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Report on the habilitation thesis of Jan Nemćik entitled': "Diffractive Electroproduction of Vector Mesons off Nuclei: Selected topics"

It was my pleasure to read and evaluate the habilitation thesis of Jan Nemćik. I knew some of his works from the literature. The author was working on related topics for quite a long time and is in my opinion expert in the field. The topic is related to different aspects of production of vector mesons (ρ, ϕ, J/ψ, Υ, and even 2S states) on proton as well as nuclear target. Different nuclear effects have been included systematically. The approach can be named as light-cone dipole approach. The author considers vector meson as a $q\bar{q}$ state of constituent quark and antiquark. The treatment is based on quantum chromodynamics and is therefore quite attractive. The approach incudes color transparency effects as well as coherence length effects as well as their competition. The shadowing effects are included in a consistent framework. The author often calculates nuclear modification factor i.e. the ratio of the production on nuclear target to its counterpart on the proton.

The thesis is contained in four main chapters.

1) Short review of the light-cone dipole phenomenology for $\gamma^* N \to VN$.

2) Incoherent production of vector mesons off nuclei.

3) Coherent production of vector meson off nuclei.

4) Gluon shadowing.

For experts it is clear that it is an almost complete list of problems related to electroproduction of vector mesons.

In addition there are 8 Appendices where related papers were attached which I find very useful.

Let me discuss now separate issues in larger degree of detail.

In the introduction the author refers to some experimental developements related to charmonium production. This introduction is not too detailed and concentrates only on J/ψ production. The important issue, in general, is in space-time picture of J/ψ production. A part of the author's papers is devoted to this issue.

The next section discusses the phenomenon of color transparency. In general, it is related to the propagation of color dipole (colorless object) through the nuclear medium. A small dipole can go through the medium more easily than large dipoles that interact more strongly with the medium. In general, there are two possible approaches, one using hadronic basis, the second using quarks and gluons. The author finds the description in terms of quarks and gluons more straightforward. The quark-antiquark system with the distance between $r \to 0$ has a cross section for the interaction with the medium $\sigma(r) \propto r^2$, i.e. vanishing for very small dipoles. In more classical approach the interaction of the vector meson in the medium is given by VN interaction and a multiple scattering picture. The author discussed formation time related to the transition of the color dipole to the normal size vector meson. In the hadronic basis, also considered by the author, the situation is slightly different. Then one has to include propagation of ground and excited states including diagonal and off-diagonal transitions. The author considers shadowing as a purely quantum-mechanical effect resulting from destructive interference of amplitudes from scattering on different nucleons. This has simultaneously probabilistic interpretation. This is related to the life-time of the hadronic fluctuation. The coherence time (or coherence length) is important issue in this context. The author defines the nuclear transparency as the nuclear modification factor. Both low-energy and high-energy limit is discussed. The author discusses interrelation of formation and coherence time. The gluon shadowing is an important phenomenon in deep-inelastic scattering at small Bjorken-x. The author is an expert on somewhat forgotten at present phenomenon of shadowing. At present one is using rather the notion of gluon saturation in this context.

The second chapter discusses problems related to the light-cone dipole phenomenology for virtual-photon-nucleon scattering. The author uses so-called mixed representation in which the wave functions depend on dipole distance and light-cone momentum fraction. The corresponding amplitudes are expressed in terms of the photon and vector meson wave functions and dipole cross section. The dipole cross section is treated rather in a phenomenological way and is rather parametrized to fit experimental data. The wave functions seem more fundamental in this context. In particular, the photon wave function can be calculated in QED. For virtual photons one has both transversely and longitudinally polarized photons. The vector meson wave function is obtained by Lorentz boost from the rest frame wave functions. The latter is taken as a Gaussian ansatz. Within the formalism it is easy to calculate the amplitude for forward meson production. The total cross section for vector meson production can be obtained by integration over relevant t variable. The t-dependence is usually not calculated from the formalism and rather experimental t-dependence is used. The calculation of Jan Nemćik nicely reproduces both the energy and Q^2 dependences obtained by the ZEUS and H1 collaborations, both for ρ and ϕ production. The approach fails at low W where phenomenological reggeon contribution must be added. The author does not include this contribution. The papers attached to this chapter are well cited. In addition to the 1S vector mesons the author discusses in his papers also 2S vector meson production. The author has found an anomalous t-dependence of the differential cross section as a function of energy and Q^2 for $V'(2S)$ light vector mesons. The anomalous dependence is a reflection of the node of the wave function.

The incoherent production of vector mesons off nuclei is discussed in chapter 3. Here one studies nuclear transparency. Since the slope for the reaction on the proton and nucleus is the same, it means that theoretically one can calculate the ratio of corresponding amplitudes squared. The light-cone Green function approach is briefly presented. There is an extended discussion of coherence length and color transparency and their manifestation in connection to experimental measurements (E665, HERMES, JLAB experiments). Jan Nemćik is a world expert deeply understanding the competition of the two effects. He has published a paper discussing anomalous (nonmonotonic) dependence on nucleus mass number for leptoproduction of $\rho'(2S)$ meson. A strong enhancement of ρ' compared to ρ has been predicted. The effect was explained as a interplay of color transparency effects with the nodal structure of the ρ' meson. Analogous studies were made for charmonia production.

In Chapter 4 the author considers coherent production of vector mesons off nuclei. In this type of processes the nucleus stays intact. In the corresponding formalism the amplitude is a coherent sum of contributions from different longitudinal and photon impact parameters. For coherent production, in contrast to incoherent production the slopes for $\gamma^* N$ and $\gamma^* A$ are different and do not cancel in the nuclear modification factor, called by the author transparency. Jan Nemćik studied the ratio of coherent cross sections for heavy and light (carbon) nuclei as a function of Q^2 and was able to explain the E665 data. The author considered different approximation (e.g. $l_c \gg R_A$) and discussed their applicabilities for lighter and heavier nuclei. As naively expected, infinite coherence limit is much better for light nuclei and poor for heavy nuclei at large Q^2. The infinite coherence lenght effects are small for ultraperipheral collisions for which $Q^2 \sim 0$. The author interestingly discusses limits of nuclear transparency for coherent and incoherent production. In the latter case the transparency may exceed 1 and approaches $A^{1/3}$ limit for heavy nuclei. It seems to me that all these interesting predictions of Jan Nemćik require more experimental studies. In the attached (to this chapter) paper the author discusses separate dependences for longitudinally and transversly polarized mesons.

The Chapter 5 disusses the effect of gluon shadowing in the context of deep-inelastic scattering rather than vector meson production. This is rather theoretical (model dpendent) problem, but very interesting in the context of nuclear shadowing in general. The effect leads to lowering the cross section at low Bjorken-x. It is also related to saturation effects in nuclei. In the infinite momentum frame it can be interpreted as fusion of gluons from different nucleons in the nucleus. This leads to gluon distributions that is not proportional to the density of nucleons. The author discusses the same phenomenon in different frames. In the literature the shadowing is discussed usually in the rest frame of the nucleus. In the author's approach the shadowing is interpreted in terms of $q\bar{q}g$ Fock-component of the photon. The corresponding formalism is shortly sketched. The author shows some results of the calculation for R_G as a function of the nuclear matter thickness for different values of Bjorken-x and a given value of photon virtuality. A strong gluon saturation occurs at small-x. The author has found that the gluon shadowing only slowly depends on photon virtuality. The gluon shadowing leads to diminishing of the nuclear cross sections for different processes. The author discusses that the nuclear cross section for incoherent production of vector mesons is rather insensitive to gluon shadowing. On the other hand it leads to stronger effect for coherent production. One of the author's paper discusses the effect of gluon shadowing in deep-inelastic scattering. He founded a strong effect at small Bjorken-x. His numerical effects has been verified with the E665 and NMC collaboration data.

In the last section the author summarizes his achievements in the field of vector meson production. A fairly complete picture emerges. The author has discussed several subtle, sometimes counterintuitive effects. The investigations of the author are rather related to large photon virtuality. This effects were studied experimentally some time ago (E665, NMC, HERMES experiment). Next generation experiments will be, if at all, in distance future and is related to the electron-ion collider project. At present such effects can be studied in ultraperipheral heavy ion collisions at RHIC and the LHC. The author does not discuss this point at all.

The papers included in this thesis are not the only papers of the author. Several other papers can be found in the literature related to high-energy proton-proton and proton-nucleus collisions. Jan Nemćik published several other papers with very good physicists, such as N.N. Nikolaev, B. Zakharov, B. Kopeliovich, J. Huefner, A. Tarasov and others. I can summarize this fact that Jan Nemćik originates from a good school of high-energy physics. The (his) papers are never academic but concentrate on the meritum of the problem and always discuss an interesting phenomenon.

In summary, Jan Nemćik is well qualified, well experienced physicist. having a scientific record absolutely sufficient for the habilitation degree. I strongly support his efforts to get the degree and will be able to defend my statement. Please, do not hesitate to ask further questions if needed.

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