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Summary: Hadron Dynamics Sessions

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1 Introduction

At this Workshop we organized four sessions on Hadron Dynamics. The first topic, *QCD Exclusive Reactions and Color Transparency*, featured talks by Ralston, Heppelman and Strikman; the second, *QCD and Inclusive Reactions* had talks by Garvey, Speth and Kisslinger. The third dynamics session, *Medium Modification of Elementary Interactions* had contributions from Kopeliovich, Alves and Gyulassy; the fourth session *Pre-QCD Dynamics and Scattering*, had talks by Harris, Myhrer and Brown. An additional joint Spectroscopy/Dynamics session featured talks by Zumbro, Johnson and McClelland. These contributions will be reviewed briefly in this summary. Two additional joint sessions between Dynamics and η physics will be reviewed by the organizers of the Eta sessions.

In such a brief review there is no way we can adequately summarize the details of the physics presented here. As a result, we will concentrate only on brief impressionistic sketches of the physics topics discussed and their interrelations. We will include no bibliography in this summary, but will simply refer to the talks given in more detail in the Workshop proceedings. We will focus on topics which were common to several presentations in these sessions. First, nuclear and particle descriptions of phenomena are now clearly converging, in both a qualitative and quantitative sense; we will show several examples of this convergence. Second, an important issue in hadron dynamics is the extent to which elementary interactions are modified in nuclei at high energies and/or densities, and we will illustrate some of these medium effects. Finally, we will focus on those dynamical issues where hadron facilities can make an important, or even a unique, contribution to our knowledge of particle and nuclear physics.

2 Medium Modification of Inclusive Hadronic Interactions

One of the first examples of medium effects in high energy reactions was the EMC effect, discovered in the early 1980's by comparing the F_2 structure function in heavier nuclei with that in deuterium. Since then one sees or predicts a rich variety of medium effects in hadronic interactions at high energies. Here

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2 Medium Modification of Inclusive Hadronic Interactions

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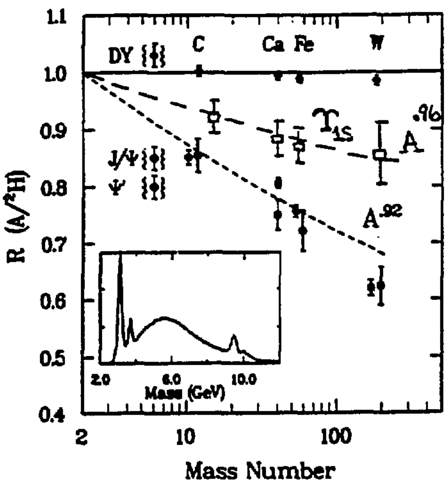

Figure 1. Target mass dependence of cross sections for Drell-Yan continuum (solid line), Υ_{1S} production (long dashed curve), and J/ψ production (short dashed curve); data from FNAL expt. E772.

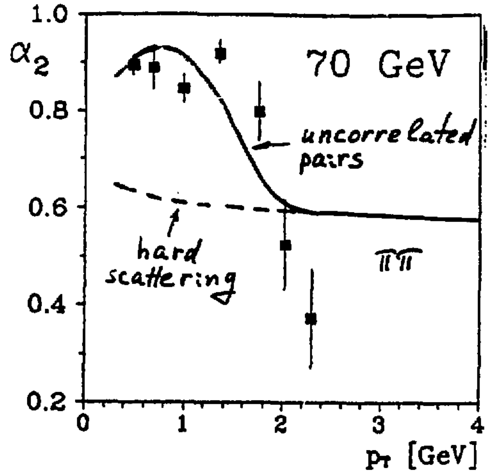

Figure 2. Production of symmetric $\pi\pi$ pairs in $p+A$ collisions. Cross sections vs. p_T, parameterized by A^{α}. Slope α increases at small p_T from production of uncorrelated pairs; slope falls at high p_T where cross section dominated by hard scattering.

we will simply list a few of these as were discussed in various talks presented in the Hadron Dynamics sessions.

First, one predicts significant nuclear effects on production of $q\bar{q}$ at high energies. Some evidence for nuclear suppression of these processes is shown in results from FNAL experiment E772, as reviewed in Garvey's talk. Fig. 1 shows the ratios of integrated yields in nuclei to those in deuterium for three different processes: the Drell-Yan continuum (DY), J/ψ resonance production, and Υ_{1S} production. The DY continuum shows no nuclear suppression, Υ_{1S} production varies like $A^{0.96}$, and J/ψ production varies like $A^{0.92}$.

Next we show some evidence for nuclear effects in the transverse momentum (p_T) dependence for production of symmetric hadron pairs in $p+A$ collisions; this was covered in the talk by Kopeliovich. If one parameterizes the production cross sections as A^{α}, then the exponent α should increase at small p_T, with this apparent "antishadowing" due to production of uncorrelated pairs which dominates at low p_T. At large p_T hard scattering processes should dominate, so the resulting exponent α should then decrease. If one parameterizes A dependence of cross sections as A^{α_2}, as shown in Fig. 2, then data shows clear separation into two regions, with α increasing at low p_T and subsequently decreasing at high p_T.

Finally, we show the predicted effects of gluon shadowing and jet quenching in relativistic heavy ion collisions. In the talk by Gyulassy, it was stressed that singles inclusive spectra are quite sensitive to effects of gluon shadowing and jet quenching. The former effect is the gluon analog of nuclear shadowing of quark structure functions at small x as observed in, say, the EMC effect. Jet quenching results from the energy loss of high p_T partons traversing dense nuclear matter. Fig. 3 shows predicted effects of jet quenching and gluon shadowing for inclusive charged singles spectra in $A+A$ scattering, relative to $p+p$, for gold. Predicted singles spectra are extremely sensitive to these effects. Also shown are the effects of these terms on $p+A$ scattering, which would need to be measured at the same energy

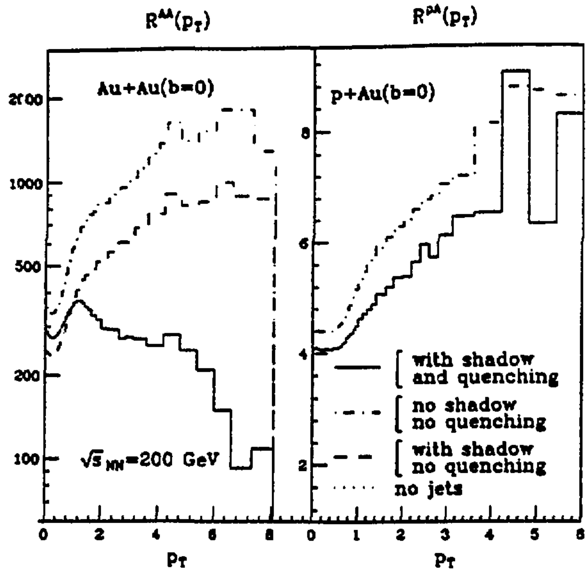

Figure 3. Predicted dependence of inclusive charged-hadron spectra in central $Au + Au$ collisions. Dot-dashed curve: neither gluon shadowing nor jet quenching included; dashed curve: shadowing but no quenching; solid curve: both shadowing, quenching included. R^{AB} is the ratio of inclusive charged hadron spectra in $A + B$ collisions to that in $p + p$.

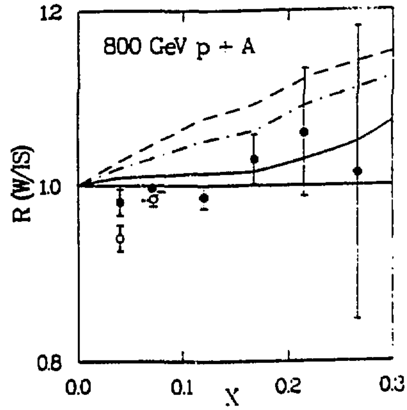

Figure 4. Ratio of Drell-Yan production in W to that in d, vs. x of target, for sufficiently large projectile x (see Eq. 1). Data is from FNAL E772, PRL 69, 1726 (1992), and curves are three phenomenological predictions for this quantity.

to disentangle the two effects.

3 Probing the Structure of the Nucleon with Hadronic Interactions

This material was covered in Garvey's talk. Ever since the pioneering deep inelastic scattering experiments of Friedman, Kendall, Taylor and collaborators at SLAC revealed scaling behavior, physicists have used progressively more precise experiments to measure quark and gluon distribution functions for the nucleon. Lepton–induced DIS reactions have provided much detailed information on structure functions. The most important contributions from hadron-induced reactions have been through Drell–Yan processes. Such processes annihilate a quark (antiquark) from the projectile with an antiquark (quark) of the same flavor in the target, producing a virtual photon which decays into a pair of charged muons.

Since the Bjorken x of the projectile and target can be varied independently in Drell–Yan processes, one can guarantee that either the projectile or target hadron produces the antiquark in this reaction. This is achieved by restricting, say, the projectile x to be large. Since for $x > 0.3$ antiquark distributions are negligible relative to valence distributions, requiring the projectile x_1 to be large and target x_2 to be small guarantees that the antiquark participating in this reaction comes from the target hadron. Precise measurement of antiquark distributions in the nucleon is of considerable interest, due to recent measurement of the Gottfried Sum Rule by the NMC collaboration. This result (obtained by integrating the difference between F_2 structure functions for n and p), implies a difference between up and down antiquark distributions in the proton,

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.14$$

at momentum transfer $Q^2 = 4$ GeV^2.

This result is surprising since most structure functions have assumed that $\bar{d}(x) = \bar{u}(x)$. Perturbative QCD contributions which break this symmetry should be small as they arise primarily from small differences between up and down current quark masses. Consequently, the most likely source of such a substantial difference is some nonperturbative effect. Drell-Yan processes should be sensitive to differences in down and up antiquark distributions. In scattering of protons from nuclei with $N \neq Z$ (relative to those on d), the ratio is sensitive to inequalities in these distributions, since

$$\frac{DY(p+A)}{DY(p+d)} \rightarrow 1 + \frac{N-Z}{A}\left[\frac{\bar{d}(x_2) - \bar{u}(x_2)}{\bar{d}(x_2) + \bar{u}(x_2)}\right] \tag{1}$$

in the limit $x_1 \rightarrow 1$. This quantity has been measured in the FNAL E772 experiment; in Fig. 4 we show experimental results vs. the predictions of three phenomenological predictions. This quantity could be extracted most effectively by comparing Drell-Yan $p+p$ processes to $p+d$; this should be accomplished in the approved FNAL experiment E866. Further fixed target experiments could be performed after construction of the FNAL main ring injector.

Perhaps the most likely nonperturbative effect which could produce a difference between up and down antiquark differences in the proton is the Sullivan effect, by which a lepton scatters from a virtual meson produced by a proton, or where a proton emits a virtual meson and the lepton scatters from the propagating nucleon. This was covered in the talk by Speth. The Sullivan process is noteworthy in that contributions from this process do not disappear (relative to perturbative effects) at very high energies. Various groups, among others Hwang, Speth and Brown, have calculated the contributions from the Sullivan process to sea quarks in Drell-Yan processes. This work is connected to a long program in which this group has undertaken a systematic treatment of meson exchange and meson interactions.

The group has taken hadronic couplings and form factors which fit meson interactions in both spacelike and timelike regions, and has used these to generate sea quark contributions to Drell-Yan processes.

Such calculations involve some uncertainties; as the group includes both strange and nonstrange mesons one must know a series of couplings and form factors. However, given these quantities this group claims to obtain reasonable agreement with observed sea quark distributions. In addition, they suggest that the bulk of the sea quark distribution in the proton might arise from nonperturbative effects, rather than from perturbative gluon production of quark-antiquark pairs.

Another approach was outlined in the talk by Kisslinger on QCD sum rules. In this method, one attempts to evaluate vacuum expectation values of operators in two ways, once by saturating them with hadronic intermediate states and once with quark-based states. The former states involve resonant and scattering states with particular quantum numbers and symmetries, and the latter involve vacuum contributions from specific quark condensates. This approach was initially used to describe particular baryonic and mesonic states, and in recent years has been extended to treat density-dependent many-body problems. This field has quite promising applications to a number of phenomena, and Kisslinger showed applications of this method to determining sea quark distributions in the nucleon.

Studies such as this demonstrate a close connection between medium-energy nuclear physics and particle phenomenology. Coupling constants and form factors extracted from nuclear physics phenomena are applied to inclusive processes at high energy. Although quantitative calculation of either

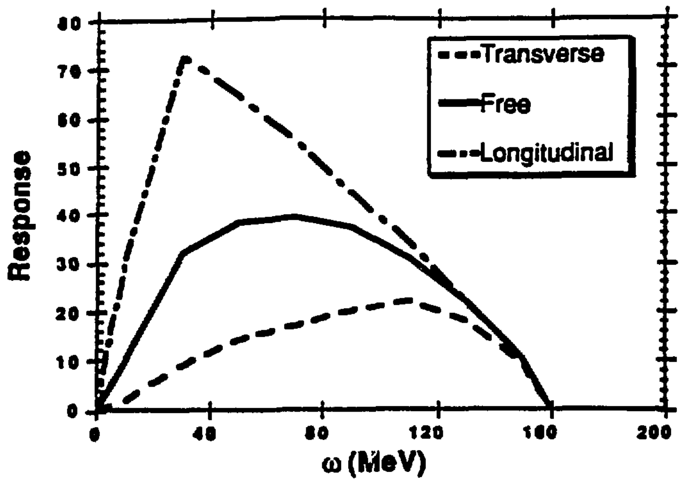

Figure 5. Predicted behavior of spin-isospin response in nuclear matter. Solid curve: free response; dashed curve: transverse response in nuclear matter; dot-dashed curve: predicted longitudinal response.

Sullivan processes or QCD sum rules involves several assumptions, these areas demonstrate a close connection between medium effects in both nuclear and particle physics.

4 Medium Effects on Nuclear Response Functions

It has long been expected that nucleon spin-isospin response functions should be modified in the nuclear environment through coupling of virtual mesons to particle-hole and Δ-hole excitations. The spin response arising from coupling to the pion should be of longitudinal form, $\sigma \cdot \mathbf{q}$, whereas ρ mesons should couple to the transverse response $\sigma \times \mathbf{q}$. The predicted nuclear effects are shown in Fig. 5. Relative to the free spin response, the longitudinal response is expected to be enhanced and softened (pushed to lower energy loss ω), while the transverse response should be quenched and hardened.

Preliminary (p,n) results on ^{12}C have been obtained at the NTOF facility at LAMPF. These are described in the contribution from McClelland, and the separated responses are shown in Fig. 6, for 495 MeV protons, corresponding to momentum transfer $q = 1.72$ fm^{-1}.

The solid curves in Fig. 6 come from RPA calculations which include a Landau-Migdal term with $g' = 0.6$. A striking feature of the data is that the theory gives good quantitative agreement with the transverse response function but disagrees substantially with theory for the longitudinal response. Also, both longitudinal and transverse response are quite similar.

The striking disagreement between theory and experiment pose a real challenge for our understanding of mesons in nuclei. This is just one aspect of a continuing problem of explaining nuclear mesonic effects, which has been summarized in a recent article by Bertsch, Frankfurt and Strikman entitled "*Where are the Nuclear Pions?*". An early explanation for the EMC effect was a small-x enhancement of the F_2 structure function in nuclei due to enhancement of the nuclear pion field. Early calculations suggested 20-40% more pions per nucleon in the nucleus than around the free nucleon, which could account for the 20% increase in the F_2 structure function in iron relative to the deuteron at small

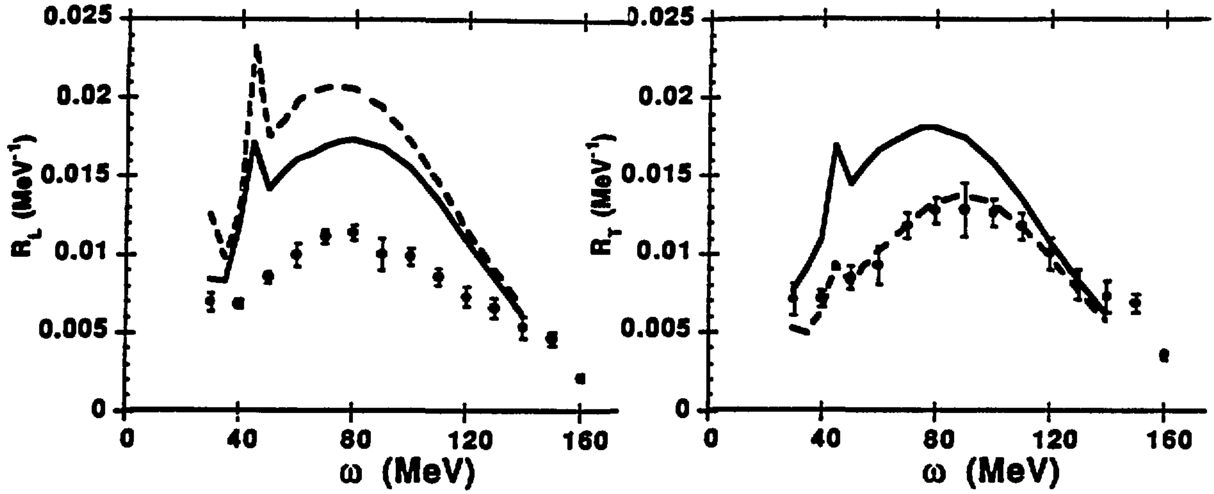

Figure 6. Spin-isospin response on ^{12}C from NTOF at LAMPF. Solid curve: RPA calculation with no short-range NN correlations; dashed curve: includes Landau-Migdal term with $g' = 0.6$. Longitudinal response R_L, transverse response R_T.

Feynman x. However, this small-x enhancement has disappeared in more recent DIS data, and at very small x a nuclear depletion due to shadowing is now observed. Pionic nuclear effects also predict a nuclear enhancement of Drell-Yan processes at small x, and these were also not observed.

We will outline here one possible explanation for this result. This is covered in the talk by G. Brown. Recently Brown, Rho and collaborators suggest that meson masses and coupling constants undergo a "universal scaling" density-dependent renormalization in nuclei, i.e. in nuclei we expect

$$\frac{M_N^*}{M_N} = \frac{f_\pi^*}{f_\pi} = \frac{m_\rho^*}{m_\rho} = \frac{m_\sigma^*}{m_\sigma} = \frac{\Lambda^*}{\Lambda} = s(\rho(r))^2 \tag{2}$$

Since the nucleon effective mass is decreased in nuclear matter, one therefore expects meson masses and couplings (other than for the pion) to be decreased in nuclei. To calculate nuclear mesonic effects in this model, one renormalizes meson masses and coupling constants at the appropriate nuclear density. The phenomenological Landau-Migdal parameter is then adjusted, e.g. to reproduce forward (p,n) cross sections.

In Fig. 7 we show the longitudinal and transverse effective interactions predicted with this model, in free space ($s = 1$) and in a nucleus equivalent to ^{12}C ($s = 0.8$). In free space at $q = 1.7$ fm^{-1}, the longitudinal potential is close to zero while the tensor piece is strongly repulsive; in the nucleus at the same momentum transfer, both longitudinal and transverse terms are weakly repulsive. It should be noted that many nuclear observables are dramatically affected by this renormalization, and that the success of this Ansatz will eventually depend on satisfactory explanation of a number of experimental phenomena. For (p,n) reactions, the universal scaling hypothesis predicts a dramatic density dependence of the central and tensor effective potentials (which are directly related to the longitudinal and transverse effective forces). Hence measurement of the same (p,n) process at different momentum transfer should show very different longitudinal and transverse response if this hypothesis is correct.

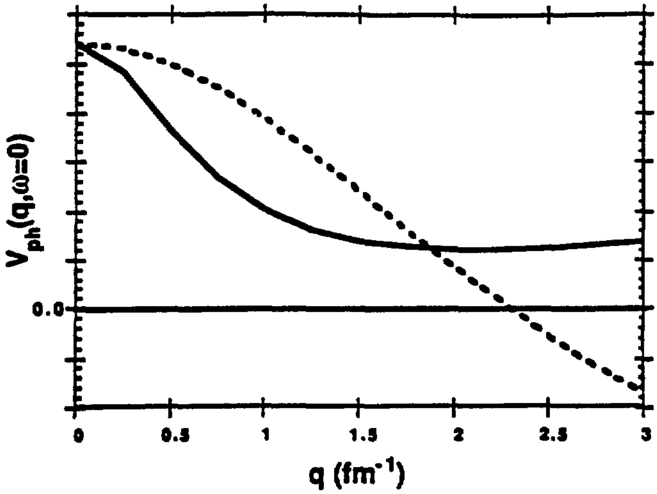

Figure 7. Brown-Rho prediction for longitudinal potential V_L (solid curve) and transverse potential V_T (dashed curve) in nuclear matter ($s = 0.8$), as function of momentum transfer q.

Experiments such as this show a close relation between nuclear phenomena over a very wide range of energy. Nuclear measurements such as (p,n) reactions, or Δ production in nuclear reactions, require understanding of the nuclear pion field. The same pion fields could produce measurable effects in both sea quark distributions in the nucleon (which can be extracted from Drell-Yan experiments or DIS measurements), and should also appear in the EMC effect.

5 Color Transparency and Exclusive Reactions

Motivated by relatively few experiments, the ideas of color transparency have generated an enormous amount of theoretical interest. This topic sits squarely at the intersection of particle and nuclear physics. The dynamics of hadron-hadron interactions are explored within a nuclear medium. In this way it is possible, at least in principle, to determine some fundamental properties of hadrons such as their size just after interactions, and their dynamic evolution with time.

The main emphasis, as noted in the introductory talk by John Ralston, has been the study of exclusive reactions at large momentum transfer. At large momentum transfers, the exclusive reaction is believed to select hadrons in the state of just the valence quarks as opposed to the normal multi-component hadrons with many gluons and $q\bar{q}$ pairs, such as are seen in low momentum transfer reactions. Thus color transparency presents the possibility of probing hadrons while in relatively simple quark configurations of small size so that perturbation theory can be applied.

Ralston also pointed out that the BNL color transparency experiment could be analyzed in a relatively model independent way. If one looks at the A dependence, one finds that the attenuation at 6 GeV/c is consistent with an 18 mb attenuation cross section, and at 10 GeV/c it is 12 mb. This is to be compared to the usual value of about 35 mb.

Mark Strikman noted that experiments which investigate large angle exclusive reactions also present

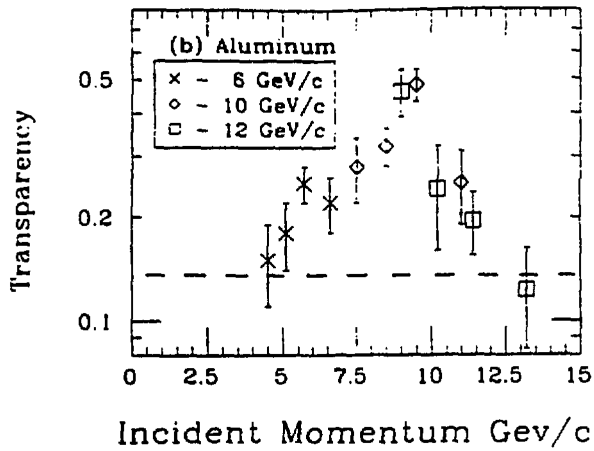

Figure 8. Transparency vs. effective beam momentum for protons on aluminum, in AGS experiment E834. *The dashed line is the Glauber prediction for the transparency.*

the opportunity to explore a number of interesting nuclear effects. Since the hadrons are scattered with momentum transfers corresponding to distances small compared to the size of nucleons, many short-range correlations can be investigated. For example, it is Strikman's view that all nuclei present the same fall off at large Fermi momentum as the deuteron. Another interesting phenomenon is to measure the relative magnitudes of N^*'s and Δ's in the nucleon. Finally he pointed out many interesting connections between color transparency and other processes such as diffractive scattering.

Steve Heppelmann summarized the present experimental situation with regard to color transparency. There are two experiments which study color transparency with large angle exclusive processes. AGS Experiment 834 measured the transparency of various nuclei for pp elastic scattering from 6 to 12 GeV/c. The behavior of the best studied element, aluminum, is shown in Figure 8. The initial rise of the transparency toward the high energy limit of 1.0 was expected in many perturbative QCD models. The sudden drop above 10 GeV/c was unexpected, and explanations require the addition of nonperturbative amplitudes. Another recent experiment at SLAC has preliminary data on the $(e, e'p)$ reaction, and see no effect. However, the momentum transfer is lower and the expected effect is smaller, so there is no definite contradiction at this time. The BNL group has been building a large solenoidal detector, EVA, which will allow more definitive measurements of color transparency up to 20 GeV/c. In addition a number of nuclear correlation studies will be possible.