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NUCLEAR EFFECTS IN PHOTOPRODUCTION AND LEPTOPRODUCTION
WHERE ARE THEY ? ARE THEY NEGLIGIBLE ?

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ABSTRACT

We discuss nuclear effects in hadronic final states in photoproduction and leptonproduction on nuclei. Whereas in photoproduction and leptonproduction on free nucleons the final states are similar, striking differences are predicted for the case of nuclear targets, the differences being the largest in multiplicity correlations. Quantitative predictions are given for the cases of practical interest : photoproduction and muonproduction on emulsion nuclei and neutrino-production in the neon and propane-freon bubble chambers. Neutrino-production on nuclei is emphasized to offer the most direct test of the formation length hypotheses.

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Abstract

1. INTRODUCTION

Nuclei are quite often used as targets in deep inelastic scattering experiments. Still, little attention has been paid to nuclear effects in lepton production. There have been good reasons not to do so, in addition to the preoccupation of the minds of physicists by more ambitious subjects like scaling violations or new flavour production. For instance, there is known to be no shadowing in the total electroproduction cross-sections: $\sigma_{\gamma A}^* \sim A^1$ within an accuracy of ± 0.02 in the exponent¹⁾.

However, additivity of the total cross-sections does not imply the lack of any significant nuclear effects in the hadronic final states. Rather strong nuclear attenuation of forward secondary particles was observed in the MIT-SLAC experiment on electroproduction on nuclei²⁾, and firm evidence for intra-nuclear cascading was found in νNe ³⁾ and muon-emulsion⁴⁾ interactions. Attenuation of forward particles and cascading were both predicted well before these experimental data appeared⁵⁾. Different aspects of lepton production on nuclei have also been discussed in recent papers⁶⁾⁻¹³⁾.

The purpose of this paper is two-fold. First, we extend the considerations of Ref. 5) to multiplicity correlations and to photoproduction on nuclei. In particular, we formulate predictions for the nucleus fragmentation dependence of the spectra of secondary hadrons. Such predictions seem important in view of the data which might soon come from $\nu_{\mu}\text{Ne}$ interactions at high energies, from muon-nucleus interactions if studied in the NA2 European Muon Experiment at CERN, from Serpukhov neutrino experiments in the heavy-liquid bubble chamber SKAT and as a by-product of the charm search experiment WA58 on photoproduction of hadrons on emulsion nuclei at CERN. Second, we revise, to a certain extent, some of the predictions of Ref. 5), since according to more recent developments in the theory of particle-nucleus interactions, the scale for the formation lengths is slightly different from that used in Ref. 5).

The nuclear effects we are discussing here are large distance effects in the formation of final state hadrons. As far as there are no genuine three-jet effects, the space-time picture of the formation of final state hadrons in deep inelastic scattering is similar to that in hadronic reactions. A comprehensive discussion of this can be found in Bjorken's lectures⁶⁾ and in Ref. 5), and should not be repeated here. A corollary is that secondary hadrons of momentum k are formed only at distances

$$l_f \approx k/m_0^2 \quad (1)$$

from the target nucleon, to be called the formation lengths. A subsequent development of the interaction process depends on the relation between ℓ_f and the radius R_A of the nucleus. Secondary hadrons with $\ell_f < R_A$, that is with momenta $k < k_{c*} = R_A m_0^2$, are formed inside the nucleus and will induce the intranuclear cascade^{*}). In the opposite case of $\ell_f > R_A$ the actual formation of hadrons takes place outside the nucleus^{16),5),6)}. In the simplest case this would imply the target independence of projectile fragmentation in the region of $k > k_c$:

$$R_y = \left(\frac{dN_s}{d^3k} \right)_A / \left(\frac{dN_s}{d^3k} \right)_N = 1 \quad (2)$$

For the composite hadrons relation (2) holds for the interactions of separate constituents, but no longer for hadrons themselves¹⁷⁾, and it is not as easy to find the direct consequences of the growing formation lengths¹⁷⁾.

The novel feature of deep inelastic scattering is that, regarding its hadronic properties, the virtual photon is equivalent to one constituent state. Let us explain this, beginning with the scaling parton model, where the scale invariant cross-section is known to come from the handbag diagram of Fig. 1. Kinematics should be such that $|k_2^2| \lesssim \mu^2$, since otherwise the off-mass shell parton-nucleon interaction amplitude vanishes. Then it turns out that $\varepsilon_1 \sim \nu$, $\varepsilon_2 \sim \nu (m^2/Q^2)$, that is the virtual photon transforms always into lopsided $q\bar{q}$ pairs, rather than into vector mesons made of symmetrical $q\bar{q}$ pairs. Only the low momentum component of the $q\bar{q}$ pair interacts with the target, whereas for the high momentum component the interaction cross-section vanishes^{18),19)}. There are no big changes when the scale invariant parton model is exchanged for QCD: quark-gluon ladder diagrams, equivalent to the handbag diagram of Fig. 1, give the dominant contribution to the cross-section²⁰⁾ and moreover, formation length arguments, though with apparently weak Q^2 dependent m_0^2 , apply to QCD jets as well²¹⁾.

As regards photoproduction, the usual nuclear shadowing has been observed: $\sigma_{\gamma A} \sim A^{0.9}$ ¹⁾. In terms of vector meson dominance this A dependence corresponds to the virtual quark-nucleon interaction cross-section $\sigma_{qN}^* \approx 5$ mb. Therefore, in many respects photoproduction on nuclei should resemble production by pions. The only difference would be that in photoproduction the fraction of two-quark collisions is smaller than that in pion-nucleus interactions.

^{*}) A rigorous field theoretic proof of the classical propagation of secondary particles at distances $\Delta Z \sim k/m^2$ from the target was given by Gottfried and Low¹⁴⁾ [see also Ref. 15)].

The hadronic final states in electro and photoproduction on nucleons are known to be very similar. In collisions with nuclei they should be dissimilar since in deep inelastic scattering the virtual photon acts as a one constituent state, while in photoproduction it acts as a two constituent state. Moreover, while there is no Q^2 dependence of the final states produced on nucleons, a specific Q^2 dependence is expected in the production on nuclei. The virtual photon (W boson) converts into the hadronic state at the distance

$$\Delta Z \approx \sqrt{Q^2} \approx \omega/m \quad (3)$$

from the target²²⁾. Values of $\Delta Z < R_A$ correspond to incoherent scattering where $\sigma_A = A\sigma_N$ and cascading takes place over half of the thickness of the nucleus. However, in the opposite case of $\Delta Z > R_A$ the hadronic component of the photon is absorbed on the surface of the nucleus, there is more cascading, and we predict the rise of the multiplicity as one moves from the region $w \lesssim (5 \div 10)A^{1/3}$ to the region $w \gtrsim (5 \div 10)A^{1/3}$.

Structure of the final state depends on the number N of the intra-nuclear interactions, which can be controlled either by increasing the size of the nucleus, or, on an event-to-event basis, by counting the number N_g of secondary protons^{*)}. In this paper, using an approach of Ref. 23), we formulate our predictions for N_g dependences of the multiplicities, single particle inclusive spectra, two particle rapidity correlations $R_2(0,0)$ and Wroblewski ratios $D/\langle N_g \rangle$. We predict the N_g independence of $R_2(0,0)$ and $D/\langle N_g \rangle$ in deep inelastic scattering, whereas in photoproduction a decrease of $R_2(0,0)$ and $D/\langle N_g \rangle$ at large values of N_g is predicted. Note, that in the vector meson dominance model there should be no drastic differences between the photo and electroproduction processes.

The rest of the presentation is organized as follows. In Section 2 we review the approach of Refs 14) and 20) to the calculation of the spectra and correlations on nuclear targets. In Section 3 we formulate our predictions for the production of hadrons in deep inelastic scattering. Section 4 is devoted to the discussion of photoproduction on nuclei. In Section 5 we summarize our main results.

*) Actually N_g is the number of secondary particles with velocities $0.3 < v/c < 0.7$.

2. FORMATION LENGTHS AND THE NUCLEAR TRANSPORT EQUATION FOR THE SPECTRA

In coherent scattering virtual photons are absorbed uniformly over the whole volume of the nucleus. In photoproduction we substitute for the photon the two constituent vector meson with absorption cross-section $\sigma^* \approx 10$ mbm, which corresponds to $\sigma_A \approx A^{0.9}$. The dependence of the final state spectrum on the distance t from the target nucleon is described by the transport equation^(5),17):

$$\begin{aligned} dN_S(t, \varepsilon)/d\varepsilon = & (dN_S(v \rightarrow \varepsilon)/d\varepsilon) \Theta(t - l_f(\varepsilon)) \exp[-(t - l_f(\varepsilon))] \\ & + \int_0^{t - l_f(\varepsilon)} d\tau \exp[-(t - \tau - l_f(\varepsilon))] \int_{\varepsilon}^v d\omega (dN_S(\tau, \omega)/d\omega) (dN_S(\omega \rightarrow \varepsilon)/d\varepsilon) \end{aligned} \quad (4)$$

The notations are self-explanatory. The distances t and τ are in units of the absorption length. In the limit $l_f(\varepsilon) = 0$ Eq. (4) is identical to the usual cascade equation, as it should be.

In the case of photoproduction Eq. (4) is applied to interactions of each constituent of the vector meson state. The novel feature is the presence of two-quark collisions in addition to single-quark collisions. In the two-quark collisions the multiplicity in the central region is doubled, while there is a depletion in the forward region. Let $S_1(v \rightarrow \varepsilon)$ be the central component of the solution of Eq. (4), and $L_1(v \rightarrow \varepsilon)$ be the leading component. Then in the two-quark collision $S_2(v \rightarrow \varepsilon) \approx 2S_1(v \rightarrow \varepsilon)$, while for the leading component we use

$$L_2(v \rightarrow \varepsilon) = \int_{\varepsilon}^v d\omega L_1(v \rightarrow \omega) L_1(\omega \rightarrow \varepsilon) \quad (5)$$

Let w_1 and w_2 be the probabilities of single and two quark collisions. Then

$$(dN_S/d\varepsilon)_{YA} \approx (w_1 + 2w_2) S_1(v \rightarrow \varepsilon) + w_1 L_1(v \rightarrow \varepsilon) + w_2 L_2(v \rightarrow \varepsilon) \quad (6)$$

In the very forward region, $\varepsilon \rightarrow v$, $L_2(v \rightarrow \varepsilon) \approx 0$. As a result, there should be an effective, energy independent, attenuation of forward particles:

$$R_y = (dN_S/d\varepsilon)_{YA} / (dN_S/d\varepsilon)_{YN} = w_1 < 1 \quad (9)$$

Equation (4) gives the spectra as a function of the cascading length t . Also the mean number $\langle N(t) \rangle$ of intra-nuclear interactions can be calculated:

$$\langle N(t) \rangle = 1 + \int_0^v d\varepsilon \int_0^t d\tau (dN_s(t, \varepsilon)/d\varepsilon) \quad (10)$$

Assuming Piosson like N distribution one can convert t dependences into N and/or N_g dependences^{23),24)}. In Ref. 23) this procedure was used successfully for the description of N_g dependences of inclusive spectra, correlation functions and multiplicity distributions.

In the case of photoproduction it is useful to introduce v_q - the number of interacting constituents of the vector meson state. Once v_q distributions are known, one can calculate the two-particle rapidity correlation $R_2^A(0,0)$ and the Wroblewski ratio $(D/\langle N_s \rangle)_A$ ^{23),25)}:

$$R_2^A(0,0) = (\langle v_q^2 \rangle - \langle v_q \rangle^2) / \langle v_q \rangle^2 + R_2^N(0,0) / \langle v_q \rangle \quad (11)$$

$$(\Phi / \langle N_s \rangle)_A^2 = (\langle v_q^2 \rangle - \langle v_q \rangle^2) / \langle v_q \rangle^2 + (\Phi / \langle N_s \rangle)_N^2 / \langle v_q \rangle \quad (12)$$

Here

$$R_2(\eta_1, \eta_2) = (d^2 N_s / d\eta_1 d\eta_2) / ((dN_s / d\eta_1)(dN_s / d\eta_2)) - 1$$

In deep inelastic scattering $v_q \equiv 1$, so that A and N_g independence of $R^A(0,0)$ and $(D/\langle N_s \rangle)_A$ is predicted. In photoproduction very large values of N_g correspond to the dominance of two-quark interactions: $v_q = 2$. Since in this case $\langle v_q^2 \rangle = \langle v_q \rangle^2$, we predict

$$R_2^A(0,0) \cong R_2^N(0,0) / 2 \quad (13)$$

$$(\Phi / \langle N_s \rangle)_A \cong (\Phi / \langle N_s \rangle)_N / \sqrt{2} \quad (14)$$

Let us now turn to a more detailed discussion, beginning with deep inelastic scattering.

3. NUCLEAR EFFECTS IN NEUTRINO, ELECTRO AND MUOPRODUCTION

Let us begin with the production of fast particles, $\varepsilon \approx \nu$, in the low energy limit of $\ell_f(\varepsilon) = 0$. In this case Eq. (4) corresponds to the usual nuclear attenuation:

$$R_y = (dN_s(t, \varepsilon)/d\varepsilon)_A / (dN_s(\nu \rightarrow \varepsilon)/d\varepsilon)_N = \exp[-t] \quad (15)$$

Finite formation lengths reduce attenuation and it vanishes altogether when $\ell_f(\varepsilon) > R_{A*}$. One can, at small $\ell_f(\varepsilon)$, define the effective absorption cross-section σ_{abs}^* :

$$\sigma_{abs}^* \simeq \sigma_{abs}^{hN} / (1 + \ell_f(\varepsilon)/\ell_{abs}) \simeq \sigma_{abs}^{hN} / (1 + \varepsilon/\varepsilon_0) \quad (16)$$

For the constituent quarks $m_0^2 = 0.7 \text{ GeV}^2$ ¹⁷⁾. Therefore, for the secondary mesons $\ell_f(\varepsilon) \approx \varepsilon/2m_0^2$, which results in $\varepsilon_0 \approx 15 \text{ GeV}$. Our predictions for the exponent α in the parametrization $R_y = A^\alpha$ are in good agreement with the data of Ref. 2) (see Fig. 2). It would be very interesting to see whether the attenuation of forward particles is weaker at higher energies ν .

The typical rapidity dependence of α is shown in Fig. 3. At high energies the region of universal spectra is followed by a shallow dip, where $\alpha < 0$, and by the cascade region of $\alpha > 0$. Such a cascading was observed recently in $\nu_\mu \text{Ne}$ interactions ³⁾, and is well described by our model (see Fig. 4). In diffraction electroproduction the effective thickness of the nucleus is larger, so that $\alpha_{diff} \approx \alpha_{incoh} (1 + a\gamma)$, where γ is the shadowing exponent in the total cross-section of diffraction electroproduction: $\sigma_A \approx \sigma_N A^{1-\gamma}$, and $a \approx 1.4$.

In deep inelastic scattering the cascade is the only source of the surplus multiplicity, whereas in hadron-nucleus interactions the main contribution to multiplicity comes from multiquark collisions. This results in the very weak A dependence of $R_\ell = \langle N_s \rangle_{\ell A} / \langle N_s \rangle_{\ell N}$ (see Fig. 5). Predictions for diffraction scattering at $w \geq (5 \div 10)A^{1/3}$ can be obtained via rescaling $A \rightarrow A^{a\gamma}$. The actual value of γ remains uncertain since in leptoproduction no shadowing has yet been observed ¹⁾. The cascade contribution to the mean multiplicity is energy independent, so that R_ℓ is a slowly decreasing function of ν and/or w . However, at $w \approx (5-10)A^{1/3}$, there should be some increase in R_ℓ of the form shown in Fig. 6.

At high energies the forward spectra should be N_g independent, whereas the cascade multiplication is higher, the higher N_g is. In Figs 7 and 8 we present

our predictions for the N_g dependences of the rapidity spectra for the cases of practical interest: νNe and $\nu(\text{CF}_3\text{Br})$ interactions at CERN and Serpukhov energies, respectively. When comparing our predictions with the data on μEm interactions (see Fig. 8) we use the empirical relation $N_h \approx 3N_g$ (in Ref. 4) the data were presented as a function of the number N_h of heavy $\nu/c < 0.7$ tracks).

All the available data give firm evidence for cascading. An important implication is that intra-nuclear cascading should be accurately taken into account in hadron-nucleus interactions as well. This conclusion, though almost trivial, is not as widely accepted as it should be. For instance, in the model of Brodsky et al.⁹⁾ the spectra and multiplicities in electroproduction on nuclei and nucleons were predicted to be identical (see, however, Ref. 11)). In the eikonal models²⁶⁾ the absence of shadowing implies that

$$F_{\gamma^*A}(\nu, Q^2) \equiv A F_{\gamma^*N}(\nu, Q^2) \quad (16)$$

and, by virtue of Abramovsky-Gribov-Kancheli rules²⁷⁾, this results in identical spectra on nuclei and on nucleons. In Refs 8), 12) and 13), where no formation length effects are considered, energy independent attenuation of forward particles is predicted. It should be emphasized that, provided that the formation length arguments hold, no quark-nucleon cross-section can be deduced from leptonproduction on nuclei, contrary to the claims in Ref. 12). In the model of Ref. 10), where strong influence of nuclear matter on formation lengths is assumed, a steep rise of R_ℓ at high energies is predicted. Thus, there is a wealth of drastically different predictions for leptonproduction on nuclei, and more accurate data are eagerly awaited.

4. PHOTOPRODUCTION ON NUCLEAR TARGETS

The probabilities w_1 and w_2 of single and two-quark collisions can easily be calculated using the usual optical model considerations. In terms of these probabilities, the height of the central plateau equals

$$R_y = w_1 + 2w_2 \simeq A^{0.045} \quad (17)$$

whereas for the very forward particles

$$R_y = w_1 \simeq A^{-0.05} \quad (18)$$

This attenuation of forward particles corresponds to an effective absorption cross-section $\sigma_{\text{abs}}^* \approx \sigma_{\text{abs}}^{\pi N}/2$. At moderate energies, $\nu \lesssim (100-200)$ GeV, the plateau is still elusive (see Fig. 3), but should appear at higher energies.

The very large values of N_g correspond to the dominance of two-quark collisions: $w_1 \ll w_2 \approx 1$. Therefore, in the central region $R_y \rightarrow 2$ for all the nuclei. However, due to finite energy effects, at 100 GeV there should be rather a shoulder-like irregularity in R_y (see Fig. 7). Predicted A and N_g dependences of mean multiplicities are shown in Figs 5 and 8. Leptoproduction and photoproduction should exhibit N_g and A dependences of the spectra, differing both quantitatively and qualitatively, and this difference could easily be observed experimentally.

Even more striking differences are expected in the two-particle correlations $R_2^A(0,0)$ and in the Wroblewski ratios $(D/\langle N_s \rangle)_A$. At low multiplicities N_g of grey tracks the term $\Delta R_2 = (\langle \nu_q^2 \rangle - \langle \nu_q \rangle^2) / \langle \nu_q \rangle^2$ is not small, whereas $\langle \nu_q \rangle$ is still close to unity. As a result, there should be some rise in $R_2^A(0,0)$ and $(D/\langle N_s \rangle)_A$, the latter being more sensitive to the presence of the ΔR_2 term. At larger values of N_g , as $\langle \nu_q \rangle$ tends to 2, and $\langle \nu_q^2 \rangle - \langle \nu_q \rangle^2 \rightarrow 0$, ΔR_2 and $(D/\langle N_s \rangle)_A$ start to decrease, approaching their limiting values given by Eqs 13) and 14). For the numerical estimates we use as an input $(D/\langle N_s \rangle)_N = 0.385$ ²⁸⁾. There are no direct experimental data on $R_2^N(0,0)$ for photoproduction, and we use the conjectured value $R_2^A(0,0) \approx 0.45$. It was obtained as follows: the short-range part $R_s(0,0)$ of the rapidity correlation function is known to equal ≈ 0.3 for all hadronic interactions ²⁹⁾, and we adopt this value for photoproduction too. For the long-range part of the correlation function we use the relation ²³⁾: $R_L(0,0) = (D/\langle N_s \rangle)^2$. The resulting predictions for N_g dependences of $R_2^A(0,0)$ and of $(D/\langle N_s \rangle)_A$ in photoproduction on emulsion nuclei are presented in Fig. 9. Shown also are ΔR_2 and $K_{22} = 1/\langle \nu_q \rangle$, which can be used to recalculate $R_2^A(0,0)$, if our conjectured value of $R_2^N(0,0)$ turns out to be wrong. Similar predictions for other nuclei seem to be of no practical interest, since there are no forthcoming experiments on the subject apart from the WA58 experiment at CERN.

The last comment is on the A dependences of $\langle N_g \rangle$. It exhibits an approximate $A^{0.38}$ and $A^{0.43}$ dependence for the ℓA and γA interactions, respectively. For the emulsion nuclei, the values of $\langle N_g \rangle$ for different projectiles are predicted to be in the ratio: $\rho A : \pi A : \gamma A : \ell A = 1.20 : 1 : 0.83 : 0.68$.

5. CONCLUSIONS

Lepto and photoproduction have been shown to offer unique possibilities for studying the mechanisms of multiple production on nuclear targets. Attenuation of forward particles and the decreasing of $(D/\langle N_s \rangle)_A$ at large values of N_g are well-established features of hadron-nucleus interactions^{30),16)}. None of these is predicted to be present in deep inelastic scattering, though they should be present in photoproduction. If confirmed experimentally, this would imply the most direct evidence for the formation length arguments.

The available data are in good agreement with our model, based on the formation length arguments. They give firm evidence for the cascade contribution to particle production. Much more accurate data will, apparently, be available soon from the neon and propane-freon bubble chamber neutrino experiments, and they may allow us to discriminate between the different models proposed.

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FIGURE CAPTIONS

- Fig. 1 : A handbag diagram for the virtual photon-hadron scattering amplitude.
- Fig. 2 : Predicted exponent α versus the data of L.S. Osborne et al.²⁾.
- Fig. 3 : Predicted exponent α in the parametrization $R_y \approx A^\alpha$ as a function of the rapidity y of secondary particles.
- Fig. 4 : Predicted rapidity dependence of R_y in ν_μ Ne interactions versus the data of Ref. 3).
- Fig. 5 : Atomic number dependence of the normalized multiplicities R in lepto and photoproduction at high energies. Shown also for the sake of comparison is R for incident pions.
- Fig. 6 : The ω dependence of the normalized multiplicity R in muon emulsion interactions versus the data of Ref. 4). The expected rise of R after the transition from incoherent to diffraction scattering is indicated by arrows.
- Fig. 7 : Predicted N_g dependence of the normalized inclusive spectra in neutrino and photoproduction on the nuclei of practical interest. Since in the emulsion experiments only emitting angles are measured, the corresponding normalized spectra are presented as a function of pseudorapidity.
- Fig. 8 : Predicted N_g dependence of normalized multiplicity R in photo and leptoproduction on nuclei of practical interest versus the data of Ref. 4) (the top figure). In the bottom figure we compare our predictions for N_g dependence of the spectra in μ Em interactions with the data of Ref. 4). Since no data on the spectra in μ N interactions are available, data points at $\langle N_h \rangle \approx 4.5$ ($N_g \approx 1.5$) were used for an absolute normalization.
- Fig. 9 : Predicted N_g dependence of the correlation parameters in photoproduction on emulsion nuclei (see text for definitions).

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