Vortex state collisions for particle physics

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Mini-workshop on Quantum effects in atomic and particle physics

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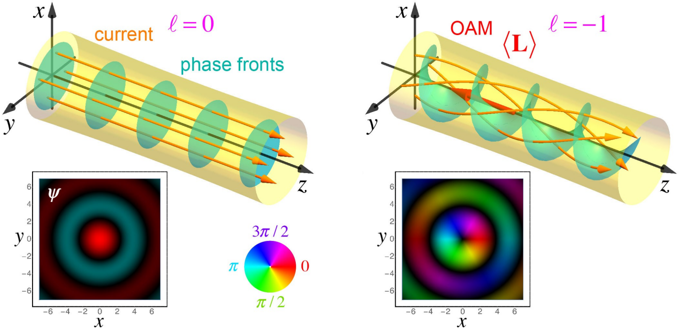
中山大學 物理与天文学院
SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS AND ASTRONOMY

Vortex states: an introduction

Cylindrical wave with phase vortex



Coordinate dependence: $\psi(\mathbf{r}) \propto e^{i\ell\varphi_r}$

Intrinsic orbital angular momentum (OAM): $\langle L_z \rangle = \hbar\ell$.

Bessel beams

Monochromatic solutions of the (scalar) wave equation:

- plane waves: definite **k**

$$\phi(\mathbf{k}) \propto \delta^{(3)}(\mathbf{k}-\mathbf{k}_0)\,, \quad \psi(\mathbf{r}) \propto \int d^3k\, \phi(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{r}} = e^{i\mathbf{k}_0\cdot\mathbf{r}}$$

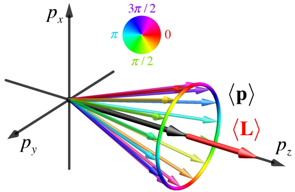
- Bessel beams: definite k_z, $\varkappa = |\mathbf{k}_\perp|$, and ℓ.
  Momentum space:

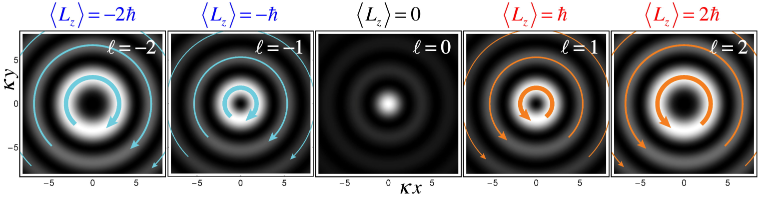
$$\phi(\mathbf{k}) \propto \delta(k_z - k_{0z})\, \delta(k_\perp - \varkappa)\, e^{i\ell\varphi_k}\,.$$

  Coordinate space:

$$\psi(\mathbf{r}) \propto \int d^3k\, \phi(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{r}} \propto e^{ik_{0z}z} e^{i\ell\varphi_r}\, J_\ell(\varkappa r_\perp)\,.$$

Vortex beams

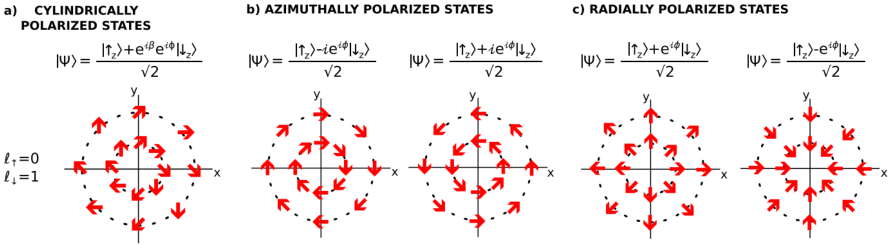




The Bessel beam is not normalizable in the transverse plane → normalizable Laguerre-Gaussian (LG) wave packet is a better option for a vortex beam.

The OAM of a vortex state

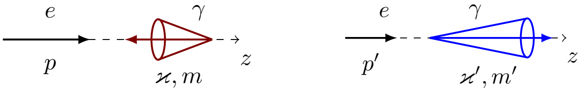
- Exact solutions for vortex photons and electrons: [Jentschura, Serbo, PRL106 (2011) 013001; Bliokh et al, PRL107 (2011) 174802; Karlovets, PRA 86 (2012) 062102; Serbo et al, PRA92 (2015) 012705] and later works.
- Spin and OAM can be entangled → many exotic polarization states possible!



[Sarenac et al, New J. Phys. 20 (2018) 103012]

Vortex photons

- Optical range vortex photons routinely studied and used since the 1980s, [Allen et al, PRA45, 8185 (1992)], with ℓ up to 10000: [Fickler et al, PNAS 113, 13642 (2016)].
- Single mode vortex X rays, e.g. $E = 1$ keV, $\ell = 30$ [Lee et al, Nat. Photonics 13 (2019) 205].
- Theoretical proposal: inverse Compton scattering of vortex optical photons off GeV range electrons [Jentschura, Serbo, PRL106 (2011) 013001] and the follow-up papers.



- Much higher cross section with ultrarelativistic partially stripped ions instead of electrons [Serbo, Surzhykov, Volotka, Ann. Phys. (Leipzig) (2021) 2100199], e.g. at the Gamma-Factory at CERN [Krasny, arXiv:1511.07794].

High energy vortex photons in China

Several groups in China:

- Jian-Xing Li's group at XJTU, Xi'an: γ photons with OAM via nonlinear Compton of UR electrons on a CP laser pulse [Ababekri et al, arXiv:2211.05467] or "laser bullets" [Liu et al, Optics Lett. 45 (2020) 395].
- Liangliang Ji's group at SIOM, Shanghai: via bremsstrahlung [Wang et al, PR Research 4 (2022) 023084; NJP 24 (2022) 043037], through vortex e^+e^- pair production [Lei et al, PRD 104 (2021) 076025; Bu et al, PR Research 3 (2021) 043159; Lei et al, 2303.10851], or non-linear Compton scattering [Bu et al, 2302.05065].
- Tongpu Yu's group in Changsha: light-fan-in-channel method [Zhang et al, High Power Laser Sci. Eng. 9 (2021) e43] or GeV-range γ and positron beams with high OAM in an all-optical laser-plasma scheme [Zhu et al, NJP 20 (2018) 083013].

Vortex particles

- 2010–2011: experimental demonstration of vortex electrons: [Uchida, Tonomura, Nature 464, 737 (2010)]; [Verbeeck, Tian, Schattschneider, Nature 467, 301 (2010)]; [McMorran et al, Science 331, 192 (2011)]. Typical values: $E = 300$ keV, ℓ up to 1000, focusing to ≈ 1 Å focal spot.
- Proposals for higher energy vortex electrons: production in magnetic fields [Karlovets, NJP 23 (2021) 033048], via scattering [Karlovets et al, EPJC 83 (2023) 372], in heavy ion collisions [Zou, Zhang, Silenko, J.Phys.G50 (2023) 015003].
- Slow vortex neutrons: first reported in 2015, unambiguously demonstrated in 2022 [Sarenac et al, Sci. Adv.8, eadd2002 (2022)].
- Slow vortex He atoms [Luski et al, Science 373 (2021) 1105].

Nuclear and particle physics with vortex states

Nuclear and particle physics with vortex states

So far only theoretical proposals...

Recent review: Ivanov, Prog.Part.Nucl.Phys. 127 (2022) 103987 [arXiv:2205.00412]

Example 1:
accessing the Coulomb phase

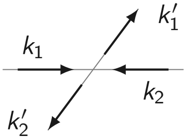
Based on:

Ivanov, PRD85, 076001 (2012); Ivanov et al, PRD94, 076001 (2016)

Vortex state scattering

Plane wave scattering $|k_1\rangle + |k_2\rangle \to |k_1'\rangle + |k_2'\rangle$:

- $\mathbf{K} = \mathbf{k}_1' + \mathbf{k}_2' = 0$ in the c.m. frame;
- differential cross section depends only on $\mathbf{k}_1'$.



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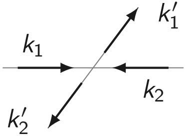
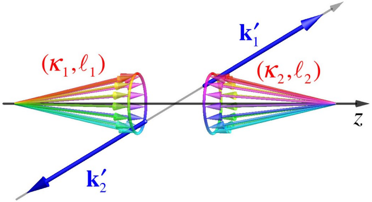




Vortex state scattering: $|\varkappa_1, \ell_1\rangle + |\varkappa_2, \ell_2\rangle \to |k_1'\rangle + |k_2'\rangle$.

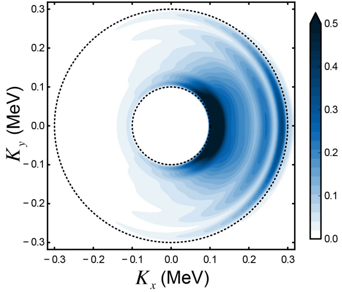
- $\mathbf{K} = \mathbf{k}_1' + \mathbf{k}_2'$ is not fixed $\Rightarrow$ distribution over $\mathbf{K}$.
- A new dimension available in vortex state scattering!

Elastic vortex electron-electron scattering

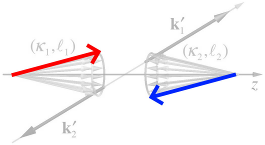
$$e(\varkappa_1, \ell_1)\, e(\varkappa_2, \ell_2) \to e(k_1')\, e(sk_2')$$

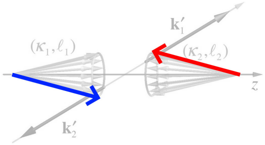
[Ivanov et al, PRD94, 076001 (2016)]

Parameters used: $E_1 = 2.1$ MeV, $k_1' = 500$ keV, $j_1 = 1/2$, $j_2 = 13/2$, $\varkappa_1 = 200$ keV, $\varkappa_2 = 100$ keV, Gaussian-smeared.



Interference fringes in the $\vec{K}_\perp$ plane between pairs of plane-wave components inside each vortex state leading to the same final state





Elastic *ee* scattering beyond Born approximation

Multi-photon exchanges make the scattering amplitude $\mathcal{M}_{PW}$ complex:

$$\mathcal{M}_{PW} = |\mathcal{M}| e^{i\Phi_C(\theta)}\,, \quad \Phi_C(\theta) = \Phi_0 + 2\alpha \ln(1/\theta)\,,$$

where θ is the c.m.f. scattering angle.

The Coulomb phase is not observable in plane wave scattering:

$$\frac{d\sigma_{PW}}{d\cos\theta} \propto |\mathcal{M}_{PW}(\theta)|^2\,.$$

Extra complications in scattering of charged hadrons, $\mathcal{M} = \mathcal{M}_{EM} + \mathcal{M}_s$, with the strong and EM contributions interfering and mixing beyond Born approximation.

- Debates on calculating $\Phi_C(\theta)$ starting from [Bethe, Ann. Phys. 3, 190 (1958)].
- Experimental measurement of $\Phi_C(\theta)$ was considered impossible.

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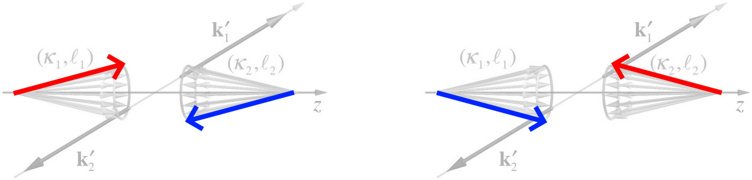
Accessing the Coulomb phase

Elastic scattering of vortex electrons gives experimental access to the Coulomb phase [Ivanov, PRD85, 076001 (2012); Ivanov et al, PRD94, 076001 (2016); Karlovets, EPL 116, 31001 (2016)].



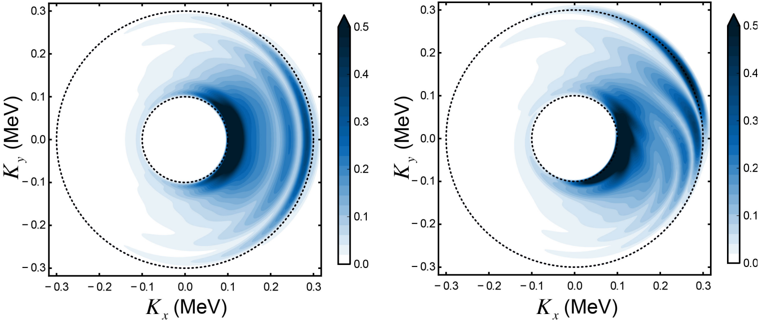
For Bessel states, two PW configurations interfere:

$$\mathcal{M} = c_a\,\mathcal{M}_a(k_{1a}, k_{2a}; k_1', k_2') + c_b\,\mathcal{M}_b(k_{1b}, k_{2b}; k_1', k_2')$$

Scattering angles are different: $\theta_a \neq \theta_b \Rightarrow \Phi_C(\theta_a) \neq \Phi_C(\theta_b)$.

$d\sigma \propto |c_a\mathcal{M}_a + c_b\mathcal{M}_b|^2$ contains the interference term sensitive to $\Phi_C(\theta)$.

Accessing the Coulomb phase



- Left: no phase; right: artificially enhanced Coulomb phase.
- Realistic Coulomb phase: azimuthal asymmetry of $\mathcal{O}(10^{-4})$.

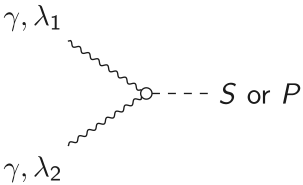
Proof-of-principle experiments challenging but possible.

Example 2:
new tool for spin physics

Based on:

Ivanov, Korchagin, Pimikov, Zhang, PRL 124 (2020) 192001, PRD 101 (2020) 096010.

Probing scalar-pseudoscalar mixing



Consider spin-0 resonance production in plane wave $\gamma\gamma$ collisions.

Only $\lambda_1 = \lambda_2 \equiv \lambda$ helicity amplitudes are non-zero.

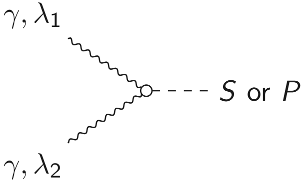
- Pure scalar: $\mathcal{L} \propto F^{\mu\nu} F_{\mu\nu} S \quad \to \quad \mathcal{M}_S \propto \delta_{\lambda_1,\lambda_2}$.
- Pure pseudoscalar: $\mathcal{L} \propto F^{\mu\nu} \tilde{F}_{\mu\nu} P \quad \to \quad \mathcal{M}_P \propto \lambda\, \delta_{\lambda_1,\lambda_2}$.
- S/P-mixture: $\mathcal{M} \propto (g_S + \lambda g_P)\delta_{\lambda_1,\lambda_2}$.

$$\sigma_\lambda \propto |g_S|^2 + |g_P|^2 + 2\lambda\, \mathrm{Re}(g_S^* g_P)\,.$$

The unpolarized cross section is insensitive to scalar-pseudoscalar mixing:

$$\sigma_0 \propto |g_S|^2 + |g_P|^2\,.$$

Probing scalar-pseudoscalar mixing



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Probing scalar-pseudoscalar mixing

Consider now collision of unpolarized vortex photon beams: flipping helicity λ with the total angular momentum m fixed.

- Pure scalar: $\mathcal{J}_S \propto (\mathcal{J}_1 + \lambda \mathcal{J}_2)\delta_{\lambda_1,\lambda_2}$, where $\mathcal{J}_1$ and $\mathcal{J}_2$ depend on m_1 and m_2 and are oscillating functions of the energy.
- Notice: $\sigma_{\lambda=+1} \neq \sigma_{\lambda=-1}$ even for a pure scalar!
- The interaction is parity-conserving but the initial state (fixed m_i for any λ_i) is not parity-invariant.

Probing scalar-pseudoscalar mixing

- Pure pseudoscalar:

$$\mathcal{J}_P \propto \lambda(\mathcal{J}_1 + \lambda\mathcal{J}_2)\delta_{\lambda_1,\lambda_2}$$

- S/P Mixture:

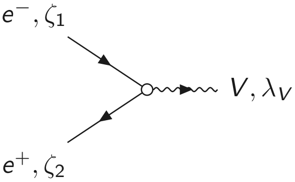
$$\mathcal{J} \propto (g_S + \lambda g_P)(\mathcal{J}_1 + \lambda\mathcal{J}_2)\,,$$

- Unpolarized cross section is sensitive to mixing:

$$\sigma_0 \propto (\mathcal{J}_1^2 + \mathcal{J}_2^2)(|g_S|^2 + |g_P|^2) + 4\mathcal{J}_1\mathcal{J}_2\,\mathrm{Re}(g_S^* g_P)\,.$$

The extra term has a different interference pattern → the amount of mixing can be determined via the energy scan of σ_0.

Polarized mesons from unpolarized e^+e^-



Spin-1 meson V produced in e^+e^- annihilation with the PW amplitude:

$$\mathcal{M}_{\zeta_1\zeta_2\lambda_V} = g\bar{v}_{\zeta_2}(k_2)\gamma_\mu u_{\zeta_1}(k_1)V^{\mu *}_{\lambda_V}(K)\,.$$

Here ζ_1, ζ_2, and λ_V are the helicities of e^-, e^+, V.

In unpolarized e^+e^- annihilation, the meson is also unpolarized:

$$\sigma(\lambda_V = +1) = \sigma(\lambda_V = -1)\,.$$

Polarized mesons from unpolarized e^+e^-

Vortex e^+e^- annihilation: the amplitude $\zeta_1 = -\zeta_2 = \zeta$ dominates:

$$\mathcal{J}_{\zeta,-\zeta,\lambda_V} \propto (\lambda_V \cos\theta_K + 2\zeta)\,(\mathcal{J}_1 + 2\zeta\mathcal{J}_2)\,,$$

where $\mathcal{J}_1$, $\mathcal{J}_2$ depend on m_1, m_2 and are oscillating functions of energy.

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Unpolarized vortex electron beam: flip helicity ζ, keeping m fixed.

The unpolarized e^+e^- annihilation is different for different λ_V:

$$\sigma(\lambda_V = +1) \neq \sigma(\lambda_V = -1)\,.$$

Polarized mesons emerge from unpolarized e^+e^- annihilation!

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The lesson

Access to spin-parity properties via unpolarized, fully integrated cross sections

⇒ a new tool for exploring the proton spin structure!

Conclusions

- Physics of vortex states of particles is an emergent interdisciplinary field linking beam physics, atomic physics, optics, nuclear and particle physics.
- Vortex photons, electrons, neutrons, and atoms were experimentally demonstrated, but only at low energies. There are ideas how to produce high-energy vortex states, to be confirmed experimentally.
- Vortex states offer new degrees of freedom in nuclear and particle physics, which lead to remarkable effects. A dedicated experimental effort is needed to verify these intriguing predictions.