Coulomb-nuclear interference effects on forward π^0 production in polarized-proton–nucleus collisions

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It was reported from the PHENIX experiment at BNL-RHIC that the transverse single spin asymmetry, denoted as A_{N}, for forward neutrons measured in transversely polarized-proton–nucleus (pA) collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ is far different from that in proton–proton (pp) collisions at $\sqrt{s} = 200\,\mathrm{GeV}$.[1)]

I presented in Refs. 2–3) that ultra-peripheral pA collisions (UPCs, also known as Primakoff effects) contribute to the measured A_{N} modestly in pAl collisions and significantly in pAu collisions, and that UPCs together with hadronic interactions successfully explain the PHENIX results. In UPCs, virtual photons (γ^*) emitted from the relativistic nucleus interact with the polarized protons and then produce the neutrons and other particles.

In the Monte Carlo simulations discussed in Refs. 2–3), electromagnetic effects (UPCs) and hadronic effects are taken into account independently. However, the interference between these two effects, called the Coulomb-nuclear interference (CNI) effects, would have nonzero amplitudes in the very small momentum-transfer region. In this report, I present the implementation of the CNI effects for forward π^0s in polarized-proton–nucleus collisions. Forward π^0 production is described by a simpler mechanism than that for forward neutrons. Natural units $\hbar = c = 1$ are used throughout.

The scattering amplitude M for single pion production in the CNI effects is given by

$$M = e^{i\phi} M_C + M_H, \tag{1}$$

where ϕ is the Coulomb phase, M_C is the Coulomb scattering amplitude, and M_H is the hadronic scattering amplitude. The Coulomb scattering amplitude via a one-photon exchange is expressed as

$$M_C = Ze(p_b + p_2)_\mu \frac{F(q^2)}{q^2} \langle p_1, k | J^\mu | p_a \rangle, \tag{2}$$

where $\langle p_1, k | J^\mu | p_a \rangle$ is the $\gamma^* + p \to p + \pi^0$ transition current[4)] and $F(q^2)$ is the form factor. The kinematic variables are defined in Fig. 1. The hadronic scattering amplitude via a one-Pomeron exchange[5)] is obtained by replacing a virtual photon with a Pomeron in Fig. 1:

$$M_H = F_A\, g_{\pi NN}\, F_{\pi N^* N}(p_{1f}^2)\, F_{I\!PNN^*}(p_{1f}^2)\, A_{I\!P}^{NN}(s, q^2)/2s \\ \times\ \bar{u}(p_1) i\gamma_5 S_N(s_1) \gamma^\mu u(p_a) \bar{u}(p_2) \gamma_\mu u(p_b)\,, \tag{3}$$

where nuclear effects are taken into account in F_A, $g_{\pi NN}$ is the pion-nucleon coupling constant, S_N is the off-shell nucleon propagator, $F_{\pi N^* N}$ and $F_{I\!PNN^*}$ are the form factors at each vertex, $A_{I\!P}^{NN}$ is the $I\!PNN$ elastic scattering amplitude, $s = (p_a + p_b)^2$, and $s_1 = (p_1 + k)^2$.

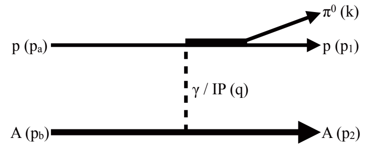

Fig. 1. Diagram of the amplitudes driven by the photon (γ^*) or Pomeron ($I\!P$) exchange in proton-nucleus collisions.

The differential cross section for single π^0 production is expressed with the Källén function $\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$ as

$$\frac{d\sigma}{dq^2} = \frac{\pi^2 |M|^2}{8\lambda(s, m_p^2, m_p^2)(2\pi)^5} \int \frac{\lambda(s_1, m_p^2, m_\pi^2)^{1/2}}{s_1} ds_1. \tag{4}$$

Figure 2 shows the cross section in pAu collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$. The dominant amplitude transits from Coulomb to hadronic at $q^2 \sim 0.02\ \mathrm{GeV}^2$. This indicates that single spin asymmetries for forward π^0s, most likely produced below $0.1\ \mathrm{GeV}^2$, are significantly modified by the interference between the Coulomb and hadronic interactions.

The estimation of single-spin asymmetries and extension of the presented framework to forward neutrons will be a topic of future investigation.

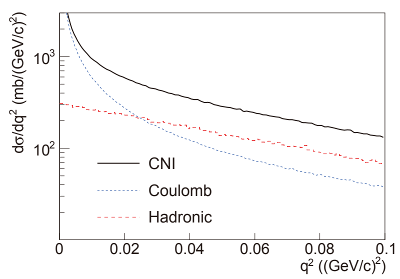

Fig. 2. Differential cross sections for Coulomb (blue dotted), hadronic (red dashed), and CNI effects (black solid).

References

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