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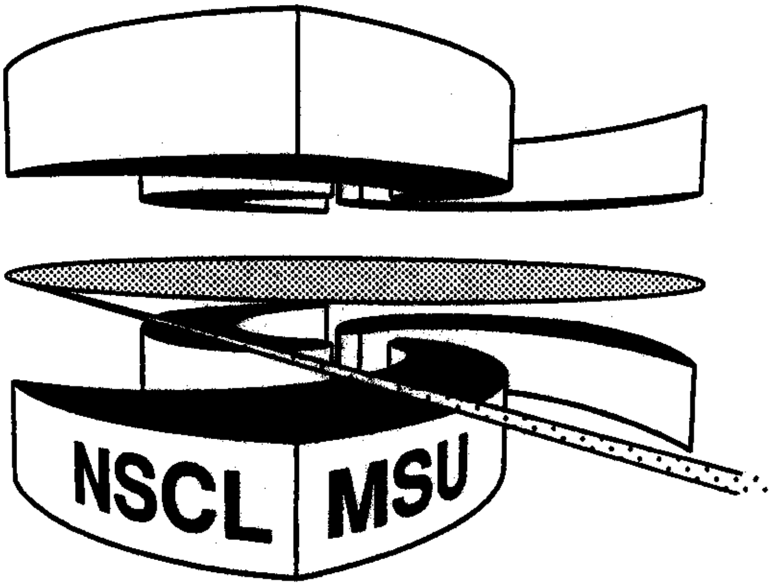
G. BAYM, L. FRANKFURT, and M. STRIKMAN



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Color transparency and color opacity in nucleus-nucleus collisions

G. Baym,[a] L. Frankfurt,[a,b] and M. Strikman[a,c]

8) Department of Physics, University of Illinois, Urbana, IL 61801
b) Current address: Cyclotron Laboratory, Michigan State University, E. Lansing, MI 48824
c) Current address: Department of Physics, Pennsylvania State University, University Park, PA 16802

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What dynamical roles do color degrees of freedom play in strong interactions? On the one hand, color forces produce confinement of quarks and gluons in individual hadrons, spontaneously break chiral symmetry in nuclear and particle physics, and determine the strong interactions among hadrons. The existence of gluons is now well confirmed in studies of hard processes, which can be described by perturbative QCD. On the other hand, the implications of color degrees of freedom for the dynamics of hadrons, as well as in the deconfinement and chiral restoration phase transitions, remains an open and important question. Color dynamics of nucleons, and nuclei, can in fact be revealed in central nucleus-nucleus collisions. The first way is through the phenomenon of color transparency in which a nucleon in a small-size color configuration can propagate through nuclear matter with little scattering.[1] The second is the effect of fluctuations of the internal color degrees of freedom on the global properties of central collisions.[2]

The idea of color transparency has its origins in the discovery by Perkins in 1955 of the (Dalitz) decays in emulsion of cosmic-ray-produced neutral pions of mean energy of order 200 GeV into an electron-positron pair and a photon.[3] Remarkably, the ionization produced by the pairs was small near the decay point, increasing with distance from the vertex. These events confirmed an earlier suggestion of D. T. King that when the e^-e^+ pair is made, the two particles are very close together on an atomic scale, so that they essentially neutralize each other and influence the emulsion only through a tiny electric dipole moment. Only when the pair separates to atomic dimensions, which for a high energy pair takes a long time owing to Lorentz time dilation, does the ionization from the pair become that of the individual electron and positron.

The direct analog of the Perkins experiment in QCD is in deep inelastic electron-hadron scattering, in which the electron produces a virtual photon which in turn produces a quark-antiquark pair. Such pair processes dominate the scattering at small Bjorken x; the existence of Bjorken scaling in this regime is the direct result of the weak interaction of this pair, when it is in a small-sized configuration, with the target. In this case the quark and antiquark essentially neutralize each other's color charge, and interact with the target only through a tiny color dipole moment.

A similar effective suppression of interaction strength is expected in the passage of high-energy hadrons through nuclei, in which the quarks composing the hadrons play the role of the electron-positron pair, and the nucleons of the nucleus that of the atoms of the emulsion. The interactions of colliding hadrons are determined by the instantaneous configurations of their color-carrying components, the quarks and gluon field, during the time of the collision. The characteristic time for oscillations between different color configurations in a relativistic hadron is, from the uncertainty principle,

$$t_{\text{osc}} \simeq \left(\sqrt{p^2 + m^{*2}} - \sqrt{p^2 + m^2}\right)^{-1} \simeq 2p/(m^{*2} - m^2), \tag{1}$$

where m is the hadron mass, p its momentum, and m^* is the mass of the lowest internally excited state of the hadron. Thus in a hadron-nucleus collision at sufficiently high incident energy, t_{osc} is greater, again as a consequence of time dilation, than the time $2R_A/c$ for the incident hadron to traverse the target nucleus; the hadron configuration is "frozen" in the collision, and is in general different in size from the average one. For example, m^* for a nucleon is $\simeq$1.5GeV, and condition (1) is satisfied for projectiles hitting heavy nuclei above $p_{\text{lab}} \gtrsim 40$ GeV/c, as at CERN and RHIC.

The cross-section for interaction with the target depends on the transverse size, r, of the frozen configuration, and will be small if r is small: $\sigma \sim \pi r^2$ – an effect of color neutralization analogous to that of the electron-positron pair in the Dalitz decay. The distribution of projectile constituents in the plane transverse to the beam leads to a distribution $P(\sigma)$ of interaction cross-sections, σ, which appears both theoretically – from quark models of hadrons – and experimentally to have a wide dispersion about the mean cross-section (the quoted value). The experimental evidence is the large single diffractive cross-sections observed in pp scattering at FNAL and the ISR, which Miettinen and Pumplin[4] explained on the basis of a broad $P(\sigma)$; underlying this distribution are the large fluctuations of color in hadrons, which should, one expects, play an important role in nucleus-nucleus collisions.

The hunt for transparency arising from small-sized hadron configurations was begun by Carroll et al.[5] in pp and (p,2p) collisions near 90° in the projectile-proton target-nucleon center of mass (AGS experiment E834), following suggestions by Brodsky and Mueller[6] that when a proton scatters quasielastically through wide angles – that is, it is given a large momentum transfer – only the small-size configurations of its quarks and gluons, from the uncertainty principle, have appreciable amplitude to survive; therefore the emerging proton will have small size and should undergo small final-state interactions in nuclei. The search is continuing in AGS experiment E850 and at NPAS at SLAC.

A straightforward way to see color transparency would be to look for events $B + A \rightarrow N + X$ in the collision of a light projectile B (e.g., ^{4}He) on a heavy nuclear target, A, in which the spectator nucleon N carries a final momentum p_N greater than the momentum per nucleon P_B/B of the projectile. Using light nuclear projectiles instead of protons offers the possibility of triggering on central collisions in which $B - 1$ nucleons interact inelastically. Since spectators in small-sized configurations can traverse the center of a heavy nucleus A without loss of energy, the probability, P_A, of a projectile nucleon penetrating the target would exceed the familiar Glauber theory result, $P_A = exp[-2R_A \rho_A \sigma_{NN}^{inel}]$. For example, for A = 240, the Glauber formula gives $P_A = 6 \times 10^{-4}$, much less than the value ~ 0.015 predicted from color screening from fully frozen configurations.

Features that could help to identify this effect are: First, P_A should increase with initial energy; as one sees from eq. (1), freezing of the projectile configurations would be only a correction at AGS energies, but should appear at CERN and RHIC energies. The longitudinal and transverse momentum distributions of the produced leading nucleons should be close to the Fermi momentum distribution in the projectile nucleus, without widening of the p_T distribution from elastic rescatterings. Furthermore, cross sections for diffractive production of baryon resonances should grow, since the small-sized configurations are not energy eigenstates; this growth in cross-sections is the QCD analog of the appearance of a central white spot in the diffraction of light by a black screen.

Experimental information on P_A in ultrarelativistic nucleus-nucleus collisions is provided by E814[7], which finds that in ^{28}S + ^{208}Pb central collisions at 14.6 GeV per nucleon, $P_A \sim 3 \times 10^{-3}$. As Barrette et al. indicate, this value, much larger than the Glauber theory prediction for central collisions, may contain contributions from admixture of noncentral collisions; with lighter beams, P_A should be closer at AGS energies to the Glauber theory prediction. This value is, however, much smaller than that expected on the basis of color transparency at CERN and RHIC energies.

Color fluctuations, including those to configurations larger than average size, also contribute to the fluctuations of global characteristics of nucleus-nucleus collisions. For example, cross-section fluctuations enhance the fluctuations of the number of NN subcollisions, and hence the fluctuations in transverse energy, E_T, over those in a description based on independent NN collisions with the average cross section.[9] Using the dispersion of σ_{NN} measured at FNAL and the ISR in single diffractive processes, we find that the effect contributes a significant fraction to the broadening of the E_T tail found by NA34 at CERN.[8]. Similarly, fluctuations in the number of NN collisions are expected to lead to fluctuations of other observables such as multiplicity and strangeness production. An important feature of such fluctuations is that they should increase with beam energy as a result of an increase in the dispersion of the NN cross section due to to increase of diffraction to high mass states.

Thermalization of matter tends, on the other hand, to destroy information about the detailed spectrum of fluctuations in the initial state. Thus fluctuations of global characteristics in central nucleus-nucleus collisions may contain nontrivial information on the possible onset of the thermalization of the produced hadron matter. This question deserves further theoretical study.

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