ statistical mechanics but perhaps not thermo- or hydrodynamics. Entropy remains, therefore, a well defined variable and the entropy change, per baryon say, is much larger in the QCD than in the liquid-gas transition. This is not a proof that either transition is easy to find, nor, more importantly, that one should not seek both assiduosly. Indeed, I am certain the last of these is passed through in regions of collapsing stellar cores, while it is also likely a two to three quark transition showed up in SN1987a [13].

The high density matter EOS is presuming to investigate at $4 - 6 GeV/c$ differs from that of interest at the much higher RHIC energies. At $200 GeV$ c. m. energy, one is concerned with high energy density in the absence of appreciable numbers of nucleons. In contrast, at the low beam momenta high density baryon-rich material is at center stage. It is this latter situation I consider here. Two criteria, often not properly separated in the reader's mind, must be satisfied to permit the occurrence of significant unusual behaviour. First, thermal equilibrium of the collision-generated high density system must be pervasive in both space and time. But equally important, in a supposed first order phase transition (only properly present in an infinite system) the onset must occur at low enough baryon density, i.e. the density intercept for the inner dashed curve in Figure 1.

2 Au+Au with ARC and EQUILIBRATION

I begin then by establishing two things, ARC's credentials as a serious cascade and secondly the energy range in which equilibration is possible. The comparison, for Au+Au collisions at $11.6 GeV/c$ per nucleon, shown in Fig 3 is between ARC calculations and *later* 1992 E866 data [16], i.e. constitutes a highly successful prediction of all single particle spectra in this massive system. The second point is made in the Fig 2 indicating the degree of compression achieved in the Au+Au collision, and more so in Fig 4 displaying the rapidity separation between target and projectile centroids in the same collision.

Figure 2 shows snap shots of baryon density in the $Au + Au$ collisions as function of time in the c.m. system. Local baryon density is defined in a small sphere of material Lorentz transformed to rest. By "colouring" target and projectile baryons differently, as in Figure 2(b) one gains valuable insight into the degree of stopping achieved in the collision and therefore better understands the apparent density enhancement. The large separation in momentum phase space allows one to a large extent to distinguish

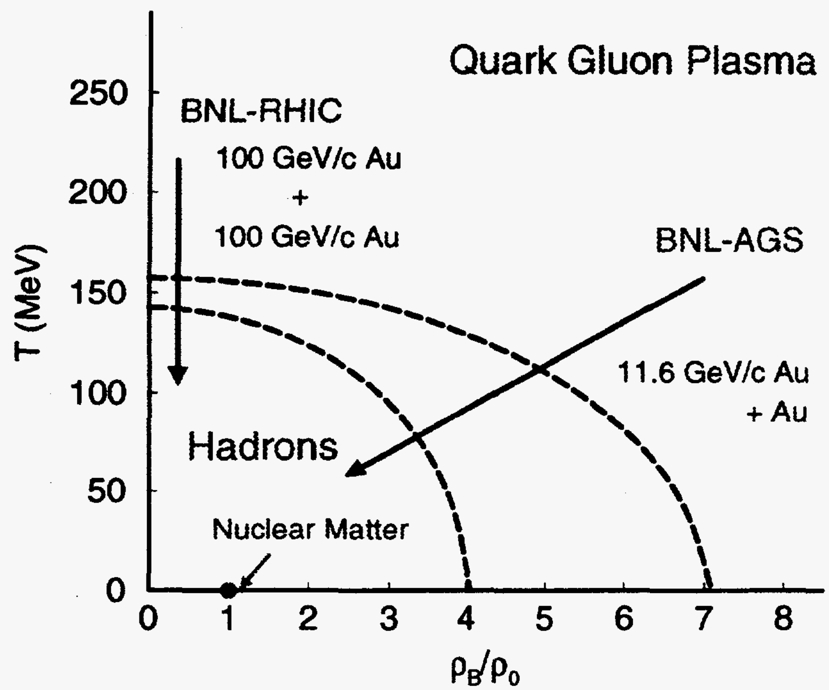
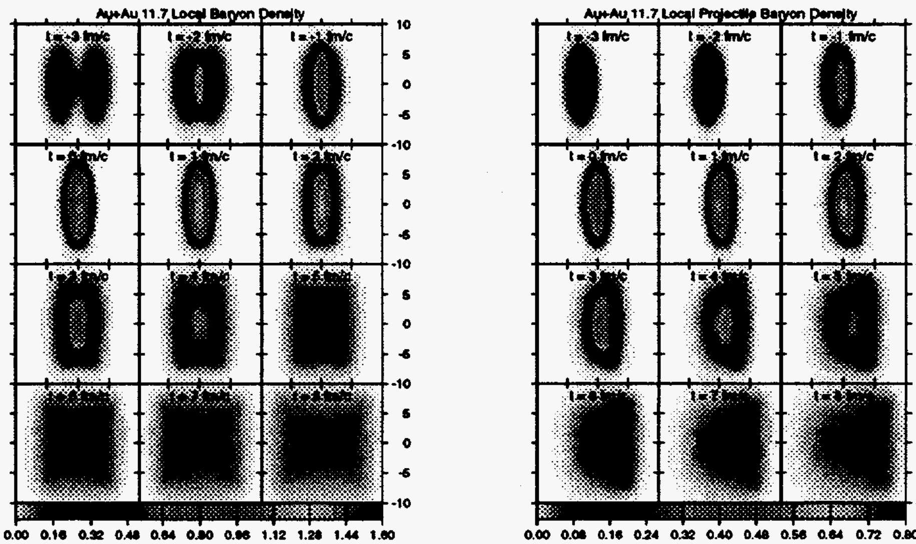
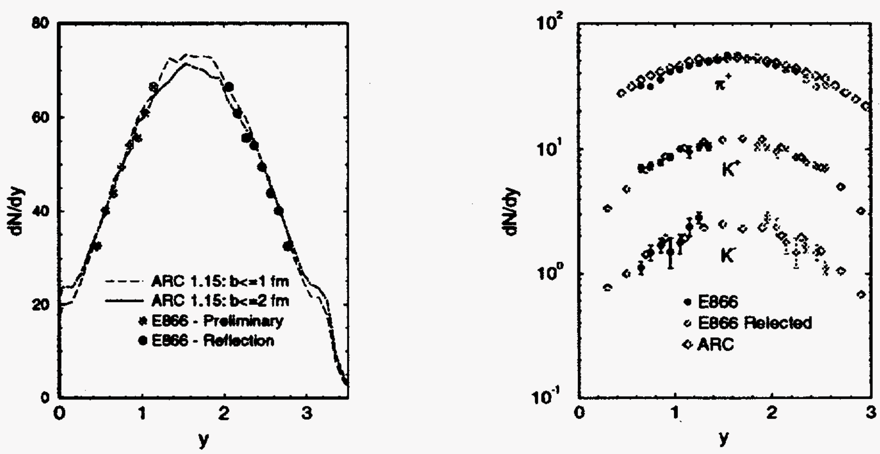


Figure 1: A schematic drawing of the QCD phase diagram, parameterized by temperature and the baryon density. Only hadronic matter is present at low temperature and baryon density. In principle, quark-gluon- plasma apprears for sufficiently high temperature or density. The dashed curves mark the boundaries between the phases. Each heavy ion collision traces a trajectory through the QCD phase diagram, starting at normal nuclear matter, temperature $T = 0$ and density ρ_0, moving to higher temperatures and/or baryon density and eventually returning to the hadronic phase. Two such trajectories are shown, one for the Au on Au collisions at BNL-AGS, which reaches high baryon densities, and the other for the BNL-RHIC energies which will achieve high temperature.



(a) (b)

Figure 2: Snapshots of a $Au + Au$ collision from ARC, showing: (a) combined local baryon density for target and projectile, (b) the density for projectile alone. Comparison of (a) and (b) suggests that compression is taking place in the target and projectile separately, i.e. the target–projectile relative motion is still appreciable throughout the collision.



(a) (b)

Figure 3:
(a) The proton rapidity distribution, in $Au + Au$ at 11.6 GeV/c [2]. (curves are ARC, dots are E866 measurements. (b) Rapidity spectra for π^+, K^+, and K^- in central $Au + Au$.

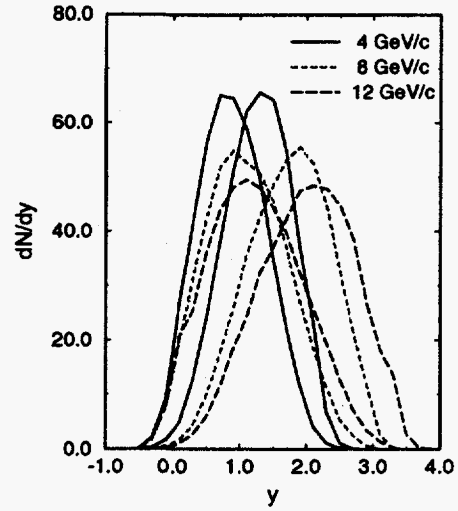
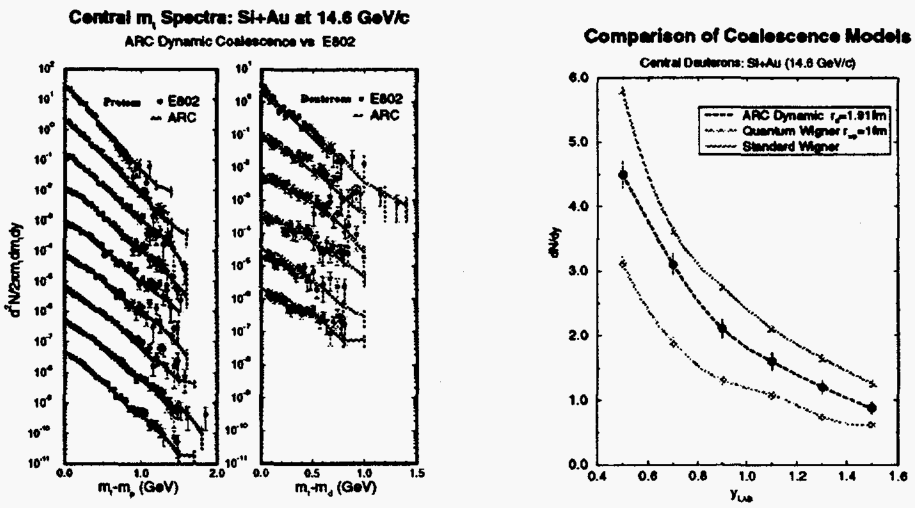


Figure 4: Rapidity spectra in $Au + Au$ for target proton and projectile proton separately as a function of beam momentum. The large separation between target and projectile central rapidities at 11.6 GeV/c reduces the effect of the high baryon density achieved.

target from projectile and view the colliding ions as essentially interpenetrating, high energy, Fermi gases. We conclude in fact from Figure 2(b) that although the local densities rise to more than 8 times normal nuclear densities, the large relative motion between target and projectile baryons renders the operative compression densities perhaps only one-half what they seem. This is apparent from: (i) the reduced density scale in the latter graph showing the evolution of the projectile by itself, and (ii) the rather large rapidity separation between target and projectile rapidity centroids in Figure 4 at the highest beam momentum 11.6 GeV/c.

Considerable transparency persists in the $Au + Au$ collision at 11.6 GeV/c and only a small fraction, less than 20% by preliminary estimates, of the material at the collision center during maximum compression, is equilibrated thermally. Most of the material is at quite reduced density, a factor undoubtedly crucial in permitting a hadronic cascade to accurately portray the collision without invoking medium effects.

Importantly, Figure 4 also indicates the reduction in this target-projectile rapidity separation as a function of decreasing collision energy. By perhaps 6 GeV/c, and certainly at 4 GeV/c the small centroid separation will not legislate against at least thermal equilibrium. Optimum conditions for generation of the matter hinted at in Figure 1 can be determined in the cascade by balancing density vs thermalisation requirements. Lower energy experiments are at this moment underway at the AGS, involving both the conventional E802 and E814 apparati and the detector EOS [1].



(a) (b)

Figure 5: (a) Central Protons and Deuterons from E802 [16] and ARC-DYNAMIC. The experimental trigger which defines central for E802 is also imposed on the ARC analysis. (b) Comparison of ARC-DYNAMIC coalescence deuterons with the Standard Wigner [21, 22, 23] ansatz and with Quantum Wigner (ARC-STATIC with nucleon wave packets spread over 1fm.)

3 DEUTERON COALESCENCE: FREEZEOUT SIZE

In recent work [8] we demonstrated that it is necessary to understand something of these quantum aspects of coalescence to extract the absolute magnitude of cluster yields. Given this, it may then also be possible that information on the size of the ion-ion interaction region, complementary to that from HBT [17], will flow from a study of deuteron production. It must be emphasized that the interaction region or "fireball" spatial extent can only be gathered from knowledge of *absolute* deuteron yields and is in general lost if, for example, the formation acceptances in position and momentum are adjusted to make theoretical yields agree with experiment or the quantal aspects are ignored, as in the oft used "cutoff" models [18, 19]. Most interesting would be the case of disagreement between an improved, self-consistent, cascade calculation and experiment. One would like to conclude, in the presence of such a discrepancy, that the fireball lives significantly longer than the cascade suggests. Ideally, this will occur near $4GeV/c$ where we expect more favourable conditions for baryon-rich plasma creation. The deuteron provides the best cluster for the present purpose because, although the simplest, its spatial dimensions remain quite comparable to those expected for ion-ion interaction region. Factorization of the calculation into a piece arising from the cascade, i.e. the pair nucleon distributions, and one arising from the coalescence, is very probably a realistic description.

One can express the deuteron yield in a particular ion event as

$$n_d = \frac{3}{4}\sum_{ij} C(\mathbf{x}_{n_i}, \mathbf{k}_{n_i}; \mathbf{x}_{p_j}, \mathbf{k}_{p_j}), \tag{1}$$

One notes, [8], there is no isospin factor of 1/2 in the latter equation as claimed in some work [14, 19]. The coalescence probability is related to the overlap of neutron, proton, and deuteron relative and cm wave functions by

$$C(\mathbf{x}_n, \mathbf{k}_n; \mathbf{x}_p, \mathbf{k}_p) = |\langle \psi_n \psi_p | \Phi_{\vec{P},\vec{R}}\, \phi_d \rangle|^2. \tag{2}$$

With gaussian wave packets throughout, characterized by nucleon and deuteron size parameters (σ, α), one obtains:

$$|\langle \psi_n \psi_p | \Phi_{\vec{P},\vec{R}}\, \phi_d \rangle|^2 = \left(\frac{4\nu}{\sqrt{2}\mu}\right)^3 \exp\left(-\frac{\nu^2(\mathbf{k}_n - \mathbf{k}_p)^2}{2}\right) \exp\left(-\frac{(\mathbf{x}_n - \mathbf{x}_p)^2}{\mu^2}\right), \tag{3}$$

where $\mu^2 = (2\sigma^2 + \alpha^2)$, and $\nu = \frac{\alpha\sigma}{\mu}$. The parameter α is related to the known deuteron charge radius but σ, characterizing the, here assumed common, spreading of the nucleon wave functions embodies the quantum dynamics of coalescence. In some (ARC-STATIC) calculations σ is assigned externally and globally for each event, remaining then as an undetermined parameter. However, David Kahana has pointed out the past collision history of the nucleon pair can be exploited to determine σ, for example from the size of the region in the pair's past light-cone, containing comoving interactants. It is such a model, ARC-DYNAMIC, that produced the results shown in Figure 5 comparing theory to experiment [20]. In Figure 5(b) ARC-DYNAMIC is compared to two alternatives Standard Wigner and Quantum Wigner. The former is the standard application of the Wigner transformation, which rewrites the formation probability in terms of two distributions for the cascade generated nucleons and one for the final deuteron. The basic ansatz in Standard Wigner, contrary to the precepts of quantum mechanics, represents the nucleon distributions by sharp (delta) functions in *both* position and momentum. Quantum Wigner uses a small wave packet size $r_{WP} \sim 1 fm$ and hence is equivalent to a "static" ARC treatment.

Clearly, Arc describes the Si+Au deuterons at $14.6 GeV/c$ very well indeed. Predictions for Au+Au at the full $11.6 GeV/c$ are shown in Figure 6. We await EOS data from intermediate energies, hopefully exhibiting an anomalous drop in deuteron yield.

4 COLLECTIVE OBSERVABLES: FLOW

Collective flow [24, 25, 26] in relativistic heavy ion collisions has long been a subject of interest, as a phenomenon likely to illuminate the nuclear equation of state [27]. Recent work by D.E.Kahana and collaborators [9, 10] has shown that flow, adequate for explaining existing BEVALAC data at 1-1.7 GeV/c [24] and new AGS data at 11.6 GeV/c [28], arises in the pure cascade ARC. The effect of mean fields is entirely absent, with only minor two-particle potential adjustments introduced through the orbit style. The latter, responsible in any case for *only a 7% increase* in flow at the

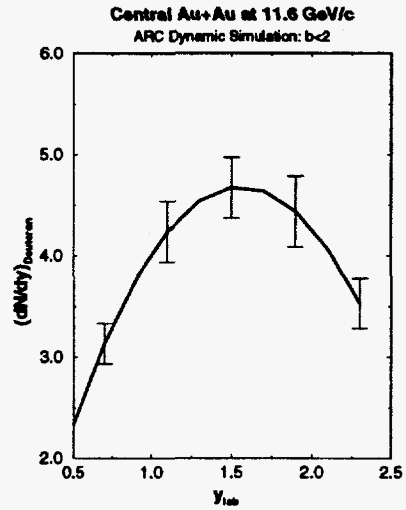


Figure 6: **Deuterons from ARC Dynamic simulation for Au+Au at 11.6 GeV/c.**

BEVALAC, is accomplished by choosing repulsive orbits in the cascade at the appropriate lower NN momenta ($\sim 0.5 - 1.7$GeV/c) and treating the two body scattering as diffractive above the effective 2π threshold [9, 10].

We do not discuss in detail the consistency with earlier cascades [26], but limit ourselves to the relevance of flow as a probe of the equation of state of colliding hadronic matter. Since the latter was explicitly excluded from the above production of flow this is not an idle question. Certainly the cascade, including as it does classical, relativistic kinetic processes, produces at least the thermal pressure of an ideal relativistic gas of resonant and stable hadrons. The potential effect of repulsive orbits adds a van der Waals character. The resultant thermal pressure may be all that is needed for flow. ARC flow calculations appear about right at both low (BEVALAC) and high (AGS) energy. Plasma created at intermediate AGS energy would be accompanied by a drop in overall pressure and might then be observed as an anomalous reduction in the flow.

Figure 7(a) and Figure 7(b) display the agreement with lower energy BEVALAC measurements and predictions for AGS energies, respectively. The AGS energy plot demonstrates the anti-flow typical for produced particles such as the π and $\bar{p}$, presumably due to absorptive shadowing. We now know from clever experiments by E877 [28] that the ARC calculations [10] are in line with data. Relevant to our present purposes is the ARC excitation function exhibited in Figure 8, displaying the two definitions of flow evaluated by David for a fixed centrality cut. It would appear from Declan Keane's presentation here that indeed nothing unusual has been seen in EOS at $4GeV/c$, but more careful comparison with ARC must be done.

I would like to thank the organisers of this conference for inviting me to this wonderful spot and my young colleagues for providing me with material to discuss.

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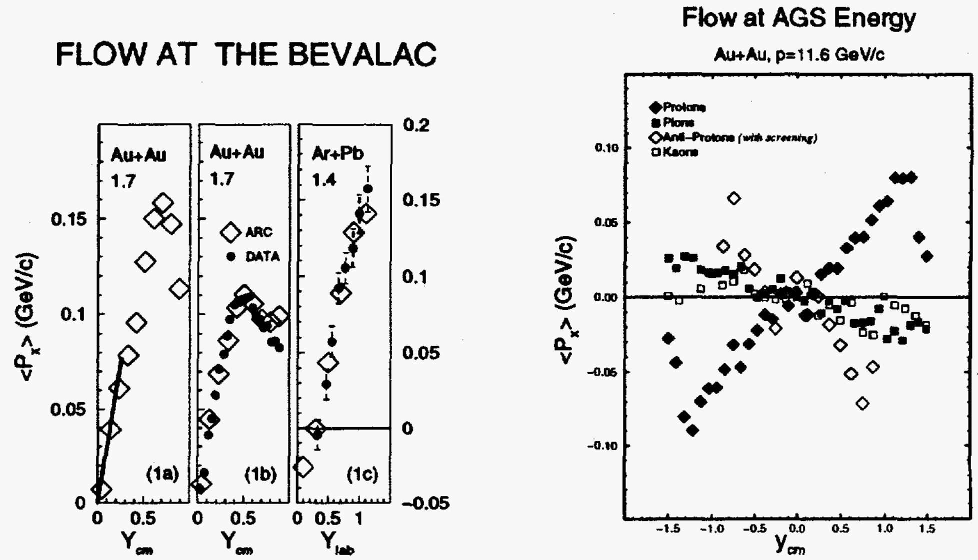

(a) (b)

Figure 7: (a) ARC vs LBL data: The beam momenta (GeV/cA) are given in each figure. (1) Plastic Ball vs ARC. The solid line indicates the Plastic Ball measured slope, corrected for dispersion in the estimated reaction plane and limited to mid-rapidity by the acceptance filter. (2) Arc vs preliminary EOS TPC data as described in [9]. (3) ARC vs Streamer Chamber data for the asymmetric system $Ar + Pb$ for a "semi-central" cut. (b) ARC flow predictions at the AGS for the primary protons and produced antiprotons, kaons (average of K^+(positive) and K^-(negative)). The latter three all have flow momentum opposite in direction to that of the nucleons i.e. exhibit absorptive shadowing.

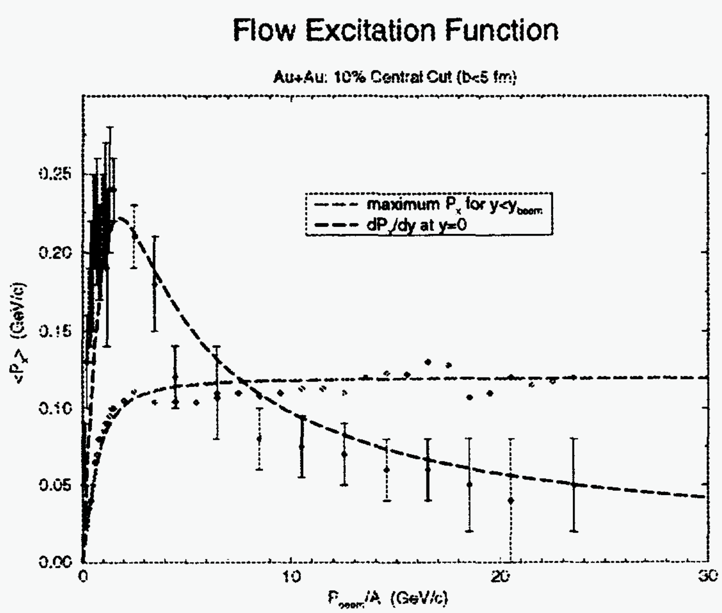

Figure 8: ARC excitation function for two definitions of flow, the slope at mid rapidity and the maximum p_x, for Au+Au in the range from LBL to AGS highest energies.

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