Infinite and Finite Nuclear Matter
Dubna, 2023

Production of twisted particles in noncentral heavy-ion collisions

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BLTP, JINR, Dubna
27 February – 3 March 2023

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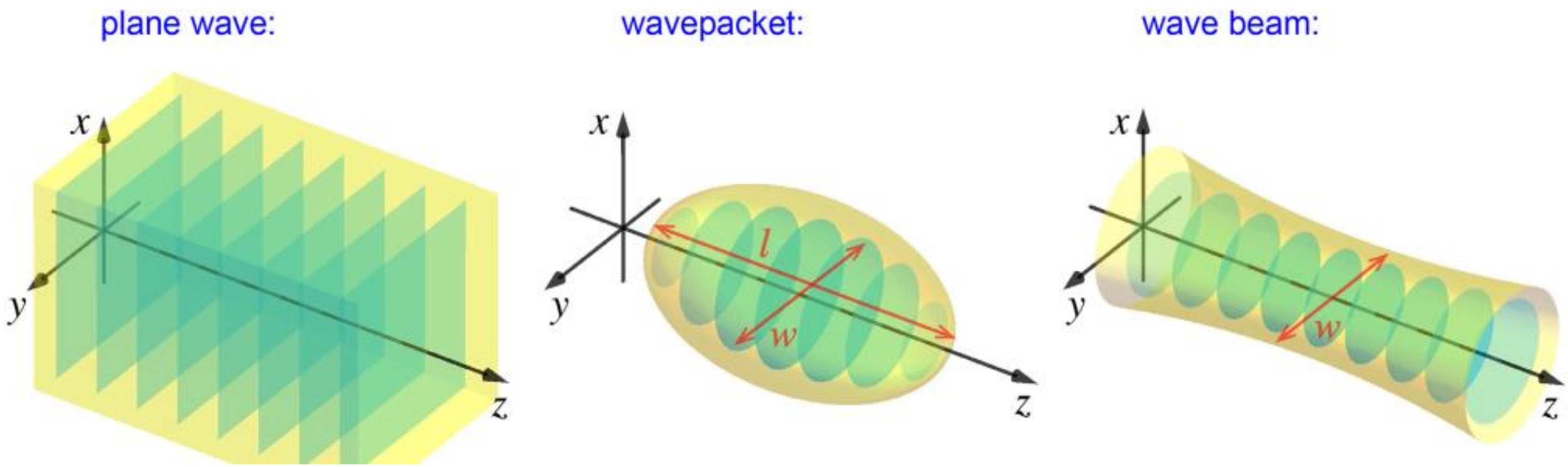
Introduction

Twisted (vortex) particles



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

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

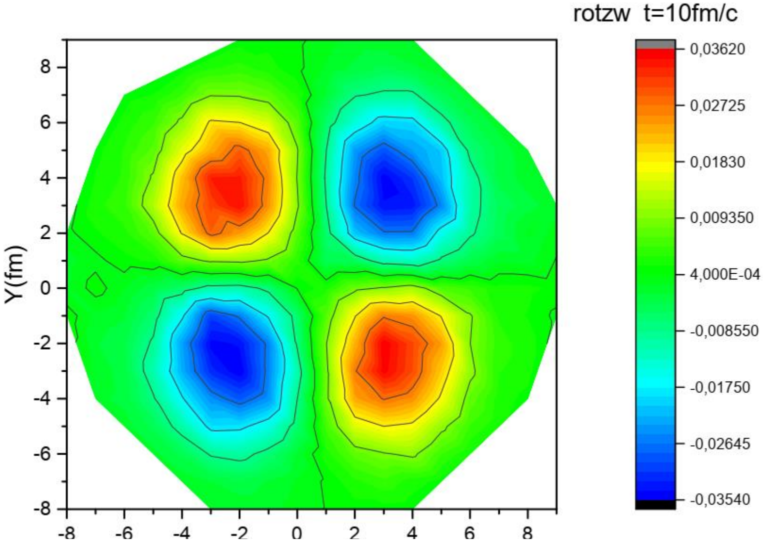
$$\mathbb{A} = \frac{C_{n\ell}}{w(z)}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|\ell|} L_n^{|\ell|}\left(\frac{2r^2}{w^2(z)}\right)\exp\left(-\frac{r^2}{w^2(z)}\right)\eta, \quad z_R = \frac{kw_0^2}{2}, \quad C_{n\ell} = \sqrt{\frac{2n!}{\pi(n+|\ell|)!}},$$

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

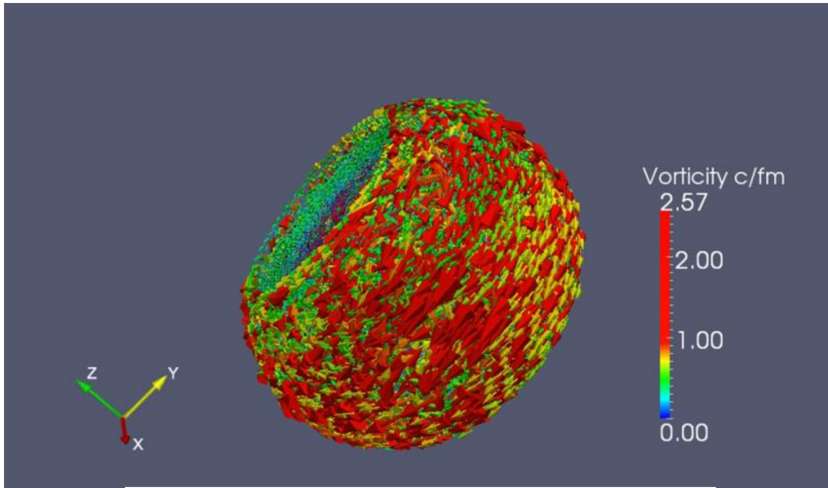
where η is the spin function and the amplitude A and the phase Φ are real.

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

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.

Production of twisted photons

IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **50** (2023) 015003 (12pp) https://doi.org/10.1088/1361-6471/aca1d6

Production of twisted particles in heavy-ion collisions

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Abstract

A prevalence of production of twisted (vortex) particles in noncentral heavy-ion collisions is shown. In such collisions, photons emitted due to the rotation of charges are highly twisted. Charged particles are produced in nonspreading multiwave states and have significant orbital angular momenta. It can be expected that an emission of any twisted particles manifesting themselves in specific effects is rather ubiquitous.

The synchrotron radiation spectrum consists of frequencies multiple to the rotation frequency of the compound nuclei, Ω:

$$\omega_j = j\Omega, \qquad j = 1, 2, 3, \ldots \tag{1}$$

Amazingly, the total angular momentum of a radiated photon is equal to $\hbar j$ and has orbital and spin parts [19, 20]. All photons with $j > 1$ are twisted. This effect confirmed by experimental data [22] clearly shows that twisted photons are widespread in nature.

[19] Katoh M *et al* 2017 Angular momentum of twisted radiation from an electron in spiral motion *Phys. Rev. Lett.* **118** 094801

[20] Epp V and Guselnikova U 2019 Angular momentum of radiation from a charge in circular and spiral motion *Phys. Lett.* A **383** 2668

[22] Katoh M *et al* 2017 Helical phase structure of radiation from an electron in circular motion *Sci. Rep.* **7** 6130

When the charges are ultrarelativistic, the spectral maximum in classical electrodynamics is defined by

$$\omega \sim \Omega\gamma^3.$$

Quantum electrodynamics leads to the different connection

between the spectral maximum ω and the particle energy $\epsilon = \gamma m$:

$$\frac{\hbar\omega}{(\epsilon - \hbar\omega)\chi} \sim 1, \qquad \chi \approx \frac{\hbar\Omega\epsilon^2}{m^3}.$$

In the general case,

$$L \sim \min\left(\hbar\gamma^3, \frac{\gamma m}{\Omega}\right).$$

For ultrarelativistic protons and valence quarks, $\Omega \sim c/\rho$. The ratio $m/(\hbar\Omega)$ is maximum in the case of $m = m_p$, $\rho = R$ and is approximately equal to 33.2. For confined constituent quarks, $m = m_q = m_p/3$, $\rho = r_p$, and the ratio $m/(\hbar\Omega)$ is approximately equal to 1.3. As a result, L is large enough ($\gamma \gg 1$) and photons emitted due to electromagnetic interactions at noncentral HIC are significantly twisted. Thus, our model-independent analysis rigorously proves a significant orbital polarization of such photons.

Production of twisted charged particles in a magnetic field

Well-known relativistic classical formulas defining the particle dynamics lead to the following relations:

$$r = |r| = -\frac{\pi_\phi}{eB}, \qquad \mathcal{L}_z = 2L_z = -eBr^2 = -\frac{\pi_\phi^2}{eB}. \tag{8}$$

The magnetic field emerging in the SPS, RHIC, and LHC experiments is of the order of $0.1\ m_\pi^2/|e|$, $m_\pi^2/|e|$, and $15\ m_\pi^2/|e|$, **respectively.**
The maximum beam radius is restricted by the area of the nonuniform magnetic field and is of the order of $r_{\max} \sim 3 \div 10$ fm
In quantum mechanics,

$$\langle r^2 \rangle = \frac{2(2n + |\ell| + 1)}{|e|B}, \qquad L_z^{\max} = \frac{|e|Br_{\max}^2}{2} - \hbar.$$

For the above-mentioned experiments, the maximum values of $|\pi_\phi|$ and $|\ell|$ defined by equations (8), (13) read $|\pi_\phi|_{\max} \sim 0.1$ GeV$/c$, $|\ell|_{\max} \sim 1$; $|\pi_\phi|_{\max} \sim 1$ GeV$/c$, $|\ell|_{\max} \sim 10$; and $|\pi_\phi|_{\max} \sim 10$ GeV$/c$, $|\ell|_{\max} \sim 10^2$, respectively.

The magnetic field at HIC is substantially nonuniform and time-dependent. The strong magnetic field *near colliding ions* [17] is able to hold charged particles even with large transversal momenta (see the precedent paragraph) in a helix. However, a quick decrease of this field with an increase of the distance from colliding nuclei strongly hampers motion of such particles in the helix and a detection of their OAMs. Therefore, we need to focus our attention on producing *paraxial* charged particles ($|\pi_\perp| \ll |\pi|$) having less transversal kinetic momenta. Even $(|\pi_\perp|/|\pi|) \lesssim 0.1$ can often be sufficient.

Some specific effects allowing one to detect such particles have been described in

Ivanov I P, Korchagin N, Pimikov A and Zhang P 2020 Kinematic surprises in twisted-particle collisions, Phys. Rev. D **101** 016007

I. P. Ivanov, Promises and challenges of high-energy vortex states collisions, Prog. Part. Nucl. Phys. **127,** 103987 (2022).

Summary

- Photons emitted due to the rotation of charges are highly twisted
- Charged particles are produced in nonspreading multiwave states and have significant orbital angular momenta
- It can be expected that an emission of any twisted particles manifesting themselves in specific effects is rather ubiquitous

Thank you for your attention