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Twisted particles in heavy-ion collisions

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The importance of twisted (vortex) particles in heavy-ion collisions is analyzed. Free twisted particles can possess giant intrinsic orbital angular momenta. Twisted particles are spatially localized and can be rather ubiquitous in laboratories and nature. Twisted photons have nonzero effective masses. Charged twisted particles can be recognized by their dynamics, magnetic moments, and specific effects in external fields.

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

$$\Psi = \mathcal{A}\exp(i\Phi), \qquad \mathcal{A} = \frac{C_{n\ell}}{w(z)}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|\ell|} L_n^{|\ell|}\left(\frac{2r^2}{w^2(z)}\right)\exp\left(-\frac{r^2}{w^2(z)}\right),$$
$$\Phi = \ell\phi + \frac{kr^2}{2R(z)} - (2n+|\ell|+1)\varphi(z), \quad C_{n\ell} = \sqrt{\frac{2n!}{\pi(n+|\ell|)!}}, \quad w(z) = w_0\sqrt{1+\frac{4z^2}{k^2w_0^4}}, \tag{1}$$
$$R(z) = z + \frac{k^2w_0^4}{4z}, \qquad \varphi(z) = \arctan\left(\frac{2z}{kw_0^2}\right), \qquad \int \Psi^\dagger\Psi r\, dr\, d\phi = 1,$$

where the real functions $\mathcal{A}$ and Φ define the amplitude and phase of the beam, k is the beam wavenumber, w_0 is the minimum beam width, $L_n^{|\ell|}$ is the generalized Laguerre polynomial, $\hbar\ell$ is the OAM, and $n = 0, 1, 2, \dots$ is the radial quantum number. Free twisted particles can possess giant intrinsic OAMs. Photons with OAMs more than $10000\hbar$ [1] and electrons with OAMs up to $1000\hbar$ [2] have been obtained. Twisted photons have nonzero effective masses [3]. Charged twisted particles can be recognized by their dynamics [4, 5], magnetic moments [6], and specific effects in external fields [7–9].

The importance of production of twisted particles at heavy-ion collisions (HIC) is evident. The similar effect of the global polarization of produced particles [10] attracts a lot of attention. To study the above-mentioned problem at noncentral HIC, one should take into account an appearance of a strong magnetic field [11] and a fast rotation of nuclear matter leading to its large vorticity [12].

The recent theoretical [13] and experimental [14] papers unambiguously show that the photons radiated by electrons in a helical or circular motion are twisted (i.e., have nonzero OAMs). The fast rotation of nuclear matter at noncentral HIC leads to a charge rotation and, therefore, to an emission of twisted photons. We suppose that other particles can also be produced in twisted states. The vorticity of nuclear matter is, to some extent, an effect similar to the twist. To describe processes taking place in a rotating nuclear matter, one often uses uniformly rotating frames. For a quantum-mechanical description of particles in such frames, it is convenient to apply the Foldy-Wouthuysen (FW) representation providing for the Schrödinger picture of relativistic quantum mechanics (see Refs. [15, 16] and references therein). The relativistic FW Hamiltonian describing a spin-1/2 particle in the frame uniformly rotating with the angular velocity $\boldsymbol{\omega}$ has the form [17]

$$\mathcal{H}_{FW} = \beta\sqrt{m^2+\boldsymbol{p}^2} - \boldsymbol{\omega}\cdot(\boldsymbol{L}+\boldsymbol{s}), \tag{2}$$

where β is the Dirac matrix and $\boldsymbol{L}$ and $\boldsymbol{s}$ are the OAM and spin operators. The eigenstates of this operator have definite integer OAMs and the corresponding eigenfunctions describe Laguerre-Gauss beams.

The above-mentioned arguments allow us to predict that the production of twisted photons and twisted massive particles with different spins should be usual in noncentral heavy-ion collisions. The production of charged twisted particles can be stimulated, besides the fast rotation of the nuclear matter, by the strong magnetic field.

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