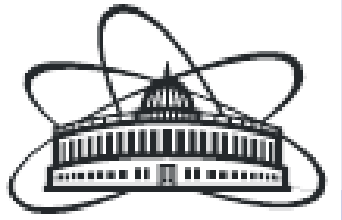

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Twisted particles in heavy-ion collisions

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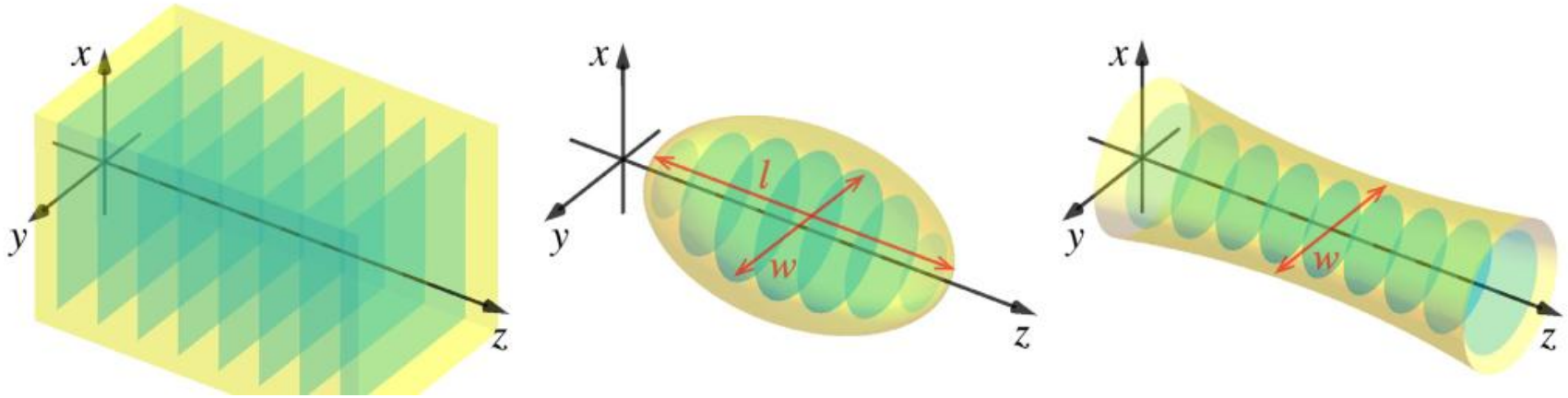
Twisted (vortex) particles

plane wave: wavepacket: wave beam:



Twisted (vortex) particles possess an intrinsic orbital angular momentum (OAM) and can be presented by wave beams and packets. Wave beams/packets are localized with respect to two/three dimensions and are described by two/three discrete transverse quantum numbers. Free twisted particle beams of photons, electrons, and neutrons are Laguerre-Gauss beams and can be described by the wave function

$$\Psi = \mathbb{A}\exp(i\Phi), \qquad \int \Psi^{\dagger}\Psi r dr d\phi = 1, \qquad w(z) = w_0\sqrt{1+\frac{z^2}{z_R^2}}, \quad R(z) = z + \frac{z_R^2}{z},$$

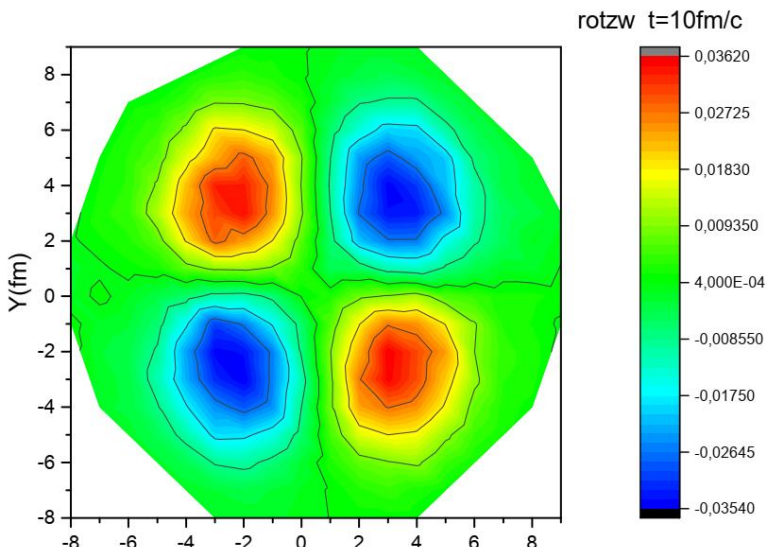
$$\mathbb{A} = \frac{C_{n\ell}}{w(z)}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|\ell|} L_n^{|\ell|}\left(\frac{2r^2}{w^2(z)}\right)\exp\left(-\frac{r^2}{w^2(z)}\right)\eta, \quad z_R = \frac{kw_0^2}{2}, \; C_{n\ell} = \sqrt{\frac{2n!}{\pi(n+|\ell|)!}},$$

$$\Phi = l\phi + \frac{kr^2}{2R(z)} - \Phi_G(z), \quad \Phi_G(z) = N\arctan\left(\frac{z}{z_R}\right), \quad N = 2n + |\ell| + 1,$$

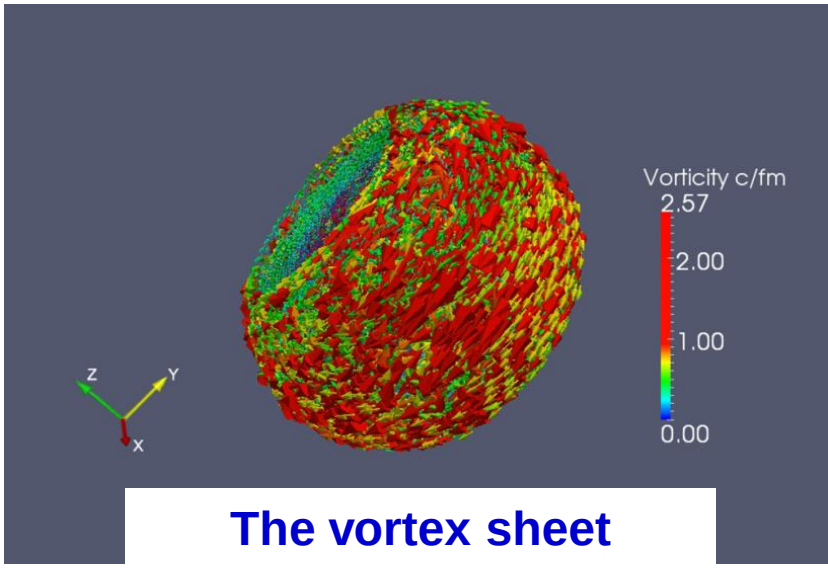
where η is the spin function and the amplitude A and the phase Φ are real.

Vorticity and hydrodynamic helicity in heavy-ion collisions

An analysis of experimental data unambiguously shows that the strongly interacting nuclear fluid appeared as a result of heavy-ion collisions is vortex and can be characterized by the vorticity field. Specific toroidal structures of vorticity field (femtometer vortex sheets) are formed.



Quadrupole structure of longitudinal vorticity



The vortex sheet

In particular, this effect leads to a significant polarization of Λ-hyperons produced in heavy-ion collisions.

M. Baznat, K. Gudima, A. Sorin, O. Teryaev, Phys. Rev. C **88,** 061901(R) (2013); **93,** 031902(R) (2016)**; 97,** 041902(R) (2018); **O. Teryaev, R. Usubov,** Phys. Rev. C **92,** 014906 (2015); **O. V. Teryaev, V. I. Zakharov,** Phys. Rev. D **96,** 096023 (2017); **G.Yu. Prokhorov, V.I. Zakharov, O.V. Teryaev,** EPJ Web Conf. **191,** 05006 (2018).

Importance of production of twisted particles at heavy-ion collisions

Is such a production rare? No, it isn't.

M. Katoh et al., Phys. Rev. Lett. **118,** 094801 (2017).

``This work indicates that twisted photons are naturally emitted by free electrons and are more ubiquitous in laboratories and in nature than ever thought." (Twisted Radiation from an Electron in Spiral Motion has been studied.) This conclusion has been perfectly confirmed in the following theoretical and experimental papers:

T. Kaneyasu et al., J. Synchrotron Rad. 24, 934 (2019); **S. V. Abdrashitov et al.,** Phys. Lett. A **382,** 3141 (2018); **V. Epp, J. Janz, M. Zotova,** Nucl. Instrum. Methods Phys. Res. B **436,** 78 (2018); **M. Katoh et al.,** Sci. Rep. **7,** 6130 (2017); **O. V. Bogdanov, P. O. Kazinski, G. Yu. Lazarenko,** Phys. Rev. A **97,** 033837 (2018); Phys. Rev. D **99,** 116016 (2019); Phys. Lett. A **406,** 114 (2019); **V. Epp, U. Guselnikova,** Phys. Lett. A **383**, 2668 (2019).

We predict that the production of other (massive) twisted particles with different spins should be ordinary at noncentral heavy-ion collisions due to a fast rotation of the nuclear fluid. We have found the relativistic Hamiltonian

$$\mathcal{H} = \beta\sqrt{m^2 + \mathbf{p}^2} - \boldsymbol{\omega}\cdot(\mathbf{L}+\mathbf{S}), \quad \beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

and stationary states of a free particle in a uniformly rotating frame being Laguerre-Gauss beams with a fixed orbital angular momentum.