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Extraction of Gluon Momentum, Spin, Parity, and Coupling from $\gamma^* N \to \psi N$ Data

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The unique ability of heavy-quark leptoproduction to probe constituent gluons is exploited. From recent $\gamma^* N \to \psi N$ data, the gluon distribution $\eta^{-1}(1-\eta)^p$, $p = 5.6^{+0.8}_{-1.2}$, is extracted and α_s/π is inferred. It is shown that measurement of σ_L/σ_T as a function of Q^2 for charm production can determine the gluon spin and parity.

As emphasized by Shifmar *et al.*[1] and by Leveille and Weiler,[2] leptoproduction of heavy-quark states offers a unique possibility for extracting information on the gluon constituents of the nucleon. This is because unlike any other process, leptoproduction's lowest-order contribution, viz., $\gamma^* G \to Q\bar{Q}$, is directly proportional to the gluon component of the nucleon wave function and independent of the quark component. In this Letter, recent ψ muoproduction data[3] along with ψ photoproduction data[4] are used to extract information on the fractional momentum distribution, spin, parity, and coupling strength of nucleon glue.

The gluon momentum distribution is inferred from the ψ excitation curve. One may prcceed either by extracting and inverting moments, or by fitting the gluon model directly to data. The starting point for either approach is the expression for cross section:

$$\sigma^{\gamma^* N\to\psi N}(s,Q^2)=f\int_{4m_c^2}^{4m_D^2}d\hat{s}\,\frac{\hat{s}+Q^2}{2MK_\nu}\sigma^{\gamma^* G\to c\bar{c}}(\hat{s},Q^2)\int_0^1\frac{d\eta}{\eta}\,G(\eta)\delta(\hat{s}+Q^2-\eta(s-M^2)). \tag{1}$$

$\sqrt{-Q^2}$ is the photon invariant mass, K_ν is a convention-dependent virtual flux factor subject to $K_\nu \xrightarrow{Q^2\to 0} \nu$, the photon lab energy. $\sigma^{\gamma^* G\to c\bar{c}}(\hat{s})$ is the photon-gluon fusion cross section, $\sqrt{s}$ ($\sqrt{\hat{s}}$) is the $\gamma^* N$ ($c\bar{c}$) center-of-mass energy, $G(\eta)$ is the gluon fractional momentum distribution, η being the fractional momentum, and M is the nucleon mass. It is assumed that integration over the interval $4m_c^2 \le \hat{s} \le 4m_D^2$ is dual to a sum on charmonium resonances, and that soft gluons mediate color rearrangement with unit probability. f is the elastic ψ fraction of produced charmonia. Taking moments of Eq. (1) over ν from threshold (ν_0) to infinity gives, for $Q^2=0$,

$$\int_{\nu_0}^{\infty}\frac{d\nu}{\nu}(2M\nu)^{1-m}\sigma^{\gamma N\to\psi N}(\nu)=f\int_{4m_c^2}^{4m_D^2}d\hat{s}\,\hat{s}^{-m}\sigma^{\gamma G\to c\bar{c}}(\hat{s})\int_0^{\min(1,\hat{s}/2M\nu_0)}\frac{d\eta}{\eta}\eta^m G(\eta). \tag{2}$$

Assuming that $G(\eta)$ falls off sufficiently fast as $\eta\to 1$, one has an approximation valid for low moments:

$$\tilde{G}(m)\equiv\int_0^1\frac{d\eta}{\eta}\eta^m G(\eta)=\int_{\nu_0}^{\infty}\frac{d\nu}{\nu}(2M\nu)^{1-m}\sigma^{\gamma N\to\psi N}(\nu)\Big[f\int_{4m_c^2}^{4m_D^2}d\hat{s}\,\hat{s}^{-m}\sigma^{\gamma G\to c\bar{c}}(\hat{s})\Big]^{-1}. \tag{3}$$

$G(\eta)$ is obtained from $\tilde{G}(m)$ through standard Mellin inverse technology. No assumptions concerning the functional form of $G(\eta)$ need be made, but the data must be interpolated.

In the alternate method of deducing a gluon momentum distribution, one must assume a functional form for $G(\eta)$ and then fit via

$$\sigma^{\gamma N\to\psi N}(\nu)=\frac{f}{2M\nu}\int_{4m_c^2}^{4m_D^2}d\hat{s}\,\sigma^{\gamma G\to c\bar{c}}(\hat{s})G\left(\frac{\hat{s}}{2M\nu}\right). \tag{1'}$$

The advantage of this method is that it is free of approximations and well suited to limited data. My approach will be to utilize the moment method, Eq. (3), to show that the form $N(1-\eta)^p$ gives a reasonable description of $\eta G(\eta)$. Then N and p will be determined by fitting via Eq. (1′).

The fusion cross section for scalar, pseudoscalar, vector, or axial vector gluons is of the form

$$\sigma^{\gamma^* G\to c\bar{c}}(\hat{s},Q^2)=\frac{2\pi\alpha e_c^2\alpha_s}{(\hat{s}+Q^2)^3}\left[F_{\ln}\ln\frac{1+\beta}{1-\beta}+F_{\mathrm{cnst}}\beta\right]. \tag{4}$$

The functions $F_{\ln}(\hat{s},Q^2)$ and $F_{\mathrm{cnst}}(\hat{s},Q^2)$ are listed in Table I for incident photons of invariant mass $\sqrt{-Q^2}$, and transverse or longitudinal polarization. e_c is the heavy-quark charge in units of proton charge, $(4\pi\alpha_s)^{1/2}$ is the quark-gluon coupling constant, and $\beta=(1-4m_c^2/\hat{s})^{1/2}$ is the velocity of either quark in the $c\bar{c}$ center-of-mass frame. Of course, only the vector gluon theory results from unbroken local gauge invariance and is asymptotically free. The other J^P assignments are considered as alternatives to quantum chromodynamics (QCD). For uniformity, the SU(3) color factor of $\frac{1}{2}$, specific to the vector theory (QCD), has been included in all the fusion cross sections. The vector gluon cross section has been given previously in Ref. 2, by Leveille and Weiler,[5] and by Gluck and Reya,[6] and discussed by several others.[7]

Figure 1 shows $\tilde{G}(m)$ up to $m=6$ for $m_c=1.5$ and vector glue (QCD). The experimental parametrization[3] $\sigma^{\gamma N\to\psi N}(\nu)=(33\text{ nb})\exp[-20/(\nu-6)]$ was input into Eq. (3). Results for the other gluon spins and parities are similar. Of particular interest is $\tilde{G}(2)$, the fraction of nucleon momentum carried by gluons. Values of $f\alpha_s\tilde{G}(2)$ are tabulated in Table I. The ranges reflect the 30% normalization error in the data of Ref. 3. For QCD I consider $m_c=1.5$ as used in charmonium spectroscopy, and $m_c=1.25$ which results from certain sum rules.[8] Any one of α_s, f, $\tilde{G}(2)$ can now be determined in terms of the other two. Since $\tilde{G}(2)\simeq 50\%$ from saturation of deep-inelastic sum rules and f can in principle be measured, I prefer to input $\tilde{G}(2)$ and f and "derive" α_s. The $O(\alpha_s)$ photon-gluon fusion mechanism presented here is expected[5] to be mainly diffractive elastic with a comparable inelastic contribution arising from processes which are formally $O(\alpha_s^2)$. Early experimental reports[9] are compatible with this prediction. Thus one expects that setting the $O(\alpha_s)$ elastic ψ fraction f to be roughly the inverse of the number of charmonium states, i.e., $\frac{1}{8}$, should be valid to a factor of 2 or so. Table I shows the α_s magnitudes resulting from $\tilde{G}(2)$

TABLE I. Cross-section terms and extracted parameters for vector, scalar, pseudoscalar, and axial vector gluons.

Gluon J^P	σ_T $F_{\ln}$	σ_T $F_{\rm cnst}$	σ_L $F_{\ln}$	σ_L $F_{\rm cnst}$	m_c (GeV)	$10^2 f\alpha_s\tilde{G}(2)$	α_s/π for $\tilde{G}(2)=0.5$, $f=\frac{1}{8}$	p (fit)	$f\alpha_s N$ (fit)
1^- (QCD)	$\hat{s}^2+Q^4+4m_c^{\,2}(\hat{s}-2m_c^{\,2})$	$-[(\hat{s}-Q^2)^2+4\hat{s}m_c^{\,2}]$	$-8Q^2m_c^{\,2}$	$4Q^2\hat{s}$	1.5	2.7–4.9	0.14–0.25	$5.6^{+0.8}_{-1.2}$	0.23 ± 0.09
					1.25	0.70–1.30	0.036–0.066	$7.3^{+0.9}_{-1.5}$	0.077 ± 0.030
0^+	$(\hat{s}+Q^2-4m_c^{\,2})^2$	$4\hat{s}(2m_c^{\,2}-Q^2)$	$16m_c^{\,2}Q^2$	0	1.5	2.2–4.0	0.11–0.20	$5.8^{+0.8}_{-1.3}$	0.19 ± 0.07
0^-	$(\hat{s}+Q^2)^2$	0	0	0	1.5	1.8–3.2	0.09–0.16	$5.7^{+0.8}_{-1.2}$	0.15 ± 0.05
1^+	$\hat{s}^2+Q^4-4m_c^{\,2}(\hat{s}-2m_c^{\,2})$	$-(\hat{s}+Q^2)^2+4m_c^{\,2}\hat{s}$	$8Q^2m_c^{\,2}$	$4Q^2\hat{s}$	1.5	4.0–7.4	0.20–0.38	$5.7^{+0.8}_{-1.2}$	0.35 ± 0.13

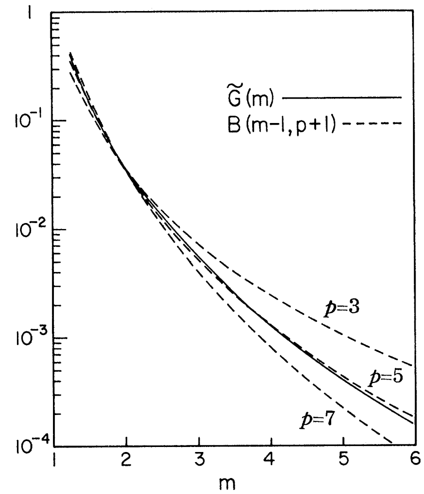

FIG. 1. Gluon moments $\tilde{G}(m)$ in units of $f\alpha_s$ (see text) compared to power-law moments $B(m-1,\ p+1) = \int_0^1 d\eta\, \eta^{m-2}(1-\eta)^p$ normalized to $\tilde{G}(2)$.

$= 0.5$ and the *Ansatz* $f=\frac{1}{8}$. In every case s/π is perturbatively small.

Returning to Fig. 1, the moments of $\eta^{-1}(1-\eta)^p$ with $p=3$, 5, 7 are shown, normalized to $\tilde{G}(m)$ at $m=2$. It is apparent that $(1-\eta)^5$ approximates $\eta G(\eta)$ very well.

Encouraged by this result I next fit this simple power behavior to the ψ excitation data. The results for each J^P assignment with errors allowing for the 30% normalization uncertainly are given in Table I. The power-law exponent is insensitive to gluon spin and parity, but sensitive to charmed quark mass. Counting rules[10] argue for

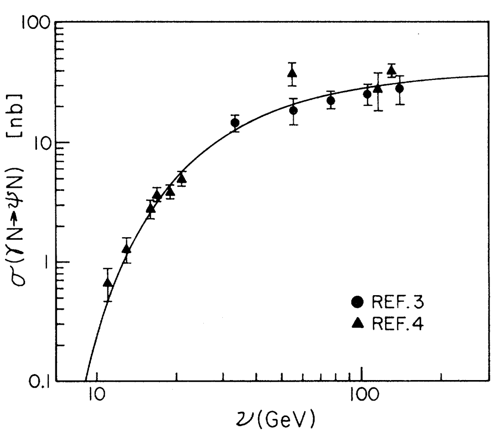

FIG. 2. QCD cross section (curve) with the fitted gluon distribution $\sim(1-\eta)^{5.6}$ for $m_c=1.5$ GeV, compared to $\gamma N\to\psi N$ data.

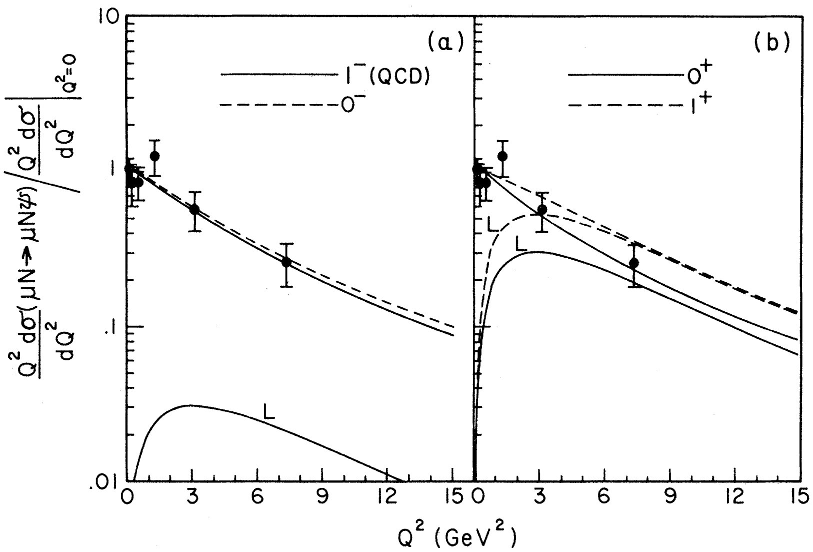

FIG. 3. Comparison of photon-gluon fusion cross sections for various gluon spins and parities to the Q^2 dependence of E_μ = 209-GeV $\mu N \rightarrow \mu\psi N$ data; (a) odd parities, (b) even parities. Curves labeled L are the contributions to ψ muoproduction from the longitudinal mode of the exchanged photon. For the 0^- assignment, the longitudinal contribution is identically zero.

the power 4 or 5 at small mass scale. All models with $m_c = 1.5$ GeV are in good agreement with this, especially when allowance is made for steepening due to $M_\psi = 3.1$ GeV scale breaking (as in QCD). On the other hand, a 1.25-GeV quark mass and its accompanying exponent are disfavored by the counting rules. For every case the fit remains faithful all the way down to threshold and gives a χ^2 per degree of freedom of 1. The quality of the fits is represented in Fig. 2 by the $m_c = 1.5$-GeV QCD case. As a consistency check on the two methods of glue extraction, one requires and finds (refer to Table I) that $N/(p+1) \simeq G(2)$.

The Q^2 dependence of ψ muoproduction offers the possibility of eliminating some production models. In Fig. 3 it is shown that all spin and parity assignments for the gluon give good agreement with data. The gluon distributions used are those obtained from the preceding data fitting, but the curves are not very sensitive to the gluon distribution or m_c. Also apparent in Fig. 3 is the fact that the QCD cross section is dominantly transverse, the pseudoscalar cross section is totally transverse, whereas the even-parity gluon cross sections are dominantly scalar. Hence, *the separation of the longitudinal and transverse photon cross sections, σ_L and σ_T, can distinguish among gluon J^P.* In these short-distance models there is no obvious correlation between virtual photon helicity and ψ helicity. Thus an extraction of σ_L/σ_T should be performed by manipulating the muon vertex (ϵ parameter), rather than measuring the relative contribution of $\sin^2\theta$ and $1+\cos^2\theta$ terms in $\psi \rightarrow \mu\mu$ rest-frame decay.

In conclusion, a consistent short-distance picture of heavy quark leptoproduction emerges from the analysis of $\gamma^* N \rightarrow \psi N$ data. Exploting recent ψ muoproduction data, I have extracted the gluon momentum distribution. The resulting power behavior agrees with dimensional counting rules and the normalization restricts $\alpha_s(M_\psi)$ to a sensible range of values. A better restriction on α_s will require an improved estimate of f, the ψ fraction of diffractively produced charmonia. Further experiment can provide this. The calculations presented in this Letter can be applied to associated charm production[2] (in which case there is no f parameter) when data permits. Furthermore, application to Υ leptoproduction will yield the gluon distribution and α_s at mass scale $M_\Upsilon \simeq 10$ GeV. Thus the tenets of asymptotic freedom [$\alpha_s(M) \sim 1/\ln M$ and steepening parton distributions] can be checked. I have compared arbitrary gluon spin and parity assignments to the Q^2 variation of ψ production. All assignments are in agreement. Measurements of σ_L/σ_T will distinguish among these J^P's.

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Effect of Pauli Blocking on Exchange and Dissipation Mechanisms Operating in Heavy-Ion Reactions

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Systematic properties of dissipation and exchange mechanisms associated with damped nuclear reactions are obtained from available data, yielding results that cannot be consistently described in a classical approach. However, correlations between energy loss and the variances of the fragment A and Z distributions are understood on the basis of an exchanged-induced dissipation mechanism, if account is taken of the Pauli exclusion principle.

Although considerable progress has been made during recent years in understanding the mechanisms operating in damped nuclear reactions, several of the most characteristic features of these processes have so far escaped a consistent theoretical description. This is particularly true for the experimentally well-established correlation[1,2] between energy dissipation and nucleon exchange. Experimental evidence is in accord with the assumption of successive exchange of single nucleons proceeding simultaneously with dissipation of relative kinetic energy in many small steps. In this work, available data are examined in order to expose the systematic properties of dissipation and exchange mechanisms associated with damped nuclear reactions. It is shown that these features cannot be understood on purely classical grounds but find a natural explanation when the fermion nature of the exchanged nucleons is taken into account. A quantal model[3] is applied attributing energy dissipation to the stochastic exchange of nucleons between two Fermi-Dirac gases in relative motion, a description expected to be relevant for the modest excitations attained in damped reactions under consideration.

In a phenomenological approach described recently,[4] use was made of the microscopic time scale provided by the exchange mechanism to de-

