SLAC – PUB – 4713
September 1988
(T/E)

Nuclear Effects in J/ψ and Lepton–Pair Production*

Stanley J. Brodsky

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309, USA

1. Introduction

High-energy processes in nuclear media provide important tests of quantum chromodynamics, since in principle one can use the nuclear environment to perturb and study the mechanisms involved in confinement and hadronization. In this talk I will discuss several examples of nuclear effects in QCD affecting the propagation and hadronization of quarks and gluons in nuclear matter. The issues include: possible signatures for quark-gluon plasma formation in heavy ion collisions, particularly J/ψ production; hadronization due to jet coalescence; the limits of validity of QCD factorization formulae due to initial- and final-state interactions; formation zone physics; shadowing of the quark and gluon structure functions of nuclei; and color transparency in hard quasielastic reactions inside of nuclei.

2. Inclusive J/ψ Production in Heavy–Ion Collisions

The production of heavy quark bound states in nuclear collisions can test many of the fundamental features of QCD. A simplifying feature of such reactions is that the underlying production subprocess involves heavy quark pair production at small transverse distances $r_\perp \lesssim 1/M_Q$. Although the production time for the $c\bar{c}$ system (in the target rest frame) is quite short, $\tau_{\rm prod} \simeq (1/M_Q)(p_\gamma/M_Q) \sim 10\ {\rm GeV}^{-1} = 2$ fm at $p_\gamma \sim 100$ GeV, the formation time required for the $c\bar{c}$ to separate to a transverse size comparable to the radius of the J/ψ is $\tau_{\rm formation} \simeq (r_{J/\psi})/v_\perp \sim \frac{1}{2}\ {\rm fm}/(\frac{1}{2}{\rm GeV}/p_\gamma) \sim 1$ fm p_γ (GeV). Thus even at $p_\gamma \sim 10$ GeV the J/ψ state is produced far from the nucleus. Such processes have become especially interesting to study in nuclear collisions because of the suggestion [1] that the attenuation of J/ψ production in central (high transverse energy) heavy ion-ion collisions relative to the lepton-pair background might provide a signal for quark-gluon plasma formation. Matsui and Satz argue that at sufficiently high "quagma" temperatures, the QCD confining force will be screened, so that it would be more favorable for the c and $\bar{c}$ to form charmed hadrons rather than combine to form the J/ψ.

Since the J/ψ formation time grows linearly with its energy [2], the influence of the plasma can only be important in the central region, $x_{J/\psi} \sim 0$. Also, because of the geometry of the nuclear collisions, one only expects suppression at low $p_T^{J/\psi}$ [3]. The ratio of J/ψ to continuum muon pairs at the same invariant mass has been measured as a function of the associated transverse energy E_T has been measured by the NA–38 group [4] at the CERN SPS. The suppression

$$\frac{[\#(J/\psi)/\#(\mu^+\mu^-)]_{{\rm high}\ E_T>50\ {\rm GeV}}}{[\#(J/\psi)/\#(\mu^+\mu^-)]_{{\rm low}\ E_T<28\ {\rm GeV}}} = 0.64 \pm 0.06$$

measured in the central region, and the observed growth with p_T (see fig. 1) are consistent with the quagma expectations, although it is perhaps surprising that oxygen-uranium collisions at 200 GeV laboratory energy per nucleon is sufficient to show plasma effects.

Is there a reasonable alternative explanation? Final-state absorption [5] of the J/ψ cannot account for the data because of the small values of the effective $\sigma(J/\psi\ p)$ cross section indicated by J/ψ photoproduction experiments. The ratio of gluon to quark structure functions in nuclei could be correlated with the produced E_T to produce J/ψ to continuum suppression, but a detailed calculation, based on a cluster model for nuclear structure functions, by Efremov et al. [6] gives only a 7% suppression.

In fact, as recently discussed by Mueller and myself [7], there is a final-state interaction effect which must be considered in the QCD description of J/ψ production. After the heavy quark pair is formed, the c or $\bar{c}$ can interact strongly with a co-moving quark or gluon spectator produced in the nuclear collision to form charmed hadrons. The "coalescence" of the charm quark with beam spectators can increase the production rate of $c\bar{q}$ or cqq states at the expense

*Work supported by the Department of Energy, contract DE–AC03–76SF00515.

Invited Talk presented at the Parallel Session on Heavy Ion Collisions of the XXIV International Conference on High Energy Physics, Munich, Germany, August 4–10, 1988

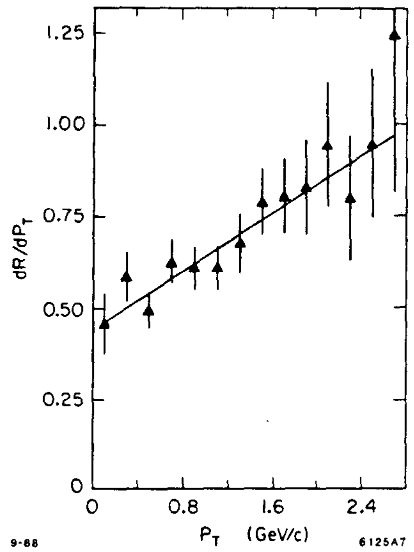

Figure 1. NA-38 data for the ratio of J/ψ production at low and high E_T as a function of the J/ψ transverse momentum P_T. The results are for $O^{18} - U$ collisions at 200 GeV/N. The line is a linear fit.

of $c\bar{c}$ formation, and the forward production of J/ψ will be strongly depleted in central nuclear collisions (high transverse energy) relative to continuum lepton-pair production because of the increased density of co-moving partons from the beam [7]. Since the co-moving spectators have low p_T, the depletion is limited to charmed quarks and J/ψ at low p_T, in agreement with fig. 1. In contrast to predictions based on the existence of a quark-gluon plasma, this depletion occurs independent of whether the target is a light or heavy nucleus! We thus urge that ion beam experiments be carried out on hydrogen or light nuclear targets where a plasma is not expected to be formed.

Alternatively, as discussed by J. Hufner et al. [8], the increased production rate with $P_T^{J/\psi}$ could be due to the increased multiple scattering of the incident gluon in long pathlength (high E_T) events, in analogy to the increased (see sec. 3) lepton-pair transverse momentum distribution in nuclei reported by the NA-10 experiment [9]. The deduced product $\sigma(gN) < p_T^2 >_{gN} \sim 0.39 \pm 0.08$ fm^2 GeV^2 is roughly twice the corresponding quark-nucleon values.

In general, particles produced at low velocities relative to other partons will have their momentum strongly distorted by final-state interactions. For example, the coalescence of the heavy quarks with beam spectators can cause severe distortions of the momentum distribution of heavy hadrons produced in the beam direction. Gunion, Soper and I [10] note that this effect, which is analogous to the Sommerfeld [11] correction in Coulomb scattering, may account for some of the anomalies observed in charm hadroproduction experiments, such as the large cross section for charmed-strange baryon production at large x_L by a 135 GeV/c hyperon beam measured by the WA-42 collaboration [12] at the SPS, the large cross sections recently reported by the E-400 group at Fermilab [13] for open charm hadron production by high-energy neutron beams, as well as the ISR results for Λ_c production in pp collisions. We find that the correction to the total production rate, integrated over relative rapidity, vanishes only as a single inverse power of the heavy quark mass, and thus may give significant corrections to charm production rates and distributions. The coalescence effect may be modified by the nuclear environment which could in turn cause an x_L-dependence of the production rate for charmed hadrons in nuclear targets.

3. QCD Factorization in Nuclear Targets

A remarkable corollary of the QCD factorization theorem for hard inclusive reactions in nuclei is the prediction that induced collinear radiation from inelastic initial- or final-state interactions does not occur at high parton energy. QCD predicts that the entire nuclear dependence of the cross section $d\sigma/dQ^2dx_L(A_1A_2 \to l^+l^-X)$ for the production of heavy lepton pairs in heavy ion collisions is contained in the quark and antiquark structure functions $G_{q/A}(x,Q)$, at least to leading order in $1/Q^2$. Factorization thus implies that the $q\bar{q} \to \mu^+\mu^-$ subprocess occurs without attenuation throughout the nucleus. In fact, one can show explicitly [14] that the initial-state radiation, normally expected to be induced by initial-state inelastic collisions as the quarks propagate throughout the nucleus, is cancelled by the destructive interference of radiation from different sources in the nucleus. This can be understood in terms of the "formation zone" principle: a quark cannot change its state or virtual mass instantaneously—a finite time $\Delta t = (1/\Delta E) = (p_q/\Delta m^2)$ is required for it to radiate a gluon. (Δm is the change in parton mass before and after radiation.) The essential criteria for the validity of factorization in a long target is given by the "target length condition": If the incident parton energy is large compared to a scale proportional to the length of its respective target: $p_q > \Delta m^2 L$, then the induced radiation is coherently cancelled, contrary to classical intuition. Although hard collinear radiation is suppressed, elastic scattering still occurs from initial- and final-state interactions, leading to smearing of the transverse momentum of the propagating parton [14].

Recent measurements of the Drell–Yan process $\pi A \to \mu^+\mu^- X$ by the NA–10 group [9] at the CERN–SPS have shown that the cross section for muon pairs at large transverse momentum is increased in a tungsten target relative to a deuteron target. This provides a measure [14,15] of the quark elastic cross section inside of nuclear matter. Since the total cross section for lepton-pair production scales linearly with A (aside from relatively small EMC–effect corrections), there must be a corresponding decrease of the ratio of the differential cross section at low values of the di-lepton transverse momentum. This is also apparent in the NA–10 data. However, these effects have not been confirmed by Fermilab experiments.

The target length condition and formation zone physics are clearly important for the general understanding of the propagation of quark and gluon jets in nuclear matter. In the case of deep inelastic lepton scattering in a nucleus, the leading hadrons of the recoil jet are formed at large distances outside the nucleus. If the recoiling parton satisfies the target length condition, it will not suffer induced collinear radiation. Low-energy gluons, emitted in the deep, inelastic lepton-quark collision, can suffer radiative losses, leading to cascading of soft particles in the nucleus. It is clearly important to study this phenomena as a function of recoil quark energy and nuclear size. Collision broadening due to elastic final-state interactions of the recoil quark should also occur. Thus one predicts that the mean square transverse momentum of the recoil quark and its leading particles will increase as $A^{1/3}$.

The nuclear dependence of structure functions [16] implies that quarks in a nucleus have smaller average longitudinal momentum than in a nucleon. Independent of the specific physical mechanism underlying the EMC effect, quarks in a nucleus would also be expected to have smaller transverse momentum. This effect may counteract to a certain extent the collision broadening of the outgoing jet.

4. Shadowing of Quark and Gluon Nuclear Structure Functions

SLAC [17] and EMC–NMC [18] measurements of deep inelastic lepton-nucleus scattering show that the structure function of a nucleus in nuclei is shadowed; i.e., falls below nucleon additivity at low $x \leq .01$. The EMC data indicates that the shadowing effect is essentially Q^2-independent, suggestive of a leading twist contribution. Shadowing of the $Q^2 = 0$ photoabsorption cross section is accounted for by vector meson dominance, but this type of contribution is relatively suppressed by at least a power of $1/Q^2$ so it cannot account for the EMC observations. Recent measurements of the nuclear dependence of J/ψ production in πA and $\bar{p}A$ collisions from the E537 [19] experiment at Fermilab are very relevant to the shadowing problem. The E537 data (see fig. 2) show a dramatic falloff of J/ψ for heavy nuclei at large $x_{J/\psi}$. The simplest explanation of this suppression is that the gluon distribution in the nucleus is strongly shadowed at low x, even more than the quark distribution at the same x.

Is it plausible that the nuclear distributions themselves are shadowed? As first shown by Landshoff et al. [20], the structure function of a parton at low x is related to the total absorptive cross section of the anti-parton at high energies, $s \approx \mu^2/x$. One expects $\sigma(gA)$ and $\sigma(\bar{q}A)$ to be surface-dominated; thus it is natural that the gluon and quark structure functions are shadowed [21]. Quantum mechanically, this occurs because of the interference of one-step and two-step scattering processes in the nuclei, as illustrated in fig. 3. Nachtmann and Pirner [22], have shown how to relate the degree of shadowing of structure functions to surface dependence of the nuclear binding energy. A somewhat different approach to shadowing based on parton coalescence and QCD evolution is given by Mueller and Qiu [23].

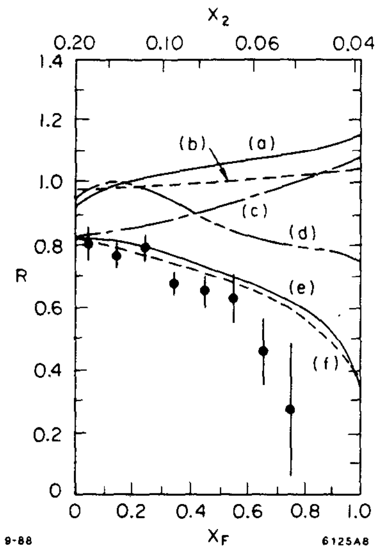

Figure 2. E537 data for the longitudinal x_F and target parton x_2 dependence of forward J/ψ production in pion-nucleus collisions. The ratio of $d\sigma/dx_F$ for tungsten over beryllium targets is shown. Curves (a–c) are model predictions for various explanations of the EMC effect. Curve (d) is the nuclear shadowing prediction of Qiu [28]. Curve (e) is a rescattering model prediction. Curve (f) is the prediction of a three-gluon fusion model of Clavelli et al. Further details and references are given in Ref. 19.

Shadowing is a general feature which will modify QCD effects in nuclei. For example, strong shadowing will limit the production of low-mass lepton pairs in nuclear collisions to the nuclear surface because of two-step processes involving the ρ, ω, and ϕ [21]. Thus one cannot use real photons or low-mass lepton pairs as simple probes of the interior region of heavy ion collisions.

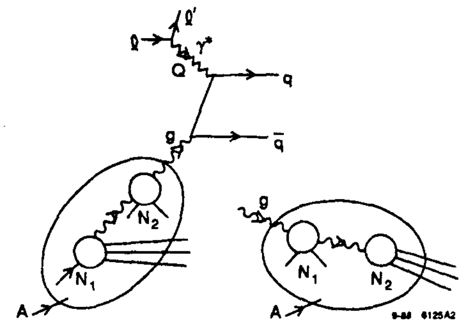

Figure 3. Interference model for nuclear shadowing. The elastic forward scattering of the parton on nucleon N_2 (two-step amplitude) attenuates the strength of the parton distribution from N_1 due to destructive coherence with the corresponding one-step amplitude. The inset figure illustrates the analogous two-step amplitude for gluon-nucleus interactions.

5. Color Transparency and Quasiexclusive J/ψ Production in $\bar{p}A$ Collisions

Perturbative QCD predicts a particularly novel phenomenon for hard exclusive processes occurring inside of a nucleus. The key observation is that only the fluctuation of the valence Fock component of a hadron's wavefunction with small transverse size of order $1/Q$ contributes to an exclusive amplitude at high-momentum transfer in QCD. Such a wavefunction component has only a small color-dipole moment, and thus has a strong interaction cross section which scales as $1/Q^2$. This implies that a hadron can hard-scatter on every nucleon in a nucleus without attenuation from initial- or final-state interactions! In contrast to inclusive hard reactions, both elastic and inelastic initial- and final-state interactions are predicted to be suppressed. Because of the finite formation time, the color-singlet state stays small over a distance which grows with its energy. The prediction that the rate for quasielastic hard-scattering exclusive processes will be additive on the number of nucleons in the nucleus at large momentum transfer and hadron energy is referred to as "color transparency" [24]. The simplest test of this phenomena is quasielastic lepton-proton scattering in the nucleus—QCD predicts a monotonic rise in the transparency ratio as the momentum transfer is raised until complete additivity is reached. The energy dependence of the formation zone effect can be isolated by studying final-state attenuation as a function of recoil proton energy at a given momentum transfer Q^2.

The first test of QCD color transparency has recently been carried out at BNL in large momentum transfer quasielastic pp scattering at $\theta_{\rm cm} \simeq \pi/2$ in several nuclear targets (C, Al, Pb) by a BNL–Columbia–Penn State collaboration [25]. The attenuation of the scattered and recoil protons as they traverse the nucleus and the out-of-plane momentum distribution dN/dp_y transverse to the x-z scattering plane were measured.

The result of the BNL experiment was unexpected. As shown in fig. 4, the quasielastic cross section is strongly attenuated at low $p_{lab} \sim 6$ GeV/c consistent with conventional Glauber initial- and final-state absorption. As p_{lab} is increased the attenuation decreases rapidly as predicted by perturbative QCD. This appears to support the color transparency prediction. However, beyond $p_{lab} = 10$ GeV/c the transparency ratio falls, and at $p_{lab} = 12$ GeV/c, normal attenuation is observed, in contradiction to the expectation from perturbative QCD that the transparency effect should become even more apparent! Thus neither conventional nuclear physics nor leading twist perturbative QCD can explain the data. However, de Teramond and I [26] note that the spin-spin correlation, A_{NN} also has a dramatic anomaly at $p_{lab} = 11.75$ GeV/c [27]. We thus have attempted to explain the origin of both phenomena in terms of the onset of new degrees of freedom; i.e., a resonance or threshold enhancement in the dibaryon system at $\sqrt{s} \sim 5$ GeV, possibly associated with the onset of charmed hadron production. Color transparency fails at a resonance since the full Fock structure of the proton is involved.

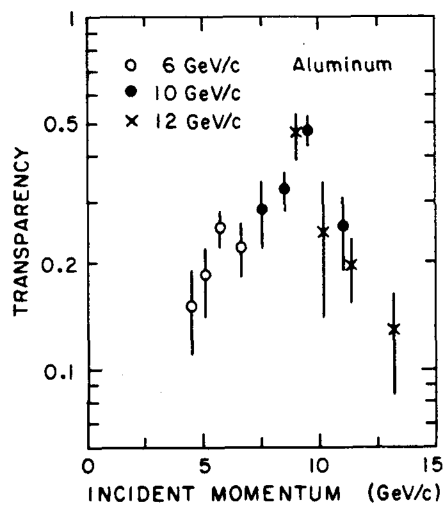

Figure 4. Measurements of the transparency ratio $T = [d\sigma/dt(pA \to pp(A-1))]/Z d\sigma/dt(pp \to pp)$ near 90° on Aluminum (from Ref. 25). Conventional Glauber theory predicts that this ratio should be constant in energy. Perturbative QCD predicts a monotonic rise.

Color transparency can also be studied by measuring quasiexclusive J/ψ production by anti-protons in a nuclear target [28]. One can study the quasiexclusive annihilation process $\bar{p}A \to J/\psi\ (A-1)$, where the nucleus is left in a ground or excited state and extra hadrons are not created. The transverse momentum integrations are controlled by the charm mass scale and thus only the Fock state of the incident anti-proton which contains three anti-quarks at small impact separation can annihilate. We can again apply the same argument as for hard elastic scattering.

Since this Fock state has a relatively small color-dipole moment, it should have a longer than usual mean-free path in nuclear matter; i.e., "color transparency." Thus, unlike traditional expectations, QCD predicts that the $\bar{p}p$ annihilation into charmonium is not restricted to the front surface of the nucleus. The exact nuclear dependence depends on the formation time for the physical $\bar{p}$ to couple to the small $\bar{q}\bar{q}\bar{q}$ configuration, $\tau_F \propto E_p$. It may be possible to study the effect of finite formation time by varying the beam energy, E_p, and using Fermi-motion to stay at the J/ψ resonance. For example, if the J/ψ is produced at nonrelativistic velocities in this low-energy experiment, it can be formed inside the nucleus. The A-dependence of the quasiexclusive reaction can thus be used to determine the J/ψ-nucleon cross section at low energies. In contrast, at high energy, such as in the Fermilab photoproduction experiments [29], the formation time of the J/ψ is so long that one can only observe the interactions of the produced $c\bar{c}$ system in the nucleus, not the J/ψ itself [7].

Acknowledgements

I thank E. Berger, G. de Teramond, J. Gunion, D. Soper, A. Mueller, J. Hufner, H. Pirner and O. Nachtmann for helpful conversations. I also wish to acknowledge the support of the Alexander von Humboldt Foundation and the hospitality of the Max Planck Institute for Nuclear Physics, Heidelberg, where this report was prepared.

References

1. T. Matsui and H. Satz, Phys. Lett. **B178,** 416 (1987).
2. See the discussions of J. D. Bjorken and A. H. Mueller in *Proceedings of the NATO Research Workshop on Hard Hadronic Processes,* St. Croix (1987).
3. F. Karsch and R. Petronzio, Z. Phys. **C37,** 627 (1988).
4. M. C. Abreu et al., presented by A. Bussiere at Quark Matter '87, Nordkirchen, Germany (1987), CERN EP/88-25.
5. A. Capella, J. A. Casado, C. Pajares, A. V. Ramallo and J. Tran Thanh Van, CERN-TH. 4974/88.
6. A. V. Efremov, Y. T. Kim, S. Yu. Shmakov and V. V. Uzhinski, JINR preprint (1988), submitted to this conference.
7. S. J. Brodsky and A. H. Mueller, Phys. Lett. **206B,** 309 (1988).
8. J. Hufner, H. J. Pirner and Y. Kurihara, University of Heidelberg preprint, to be published.
9. P. Bordalo et al., Phys. Lett. **193B,** 368,373 (1987); B. Betev et al., Z. Phys. **C28,** 9,15 (1985).
10. S. J. Brodsky, J. F. Gunion and D. Soper, Phys. Rev. **D36,** 2710, 1987.
11. A. Sommerfeld, *Atombau and Spektallinen* (Vieweg, Braunschweig, 1939).
12. S. F. Biagi et al., Z. Phys. **C28,** 175 (1985).
13. C. Shipbaugh et al., Phys. Rev. Lett. **60,** 2117 (1988).
14. S. J. Brodsky, G. T. Bodwin and G. P. Lepage, *Proceedings of the Volendam Multiparticle Dynamic Conference,* 1982, p. 841; *Proceedings of the Banff Summer Institute,* 1981, p. 513; and to be published. This effect is related to the formation zone principle of L. Landau and I. Pomeranchuk, Dok. Akademii Nauk SSSR **92,** 535,735 (1953).
15. For further references and a phenomenological analysis, see P. Chiappetta and H. J. Pirner, Nucl. Phys. **B291,** 765 (1987).
16. J. J. Aubert et al., Phys. Lett. **123B,** 275 (1983).
17. R. G. Arnold et al., Phys. Rev. Lett. **52,** 727 (1984).
18. EMC collaboration (NA2, NA28); NMC collaboration (NA37).
19. S. Katsanevas et al., Phys. Rev. Lett. **60,** 2121 (1988).
20. P. V. Landshoff and J. C. Polkinghorne, Phys. Rev. **D10,** 891 (1974) and references therein; S. J. Brodsky, F. C. Close and J. F. Gunion, Phys. Rev. **D8,** 3678 (1973) and Phys. Rev. **D6,** 177 (1972).
21. S. J. Brodsky, to be published.
22. O. Nachtmann and H. Pirner, Annalen der Physik **7,** 13 (1987).
23. J. Qiu, Nucl. Phys. **B291,** 746 (1987).
24. A. H. Mueller and S. J. Brodsky, talks presented at the *Fermilab Workshop on A^α Physics,* 1982; A. H. Mueller, *Proceedings of the Moriond Conference,* 1982; S. J. Brodsky, *XIII International Symposium on Multiparticle Dynamics,* Volendam, 1982. See also, G. Bertsch, S. J. Brodsky, A. S. Goldhaber and J. F. Gunion, Phys. Rev. Lett. **47,** 297 (1981).
25. S. Heppelmann et al., *DPF Meeting,* Salt Lake City, 1987; A. S. Carroll et al., Phys. Rev. Lett. **61,** 1698 (1988).
26. S. J. Brodsky and G. de Teramond, Phys. Rev. Lett. **60,** 1924 (1988).
27. G. R. Court et al., Phys. Rev. Lett. **57,** 507 (1986) and references therein.
28. S. J. Brodsky, SLAC-PUB-4451, published in *Proceedings of the 4th LEAR Workshop,* Villars-sur-Ollon, Switzerland (1987).
29. M. D. Sokoloff et al., Phys. Rev. Lett. **57,** 3003 (1986).