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Relativistic electron vortices beyond the paraxial approximation

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Although many properties of the vortex particles with orbital angular momentum (OAM) ℓ can be described within a model of a non-normalized Bessel beam, it does not allow one to go beyond a paraxial approximation, which is crucial for proper study of the spin-orbit effects and for scattering problems in atomic physics, nuclear and high-energy physics, especially when the quantum interference and coherence play an important role. Accurate estimates of the non-paraxial effects require that the vortex wave packets be 3D localized, described in a Lorentz invariant way, and applicable beyond the paraxial regime. Despite the recent interest in the relativistic electron vortices, such a model is still lacking. Here we develop a model of a packet that is Gaussian in momentum space, localized both in 3D space and time, characterized by a mean 4-momentum, by a momentum uncertainty $\sigma \sim 1/\sigma_{\perp}$, which is a Lorentz scalar and vanishing, $\sigma \ll m$, in the paraxial regime, and by the OAM. We argue that this wave packet is a more adequate model for relativistic vortex electrons and calculate the non-paraxial corrections to the observables like energy, magnetic moment, etc. We find that compared to the ordinary Gaussian beam for which they are $\sim \lambda_c^2/\sigma_{\perp}^2 \ll 1$ (λ_c is a Compton wave length and $\sigma_{\perp}$ is a beam width), these corrections are ℓ times enhanced and can reach 10^{-3} for already available beams with $\ell > 10^3$ and $\sigma_{\perp} < 1$ nm. We discuss possible means for detecting these effects.

Author: Dr KARLOVETS, Dmitry (Tomsk State University)

Presenter: Dr KARLOVETS, Dmitry (Tomsk State University)

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