Vortex states as a new tool for hadronic physics

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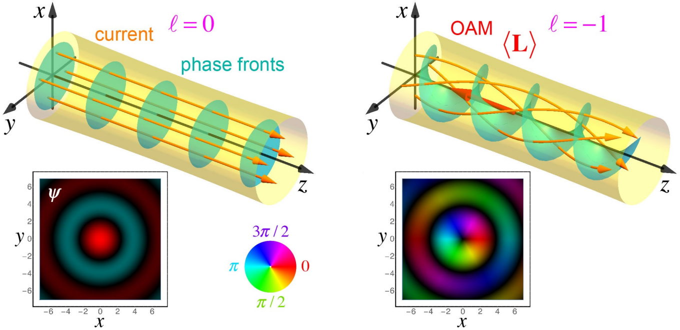
SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS AND ASTRONOMY

Vortex states: an introduction



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

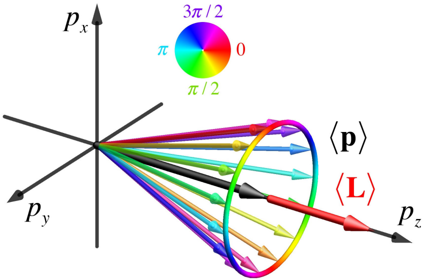
Intrinsic orbital angular momentum (OAM): $\langle L_z \rangle = \hbar\ell$.

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.

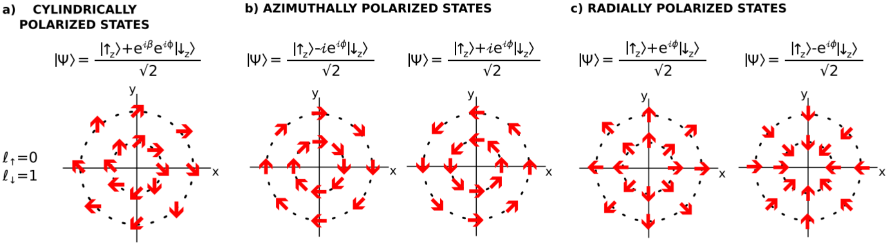


Vortex states are coherent superpositions of plane waves with azimuthal-angle dependent phase factors.

This coherence makes vortex states a unique probe of particle structure and interactions.

Spin-OAM entangled states

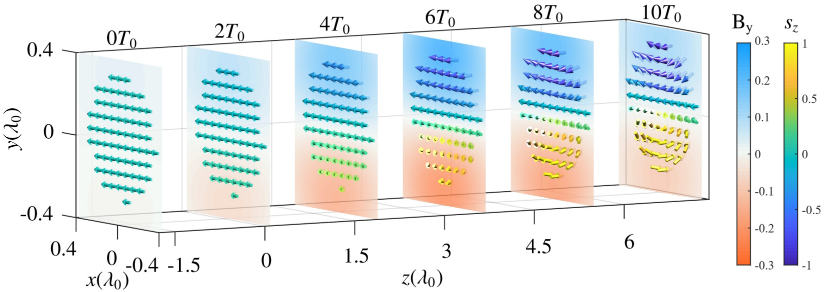
- Exact solutions for vortex photons and electrons: [Jentschura, Serbo, PRL106 (2011) 013001; Bliokh et al, PRL107 (2011) 174802; Karlovets, PRA 86 (2012) 062102; Serbo et al, PRA92 (2015) 012705] and later works.
- Spin and OAM can be entangled → many exotic polarization states possible!



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

Spin-OAM entangled states

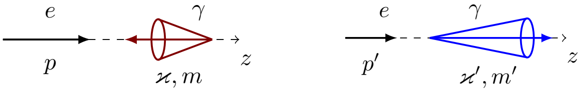
An impressive proposal from the XJTU team: Li et al, 2504.11113:
Generation of Relativistic Structured Spin-Polarized Lepton Beams.



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

$\Rightarrow$ more details in talk by Jian-Xing Li on Monday.

- 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.

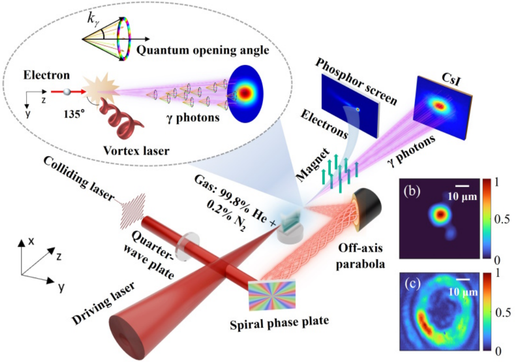


- Much higher cross section with ultrarelativistic partially stripped ions instead of electrons [Serbo, Surzhykov, Volotka, Ann. Phys. (Leipzig) (2021) 2100199], e.g. at the Gamma-Factory at CERN [Krasny, arXiv:1511.07794].

Recent big news from SJTU: Wei et al, 2503.18843:

Experimental Evidence of Vortex γ-Photons in All-Optical Inverse Compton Scattering.

- All-optical scheme, using multi-MeV electrons from LWFA.
- γ energies peak at 0.8 MeV; OAM expected to be close to the driving LG beam $\ell = 7$.
- The evidence of vorticity is indirect (anomalous broadening), but it is still a big step forward!



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].

What about vortex protons? Ions? muons? Some experimental work is underway!
$\Rightarrow$ talks by Zou Liping on Monday and by Huang Junren on Tuesday.

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Nuclear and particle physics with vortex states

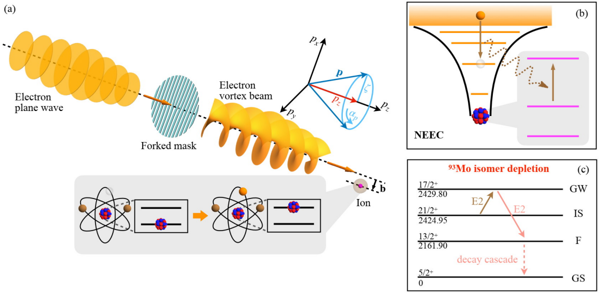
Nuclear and particle physics with vortex states

So far only theoretical proposals...

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

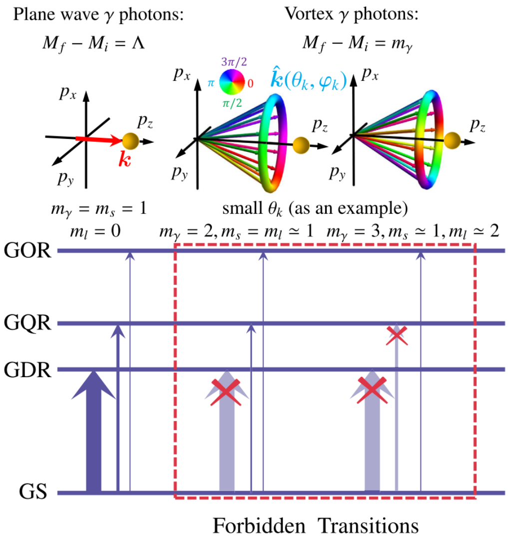
Example 1:
a novel nuclear physics tool

NEEC: Nuclear excitation by electron capture



Internal conversion: Atomic electron transitions $\leftrightarrow$ nuclear excitations.
Controlling long-lived nuclear isomer state via electron capture by an ion: [Pálffy et al, PRL99, 172502 (2007); Chiara et al, Nature 554, 216 (2018)]

Capture of vortex electrons on specific orbitals $\to$ strong enhancement predicted [Wu et al, PRL128, 162501 (2022)].



- 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 → effectively suppressing GDR [Lu et al, PRL131, 202502 (2023); arXiv:2503.12812] ⇒ talk by Jian-Xing Li on Monday.
- But b must be controlled within a few fm → serious challenge!

Elastic neutron scattering

Cold neutron scattering on nucleus [Schwinger, PR 73, 407 (1948)]:

- strong interaction amplitude a,
- electromagnetic interaction via neutron magnetic dipole moment μ_n.

The total scattering amplitude ($\vec{n}$, $\vec{n}'$ — unit vectors; λ, λ' — helicities):

$$f_{\lambda\lambda'}(\vec{n},\vec{n}') = w'^{\dagger}_{\lambda'}(a + i\vec{\sigma}\cdot\vec{B})w_\lambda\,, \quad \vec{B} = \beta\frac{[\vec{n}\times\vec{n}']}{(\vec{n}-\vec{n}')^2}\,, \quad \beta = \frac{\mu_n Z e^2}{m_p c^2}.$$

Strongly peaked in the forward direction: $\vec{n}' \approx \vec{n}$.

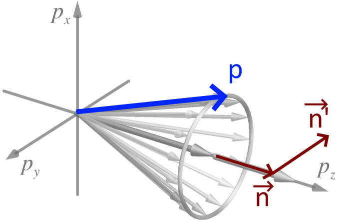
If neutron is polarized along $\vec{\zeta}$, the cross section summed over final polarizations is

$$\frac{d\sigma(\vec{n},\vec{n}',\vec{\zeta})}{d\Omega'} = |a|^2 + |\vec{B}|^2 + 2(\vec{B}\cdot\vec{\zeta})\,\mathrm{Im}\,a\,.$$

Not sensitive to ζ_z nor to $\mathrm{Re}\,a$.

Elastic vortex neutron scattering

Schwinger scattering changes for vortex neutron [Afanasev, Karlovets, Serbo, PRC 103 (2021) 054612].



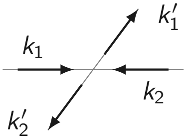
- Cross section peaks at $\vec{n}'$ parallel to the $\vec{p}$, not $\vec{n} \propto \langle \vec{p} \rangle$.
- $\Rightarrow$ Sensitivity to ζ_z!
- $\Rightarrow$ Helicity asymmetry reveals $\mathrm{Re}\, a$!

Predictions can be checked once high-flux vortex neutron beam is available.

Vortex neutron decay is by itself an interesting process: [Kou, Guo, Chen, PLB 862 (2025) 139332; Pavlov, Chaikovskaia, Karlovets, PRC 111 (2025) 024619].

Example 2:
probing the phase of a scattering amplitude

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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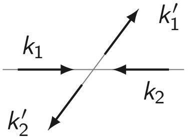
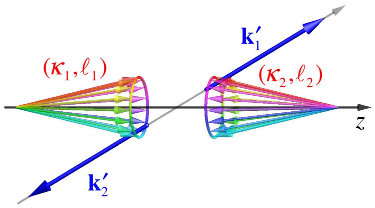




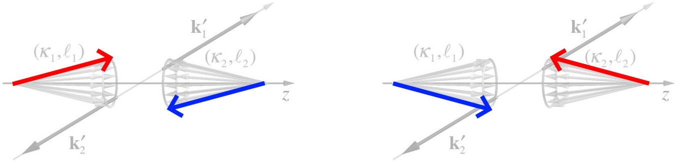
Vortex state scattering: $|\varkappa_1, \ell_1\rangle + |\varkappa_2, \ell_2\rangle \to |k_1'\rangle + |k_2'\rangle$.

- 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!

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)].

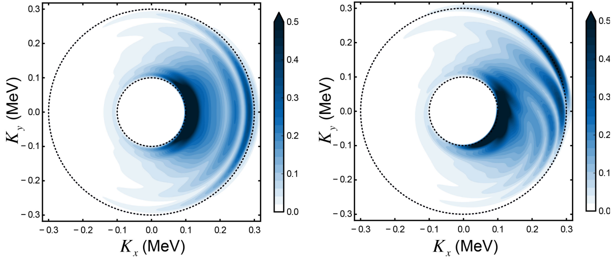


$$\mathcal{M} = c_a\,\mathcal{M}_a(k_{1a}, k_{2a}; k_1', k_2') + c_b\,\mathcal{M}_b(k_{1b}, k_{2b}; k_1', k_2'), \quad d\sigma \propto |c_a\mathcal{M}_a + c_b\mathcal{M}_b|^2$$

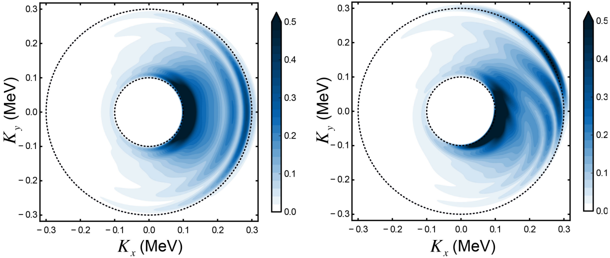
Scattering angles are different: $\theta_a \neq \theta_b \Rightarrow$ phases are different $\Phi(\theta_a) \neq \Phi(\theta_b)$.

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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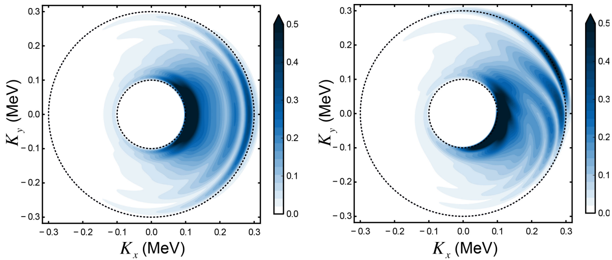

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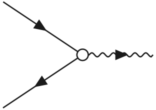
Example 3:
a new tool for spin physics

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:

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

Here ζ_1, ζ_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:

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

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:

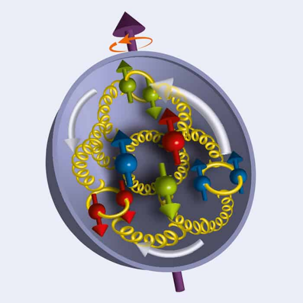
$$\sigma(\lambda_V = +1) \neq \sigma(\lambda_V = -1)\,.$$

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

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

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

- The structure of a high-energy proton is extremely complicated!
- Unintegrated structure functions, TMDs, spin/OAM of quarks and gluons, ... are studied via differential cross sections, SIDIS, spin asymmetries etc.
- Any source of complementary information will be very welcome!



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

$\Rightarrow$ Vortex DIS as a new tool for exploring the proton spin structure!

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:
  - initial-state adjustable OAM,
  - topologically protected coherence,
  - new dimensions in the final phase space,
  - much richer polarization options impossible for plane waves.
- Many remarkable effects, difficult or impossible for PW scattering, are theoretically predicted!
- A dedicated experimental effort is needed to verify these intriguing predictions.

  Every new experimental result $\Rightarrow$ a PRL or higher!
- In Zhuhai, we are actively studying various novel opportunities offered by high-energy vortex states and are looking to extend cooperation!

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