Contribution ID: **46** Type: **Oral presentation**

Non-paraxial effects in the quantum scattering of wave packets

Wednesday 11 July 2018 12:30 (30 minutes)

A customary relativistic quantum scattering theory implies that all the particles in a reaction have definite momenta, that is, they are described by the delocalized plane waves. When the well-normalized wave packets are used instead (say, of Gaussian form), the scattering cross sections get corrections of the order of $\lambda_c^2/\sigma_\perp^2 \ll 1$ where λ_c is a Compton wave length of a particle with a mass m and $\sigma_\perp$ is a beam width. For modern electron accelerators, they do not exceed 10^{-16}, whereas for the well-focused beams of electron microscopes they can reach 10^{-6}. Here we show that these non-paraxial effects are enhanced when one collides non-Gaussian packets instead: the vortex beams with high orbital angular momentum $\ell \gg \hbar$, the quantum superpositions like the so-called Schrödinger cats, etc. Moderately relativistic vortex electrons with ℓ up to 10^3 have been recently generated, they have large mean transverse momentum, which grows as $\sqrt{\ell}$, and, as a result, the non-paraxial effects in scattering are ℓ times enhanced for these beams and can reach 10^{-3}. We calculate the non-paraxial corrections to the plane-wave cross section in a model-independent way, give examples from QED and QCD, study a contribution of a phase of a scattering amplitude, compare different models of the in-states, and show that for well-focused beams these effects can compete with the two-loop contributions to the basic QED processes like $e^-e^- \to e^-e^-$, $e^-\gamma \to e^-\gamma$, etc.

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Session Classification: Workshop on Quantum Foundations and Quantum Information