Vortex states as a novel tool for particle physics

Igor Ivanov

School of Physics and Astronomy, SYSU, Zhuhai

Chirality 2026

Zhuhai, China

November 17, 2026

Based on: I.P.Ivanov, Prog.Part.Nucl.Phys. 127 (2022) 103987 and earlier works

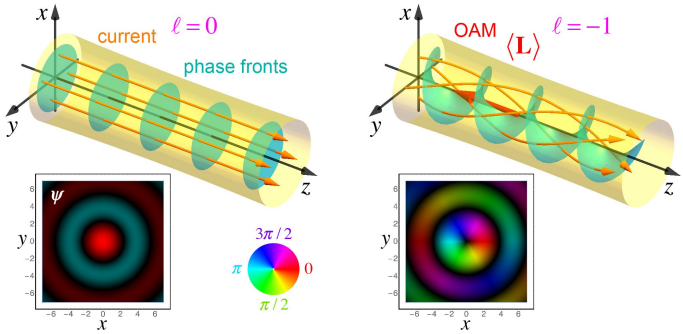


中山大學 物理与天文学院

SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS AND ASTRONOMY

Vortex states: an introduction

Cylindrical wave with phase vortex



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

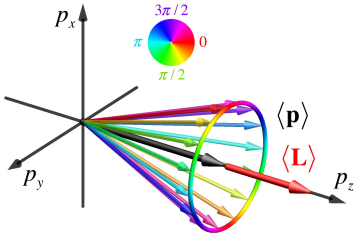
Intrinsic orbital angular momentum (OAM): $\langle L_z \rangle = \hbar\ell$.

Vortex beams in momentum space

- Plane wave (PW): $\phi(\mathbf{k}) \propto \delta^{(3)}(\mathbf{k} - \mathbf{k}_0)$.
- Bessel state:

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

- Laguerre-Gaussian (LG) wave packets: normalized vortex states.



Vortex states are coherent superpositions of plane waves with azimuthal-angle dependent phase factors.

Coherence + intrinsic OAM $\rightarrow$ a unique probe of particle structure and interactions.

Spin-OAM entangled states

- Exact solutions for vortex photons and electrons are constructed as eigenstates of helicity λ and the total AM projection J_z.

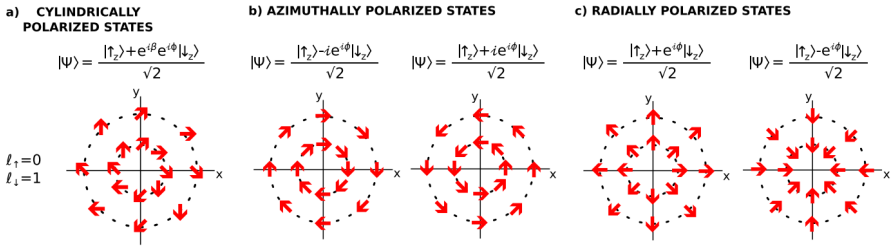
  [Jentschura, Serbo, PRL106 (2011) 013001; Bliokh et al, PRL107 (2011) 174802; Karlovets, PRA 86 (2012) 062102; Serbo et al, PRA92 (2015) 012705] and later works.

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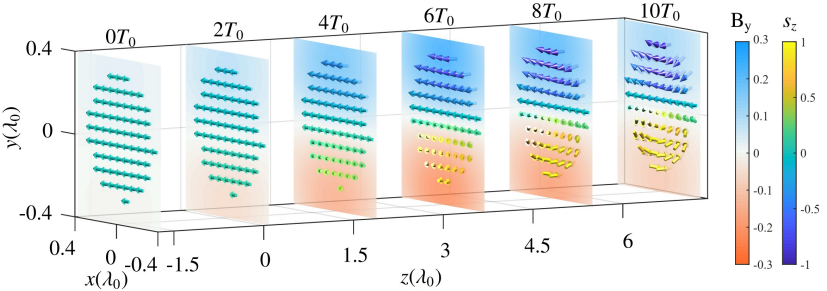
- Spin and OAM can be entangled $\rightarrow$ many exotic polarization states possible!



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

Spin-OAM entangled states

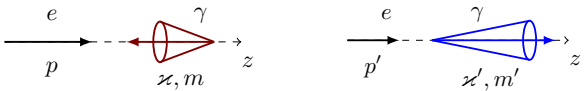
Li et al, PRL135 (2025) 13, 135001: Generation of Relativistic Structured Spin-Polarized Lepton Beams



OAM-spin entangled vortex electron beams can be obtained via interaction with specially designed velocity-matched THz waveguide modes.

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.

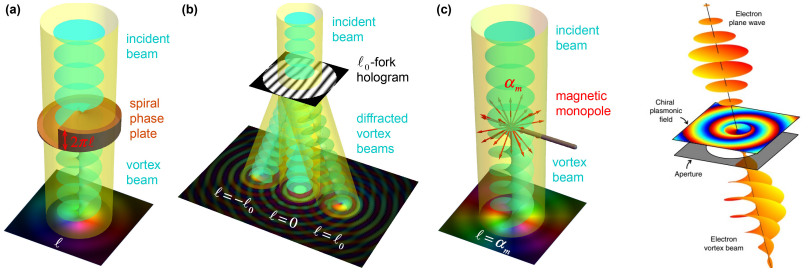


The first realization of this scheme: [Wei et al, 2503.18843]: Experimental Evidence of Vortex γ-Photons in All-Optical Inverse Compton Scattering; $E_\gamma \approx 0.8$ MeV; $\ell = 7$.

- 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].

Vortex electrons

- 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.



Bliokh et al, Phys. Reports 690 (2017) 1; Vanacore et al, Nature Mat. 18 (2019) 573 + other methods.

Vortex particles

- Proposals for higher energy vortex electrons: production in magnetic fields [Karlovets, NJP 23 (2021) 033048], via scattering [Karlovets et al, EPJC 83 (2023) 372], acceleration in a linac [Baturin et al, PRA 106 (2022) 4, 042211; Karlovets, Grosman, Pavlov, PRL136 (2026) 8, 085002].
- $\Rightarrow$ talk by Dmitry Karlovets this afternoon.
- 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].

What about higher energies? Experimental work underway, e.g. by the ITMO-JINR team [Dyatlov et al, 2024 International Conference Laser Optics (ICLO); 2509.00732].

What about vortex protons? Ions? muons? Some ideas are being explored.

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Nuclear and particle physics with vortex states

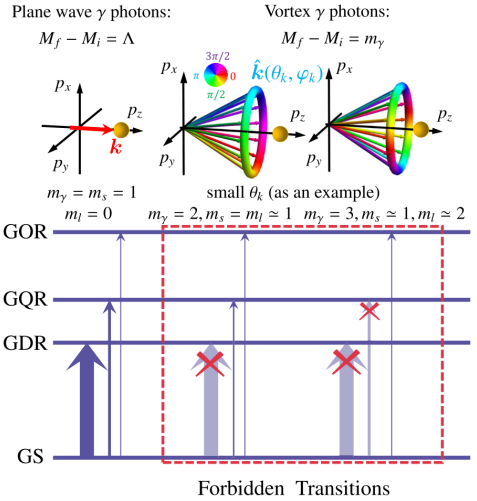
Nuclear and particle physics with vortex states

So far only theoretical proposals...

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

Example 1:
a novel nuclear physics tool

Selective excitation of nuclear multipole transitions



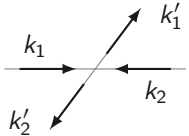
- Giant resonances in nuclear excitation: collective motion of p vs n densities.
- Photo-nuclear reactions dominated by the giant dipole resonance (GDR).
- For a vortex gamma photon, selection rules change $\rightarrow$ effectively suppressing GDR [Lu et al, PRL131, 202502 (2023); PRC113, 044315 (2026)].
- Probing vortex MeV-scale γ photons with nuclear resonance fluorescence [Chen, Niu, Chen, 2608.16533].
- But b must be controlled within a few fm $\rightarrow$ serious challenge!

Example 2:
probing the phase of a scattering amplitude

Vortex state scattering

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

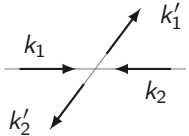
- $\mathbf{K} = \mathbf{k}_1' + \mathbf{k}_2' = 0$ in the c.m. frame;
- differential cross section depends only on $\mathbf{k}_1'$.

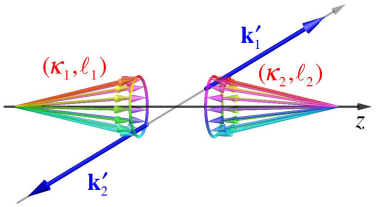


Vortex state scattering

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





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

- The final particles are PW $\to$ detect them with traditional detectors!
- $\mathbf{K} = \mathbf{k}_1' + \mathbf{k}_2'$ is not fixed $\Rightarrow$ distribution over $\mathbf{K}$.
- A new dimension is available in vortex state scattering!

No need to recalculate Feynman diagrams; just wave packet integrations.

$$S_{PW} = i(2\pi)^4 \delta^{(4)}(k_1 + k_2 - k_1' - k_2') \frac{\mathcal{M}(k_1, k_2)}{\sqrt{16 E_1 E_2 E_1' E_2'}} .$$

Non-plane-wave initial states, $\varphi_i(\vec{k})$ [Kotkin, Serbo, Schiller, IJMPA7 (1992) 4707; Karlovets, Serbo, PRD101, 076009 (2020)]:

$$S = \int \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 k_2}{(2\pi)^3} \varphi_1(k_1) \varphi_2(k_2) S_{PW}$$

The number of events per unit time: $d\nu = \frac{(2\pi)^7 \delta(E)}{4 E_1 E_2} |f|^2 \frac{d^3 k_1'}{(2\pi)^3 2E_1'} \frac{d^3 k_2'}{(2\pi)^3 2E_2'}$,

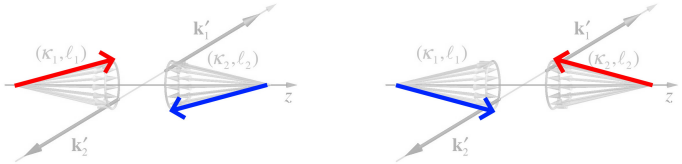
$$f = \int \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 k_2}{(2\pi)^3} \varphi_1(k_1) \varphi_2(k_2) \delta^{(3)}(\vec{k}_1 + \vec{k}_2 - \vec{K}) \mathcal{M}(k_1, k_2) .$$

Cross section defined via $d\nu = d\sigma \cdot L$, with L being the luminosity function.

Accessing the Coulomb phase

Usual PW scattering: $\mathcal{M} = |\mathcal{M}| e^{i\Phi(\theta)}$ but we measure only $d\sigma \propto |\mathcal{M}|^2$.

Scattering of vortex states gives experimental access to the phase $\Phi(\theta)$ [Ivanov, PRD85, 076001 (2012); Ivanov et al, PRD94, 076001 (2016); Karlovets, EPL 116, 31001 (2016)].

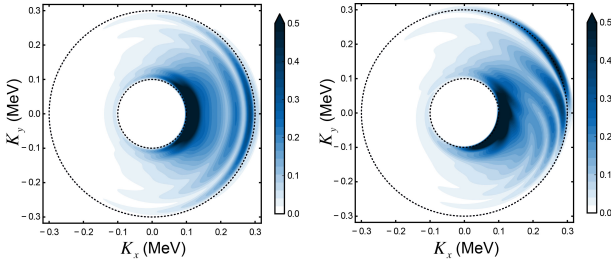


$$f = c_a\, \mathcal{M}_a(k_{1a}, k_{2a}; k_1', k_2') + c_b\, \mathcal{M}_b(k_{1b}, k_{2b}; k_1', k_2')\,, \quad d\sigma \propto |c_a \mathcal{M}_a + c_b \mathcal{M}_b|^2$$

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

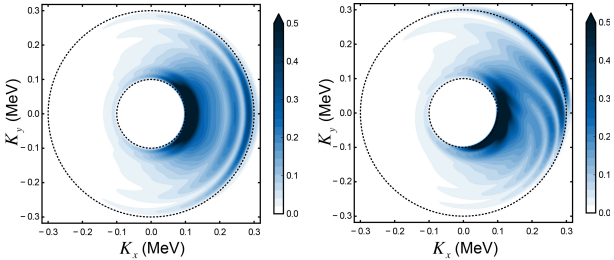
The interference term is sensitive to $\Phi(\theta)$ and can be extracted via azimuthal asymmetry.

Probing the phase of the total amplitude



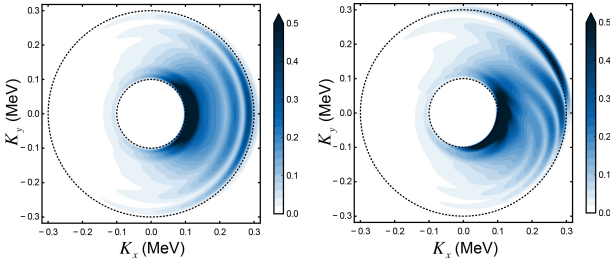
- Example of elastic $ee \to ee$ scattering [Ivanov et al, PRD94, 076001 (2016)]: left: real $\mathcal{M}$; right: $\Phi(\theta) = a \ln(1/\theta)$, as in the Coulomb phase.
- Can be very helpful in "complete experiment" measurements of hadron photoproduction, such as $\gamma p \to K^+\Lambda$, with many interfering partial waves, e.g. [Wunderlich, Beck, Tiator, PRC 89 (2014) 055203].
- The relative phase between the EM formfactors of the proton G_E vs G_M in the timelike region via vortex $p\bar{p} \to e^+e^-$ annihilation in fully unpolarized setting [Korchagin, PRD 111 (2025) 076005].

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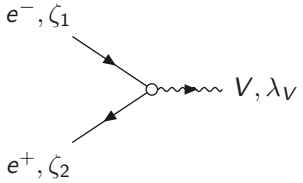
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Example 3:
a new tool for spin physics

Based on:

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

Polarized mesons from unpolarized e^+e^-



Consider PW e^+e^- annihilation into a spin-1 meson V (paraxial approximation but not in c.m.f.):

$$\mathcal{M}_{\zeta_1\zeta_2\lambda_V} \propto \bar{v}_{\zeta_2}(k_2)\gamma_\mu u_{\zeta_1}(k_1) V^{\mu *}_{\lambda_V}(K) \quad \propto \quad \lambda_V \cos\theta_V + 2\zeta\,.$$

Here $\zeta \equiv \zeta_1 = -\zeta_2$ and λ_V are the helicities of e^-, e^+, V.

$\sigma \propto (\lambda_V \cos\theta_V + 2\zeta)^2$. 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:

$$\begin{aligned} \mathcal{M}_{\zeta,-\zeta,\lambda_V} &\propto (\lambda_V \cos\theta_V + 2\zeta)(\mathcal{J}_1 + 2\zeta\,\mathcal{J}_2) \\ &= (\mathcal{J}_2 + \mathcal{J}_1\lambda_V \cos\theta_V) + 2\zeta\,(\mathcal{J}_1 + \mathcal{J}_2\lambda_V \cos\theta_V)\,, \end{aligned}$$

where $\mathcal{J}_1$, $\mathcal{J}_2$ depend on the vortex parameters and are oscillating functions of energy.

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where $\mathcal{J}_1$, $\mathcal{J}_2$ depend on the vortex parameters and are oscillating functions of energy.

The unpolarized e^+e^- annihilation now depends on λ_V:

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

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

The origin: intrinsic spin-orbital interaction within vortex states.

Helicities $\zeta = +1/2$ and $\zeta = -1/2$ exhibit different spatial distributions!

Conclusions

- Physics of vortex states is an emergent interdisciplinary field linking beam physics, atomic physics, optics, nuclear and particle physics.
- Vortex states offer new degrees of freedom never used in nuclear and particle physics:
  - adjustable, topologically protected initial-state OAM,
  - new dimensions in the final phase space,
  - spin-OAM entanglement: much richer polarization options available.
- Remarkable effects, which are difficult or impossible for PW scattering, are theoretically predicted and await experimental verification.

Further input from the nuclear, hadronic, and HEP communities is welcome!