Recent progress in the physics of twisted particles

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Twisted (vortex) particles with intrinsic orbital angular momenta (OAMs) even in free space are of significant importance in modern physics and have important applications. Twisted photons and electrons were discovered in 1992 and 2010, respectively. The maximum observed OAMs were about 10000$\hbar$ for photons and 1000$\hbar$ for electrons. Recently, twisted neutrons, atoms, and molecules were also discovered. In a magnetic field, charged particles move in a helical trajectory (on a circle in the transverse plane). In the quantum-mechanical picture, a particle trajectory cannot be defined, but its equations of motion are equivalent to the corresponding classical ones. Twisted particles in free space are not under the influence of any external forces. Twisted states appear as the coherent superpositions of noninteracting partial de Broglie waves with different directions of transverse momenta.[1–3]

While twisted states seem to be exotic, they have probably a wide dissemination in the Universe for at least two reasons. First, it has been theoretically and experimentally proven that photons radiated by charges in a helical or circular motion possess nonzero OAMs. Second, charged particles in a magnetic field are produced in twisted states and conserve their OAMs upon transitioning to a field-free environment.

The methods of producing twisted particle beams are continuously improving. The first twisted light beam was generated using two astigmatic lenses that introduce a Gouy phase shift, transforming a Hermite-Gauss beam to a Laguerre-Gauss one that carries nontrivial OAM. Azimuthal and radial indices of the produced beam depend on the initial Hermite-Gauss mode. A contemporary popular method of generating twisted light involves using spiral phase plates (or mirrors). When a plane (untwisted) optical wave passes through a plate with spatial variations of thickness or refractive index, it acquires a spiral phase with a specific OAM. Computer-generated holograms are also effective in constructing the spiral phase. Specifically, a diffraction grating with dislocations divides the incoming beam into several diffraction waves, each carrying distinct OAMs. The topological charge of vortices increases with the diffraction order (Figure 1). A spatial light modulator is an electronic liquid-crystal device that is computer controlled and creates dynamic vortices, arrays of vortices, and other types of

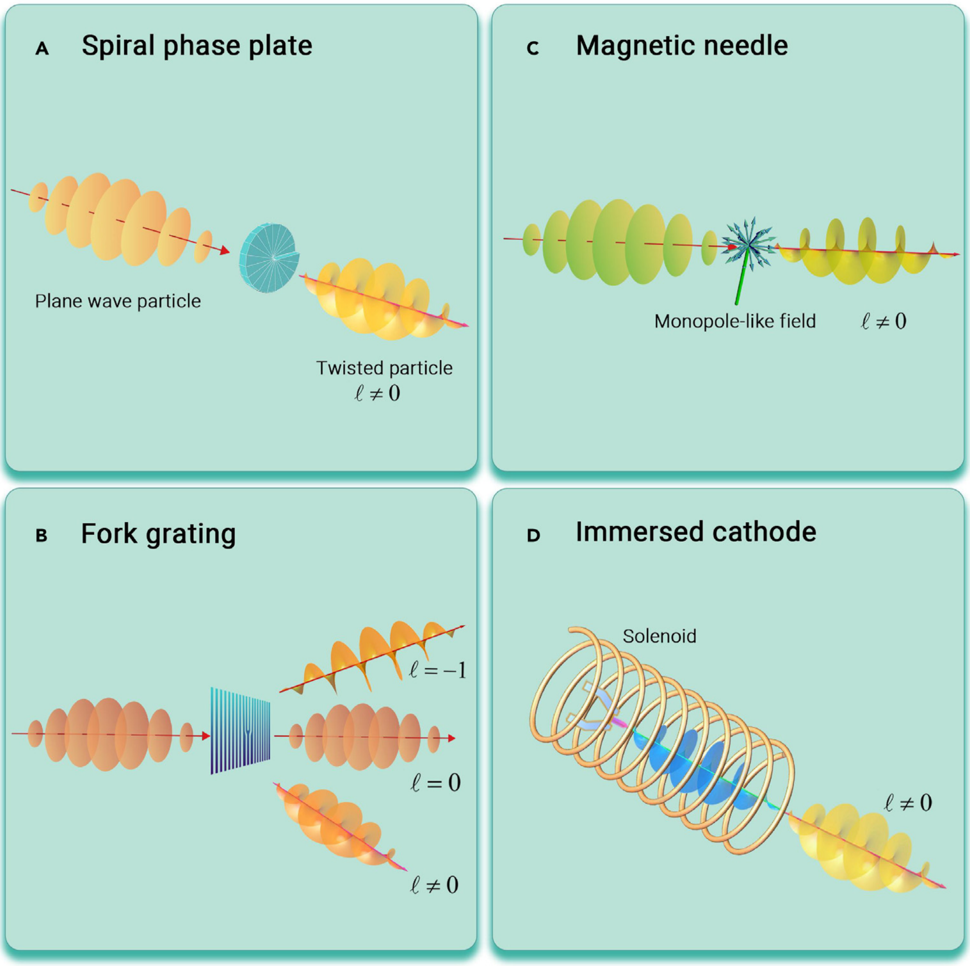

Figure 1. Methods of generation of twisted particle beams Four ways are shown with the use of (A) spiral phase plates, (B) fork grating holograms, (C) magnetic needle (only for charged particles), and (D) immersed cathode.

beams through a hologram with varying refractive index. A q-plate is a birefringent liquid crystal with a topological charge q. Several recently developed techniques involve using digital devices, photon sieves, metasurfaces, specific laser generators, microcavities, and on-chip gratings. Twisted photon beams in the extreme ultraviolet range have been experimentally demonstrated since 2017. A practical means of generating twisted photons in the X-ray domain (and beyond) utilizes undulators in electron accelerators like synchrotron radiation facility of third generation and free-electron laser oscillators.[1,2,4]

The methods of production of twisted electrons and photons share similarities[3] through the use of spiral phase plates, hologram diffraction gratings, and mode conversions. Other methods utilize the presence of electron charge. A highly efficient method uses a thin magnetic needle. Its special monopole-like magnetic field endows electrons with a quantized Dirac phase and nonzero OAMs (Figure 1C). Recently, electrostatic devices have enabled the generation of twisted electrons with tunable OAMs up to $1000\hbar$.[4]

Generating the twisted charged particles inside a solenoid with an immersed cathode technique (Figure 1D) is a recent promising method with potential use in accelerators physics. Another new idea is converting untwisted charged particles into twisted ones by passing them through a solenoid. Investigation of generation and beam dynamics of twisted particles in accelerator physics is emerging.

Twisted (vortex) beams, due to their new properties and effective production methods, have numerous applications. Twisted photons are already applied in nearly all advanced optics. OAM-entangled photon pairs realized in quantum entanglement have begun utilizing twisted photons in quantum information science. Free-space information transfer using twisted light has been accomplished. The application of the optical-beam OAM as a new degree of freedom for a multiplex modulation has essentially expanded opportunities of optical communications. Due to the advantages of spiral phase in phase-contrast microscopy, twisted photon beams have been employed in high-resolution imaging. Twisted photon beams also have numerous applications in nanotechnology, optical machining, nonlinear optics, chemistry, astronomy, and potentially in high energy physics.[2,4] Twisted electron beams are also widely used.[3] A promising application is electron microscopy. Owing to giant magnetic moments of twisted electrons, their specific interaction with matter provides new information about samples and increases microscope resolution. The resolution is provided at atomic level, which initiates new ways for mapping crystallographic, magnetic, and chiral properties of matter and the internal dynamics of atomic systems. Twisted electrons can be used for manipulating nanoparticles. The novel properties caused by electrons' OAM can also be utilized in spintronics.

The existence of twisted particles is significant for high energy physics. Twisted particles have been theoretically examined in various processes, such as bremsstrahlung by vortex electrons, high-energy twisted particle generation in collisions of twisted photons and electrons with atoms, the generation of stripped heavy ions during twisted-electron collisions with ions, inverse Compton scattering, hadron production from the scattering of twisted photons and protons, ultrarelativistic heavy-ion collisions, spin physics with twisted electron (positron) scattering and annihilation, and deep inelastic scattering of relativistic vortex electrons with hadrons and nuclei. All these processes can have important applications, e.g., for detecting twisted particles produced in heavy-ion collisions.

The precise determination of OAMs is critical for its application. Fortunately, multiple techniques can achieve this purpose, notably for twisted light.[1] A commonly used technique is the interference of a vortex beam with an inclined plane wave that produces a fork-like interferogram. The vortex order and sign can be precisely determined by counting the number of forks in the pattern and their relative orientations. Other interference methods that can be employed to measure the beam OAM include double-slit interference, multipoint interferometer, Mach-Zehnder interferometer, etc. The use of diffraction is another effective method, which enables the division of different OAMs through the use of aperture diffraction, grating diffraction, cylindrical lenses, etc. The OAM value can be extracted from the diffraction pattern in the far field. Other effective techniques such as geometric coordinate transformation, surface plasmon polaritons, and machine learning have been recently developed. However, some of these methods cannot be directly applied to twisted electron beams due to limited complex electron-optical elements. Learning from optics, modern methods for electrons[3] utilize the diffraction or interference based on holograms, apertures, and multi-pinhole. Direct manipulation of the wave phase using an astigmatic phase plate is another way to measure electron OAMs. Recently, an OAM sorter that uses electrostatic phase elements and achieves the OAM resolution of $1.5\hbar$ was demonstrated. Nevertheless, currently available measurements are inefficient because the limited transparency of measurement devices causes the loss of most beam intensity. Nondestructive measurement has emerged as an urgent issue to be addressed. One possible way to overcome this challenge involves detection of magnetic moment. However, its nondestructive measurement remains challenging in actual experimental setups.[3,4] Quantum scattering processes offer alternative possibilities. For example, in Compton scattering of twisted photons by electrons, the kinematics and angular distribution of scattered photons rely on the OAM and the opening angle of incident beams.[4]

Theoretically, optics[1,2] and *nonrelativistic* quantum mechanics (QM)[3] are commonly used to describe twisted light and electron beams, respectively. However, this is not entirely appropriate for electron beams with energies of 200–300 keV. Lorentz-invariant wave functions and quantum properties of twisted relativistic fermions have been determined in the Dirac representation[4] in both paraxial and nonparaxial regions. In this representation, initial equations are covariant. Due to this covariance, the Dirac representation is commonly used in the quantum field theory[4] and is also applied in QM for a determination of some beam properties.

Relativistic QM can also be presented in the Schrödinger form using the Foldy-Wouthuysen (FW) representation. This circumstance is particularly promising for twisted beams. The advanced FW transformation method gives *exact* expressions for leading terms in the FW Hamiltonian proportional to the zero and first powers of the Planck constant and even for terms proportional to $\hbar^2$ that describe contact interactions. In the FW representation, relativistic quantum dynamics of twisted Dirac particles in arbitrary electric and magnetic fields have been constructed. The new effect of a radiative orbital polarization of a twisted electron beam in a magnetic field resulting in a nonzero average projection of the intrinsic OAM on the field direction (i.e., the orbital Sokolov-Ternov effect) has been predicted. Twisted particles possess a tensor magnetic polarizability calculated for the electron and a measurable (spectroscopic) electric quadrupole moment. Methods for measuring these parameters have been proposed. The relativistic consideration confirms the model of structured (including twisted) particles as centroids with definite average longitudinal momenta and a hidden transverse motion. These particles (including photons) have nonzero effective masses that are quantized.[5] A general quantum-mechanical solution has been found for relativistic Dirac particles in uniform magnetic fields describing relativistic Laguerre-Gauss beams, which contains the well-known Landau result as a specific case.

Currently, theoretical, experimental, and applied investigations of twisted particles are rapidly developing worldwide.

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DECLARATION OF INTERESTS

The authors declare no competing interests.