Coherent Vector Meson Production from Deuterons at Intermediate Energies

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Introduction: Exclusive vector meson production from nucleons and nuclei can be used to investigate the transition from non-perturbative to perturbative strong interaction mechanisms. At intermediate photon energies $3 \leq \nu \leq 30\,GeV$ and low momentum transfers $Q^2 \lesssim 1\ GeV^2$ contributions to the vector meson production amplitudes, $f^{\gamma^* N \to VN}$, from hadronic components of the interacting photon with large invariant mass are suppressed. The restriction to light hadronic states leads to vector meson dominance (VMD). Here, as seen from the laboratory frame, the vector meson is formed prior to the interaction with the target (see e.g. [1,2]). This is different at large momentum transfers $Q^2 \gg 1\ GeV^2$ and $x \ll 0.1$. Here quark-gluon wave packets are produced in the γ^*-nucleon interaction which can be described within perturbative QCD [3]. For example, in the case of longitudinally polarized photons short distance dominance leads at large Q^2 to the production of color-dipole quark-antiquark pairs with small transverse size. Long after this initial hard interaction the final state vector meson is formed.

Interesting information on the production process can be obtained by embedding it into nuclei. Here details about the initially produced quark-gluon wave packet and the formation of the finally measured vector meson are probed via the interaction with spectator nucleons. In this context we discuss coherent photo- and leptoproduction of vector mesons from deuterons at photon energies $3 \leq \nu \leq 30\,GeV$ and $0 \leq Q^2 \leq 10\,GeV^2$. In this kinematic regime one is most sensitive to the transition from non-perturbative to perturbative production mechanisms.

In the considered process the following scales seem to be most relevant: the average **transverse size** of the wave packet which for the case of longitudinal photons is $b_{ej} \approx 4 \ldots 5/Q$ for the contribution of the minimal Fock space component at $Q^2 \gtrsim 5 GeV^2$ [4]. For these Q^2 it amounts to less than a third of the typical diameter of a ρ meson ($b_\rho \approx 1.4\,fm$). The finally measured vector meson is formed after a typical **formation time** $\tau_f \approx 2\nu/\delta m_V^2$. Here $\delta m_V^2 \sim 1\,GeV^2$ is the characteristic difference of the squared masses of low-lying vector meson states. For energies $\nu \simeq 10\,GeV$ one finds $\tau_f \simeq 4\,fm$. Therefore in the considered kinematic region details about the expansion of the initially produced wave packet are expected to significantly influence the production of vector mesons from nuclei. Perturbative QCD suggests that contributions from re-scattering off spectator nucleons in nuclear production processes decrease at large photon energies with rising Q^2. This phenomenon is commonly called color coherence or color transparency [5].

However dominant contributions to high-energy photon-induced processes result from large longitudinal space-time intervals which increase with the photon energy [1]. In the considered kinematic domain the characteristic **longitudinal interaction length** $\lambda \approx 2\nu/(m_V^2 + Q^2)$ turns out to be of the order of typical nuclear dimensions and can have a major influence on the scattering process. A systematic investigation of the role of the longitudinal interaction length is most important, even for a qualitative understanding of photon-induced processes.

Probing the longitudinal interaction length: High-energy photon-induced processes are dominated by contributions from large longitudinal space-time intervals. For coherent vector meson production from deuterons characteristic distances can be extracted from the corresponding production amplitude [6,7]. For the single scattering (Born) contribution, where only one nucleon participates in the interaction, one finds:

$$\delta_1 \sim \frac{2\nu}{Q^2 + m_V^2 - t}. \tag{1}$$

t is the squared momentum transferred to the deuteron, and m_V denotes the mass of the produced vector meson. In double scattering, where both nucleons participate in the scattering process, one has:

$$\delta_2 \sim \frac{2\nu}{Q^2 + 2\langle m_h^2\rangle - m_V^2 + t}. \tag{2}$$

Here $\langle m_h^2\rangle$ stands for the average squared mass of the intermediate hadronic states which are produced in the initial scattering of the incident photon.

In the following we discuss two possibilities for a detailed investigation of the characteristic longitudinal interaction length in vector meson production. Up to now systematic studies of this kind have not been carried out. They are, however, very well feasible at TJNAF.

At moderate photon energies $\nu \gtrsim 3\,GeV$ the longitudinal interaction distance for single scattering (1) is for small values of the momentum transfer t typically of the order of the deuteron size. Consequently in this kinematic region, which is governed by the single scattering contribution, a strong dependence of the production cross section on ν is expected. For illustration consider the ρ meson photoproduction cross section, calculated within vector meson dominance, normalized as (for a detailed discussion see [6,7]):

$$R_\delta = \frac{d\sigma_{\gamma d}}{dt} \Big/ \frac{d\sigma_{\gamma d}}{dt}(\delta_1, \delta_2 \to \infty). \tag{3}$$

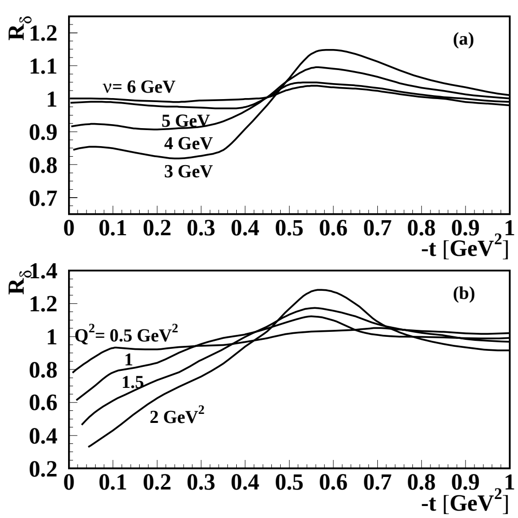

FIG 1: *The cross section ratio R_δ for photoproduction (a). R_δ for leptoproduction (b) for $\nu = 6\,GeV$.*

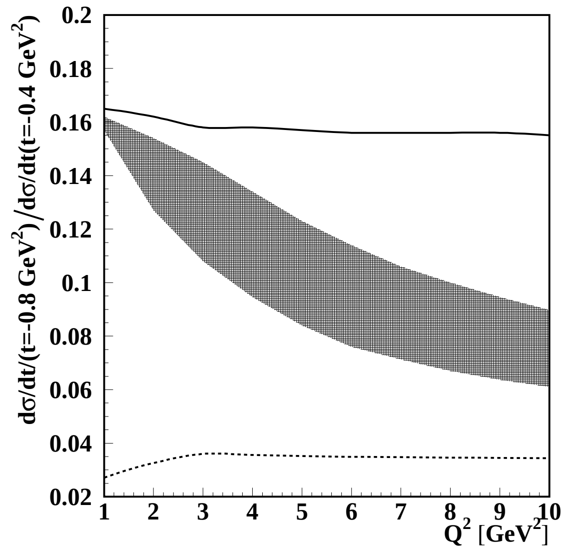

FIG 2: *The Q^2-dependence of the cross section ratio for coherent ρ production from unpolarized deuterons taken at $t = -0.8;\ -0.4\,GeV^2$. The solid line – complete VMD, the dashed – Born. The shaded area results from QDM.*

At $t \simeq -0.1\,GeV^2$ one observes a 15% rise of R_δ for an increase of the photon energy from 3 to $6\,GeV$ as shown in Fig.1a. At large $-t > 0.7\,GeV^2$, where double scattering dominates, only minor variations of the production cross section occur. This is due to the fact that the corresponding interaction length is larger than for single scattering. Thus, the difference in the t-dependence of the longitudinal interaction length for single and double scattering reveals itself through a different pattern in the energy dependence of the production cross section at small and large t. For other low-mass vector mesons similar effects are expected.

In high-energy leptoproduction processes the longitudinal interaction lengths $\delta_{1,2}$ (1,2) exhibit also a characteristic Q^2-dependence. At moderate values of $0.5 \lesssim Q^2 \lesssim 2\,GeV^2$ a strong Q^2-dependence of vector meson production is therefore anticipated. Indeed we observe in Fig.1b at $t \approx -0.1\,GeV^2$ a decrease of R_δ by approximately 50%, if Q^2 rises from 0.5 to $2\,GeV^2$.

Search for color coherence: To investigate color coherence effects one needs to study the Q^2-dependence of vector meson production in kinematic regions where contributions from double scattering dominate. However it is mandatory to account for possible modifications due to changes of the characteristic longitudinal interaction lengths δ_1 and δ_2 from Eqs.(1,2). Or, even better, the kinematics should be chosen such that these length scales stay reasonably constant. For $Q^2 > 1\,GeV^2 > m_V^2, |t|$ this can be achieved in an approximate way by keeping the Bjorken scaling variable x fixed. It should be mentioned that large size fluctuations of the minimal wave function of longitudinally polarized photons are suppressed by a factor $1/Q^2$ as compared to the transverse case (see e.g. [3]). Therefore color coherence effects should arise earlier in the longitudinal channel. The maximal signal which can result from color coherence is determined by the difference between the Born cross section, which results from single scattering only, and the full production cross section at $Q^2 \approx 0$. It can be enhanced if one considers the ratio

$$R_{ct} = \left(\frac{d\sigma_{\gamma^* d}}{dt}\right) \Big/ \left(\frac{d\sigma_{\gamma^* d}}{dt}\right)_{Born} \tag{4}$$

at large and moderate $|t|$. In Fig.4 we present R_{ct} for ρ meson production taken at $x = 0.1$ for $t = -0.4\,GeV^2$ and $t = -0.8\,GeV^2$. The Born cross section and the full vector meson dominance calculation differ by a factor four, leaving reasonable room for an investigation of color coherence. We also show results obtained from the quantum diffusion model (QDM) varying involved model parameters within a reasonable range [8]. A large sensitivity to details of the expansion of the originally produced small wave packet is found. (For a detailed discussion see [7].)

Summary: The space-time structure of exclusive production processes contains valuable information on the transition from non-perturbative to perturbative strong interaction mechanisms. The use of nuclear targets is of advantage here since they allow to probe the production process at typical length scales of around $2\,fm$, as given by the average nucleon-nucleon distance.

We have outlined possibilities to investigate the characteristic longitudinal interaction length in vector meson production. Such studies, which have never been systematically pursued, are feasible at current CEBAF energies.

Furthermore, we have explored color coherence effects in vector meson production. At intermediate energies, as considered for an upgrade of CEBAF, a large sensitivity to details on the formation of the final vector meson is expected. As a consequence new information on the onset of perturbative interaction mechanisms could be obtained.

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