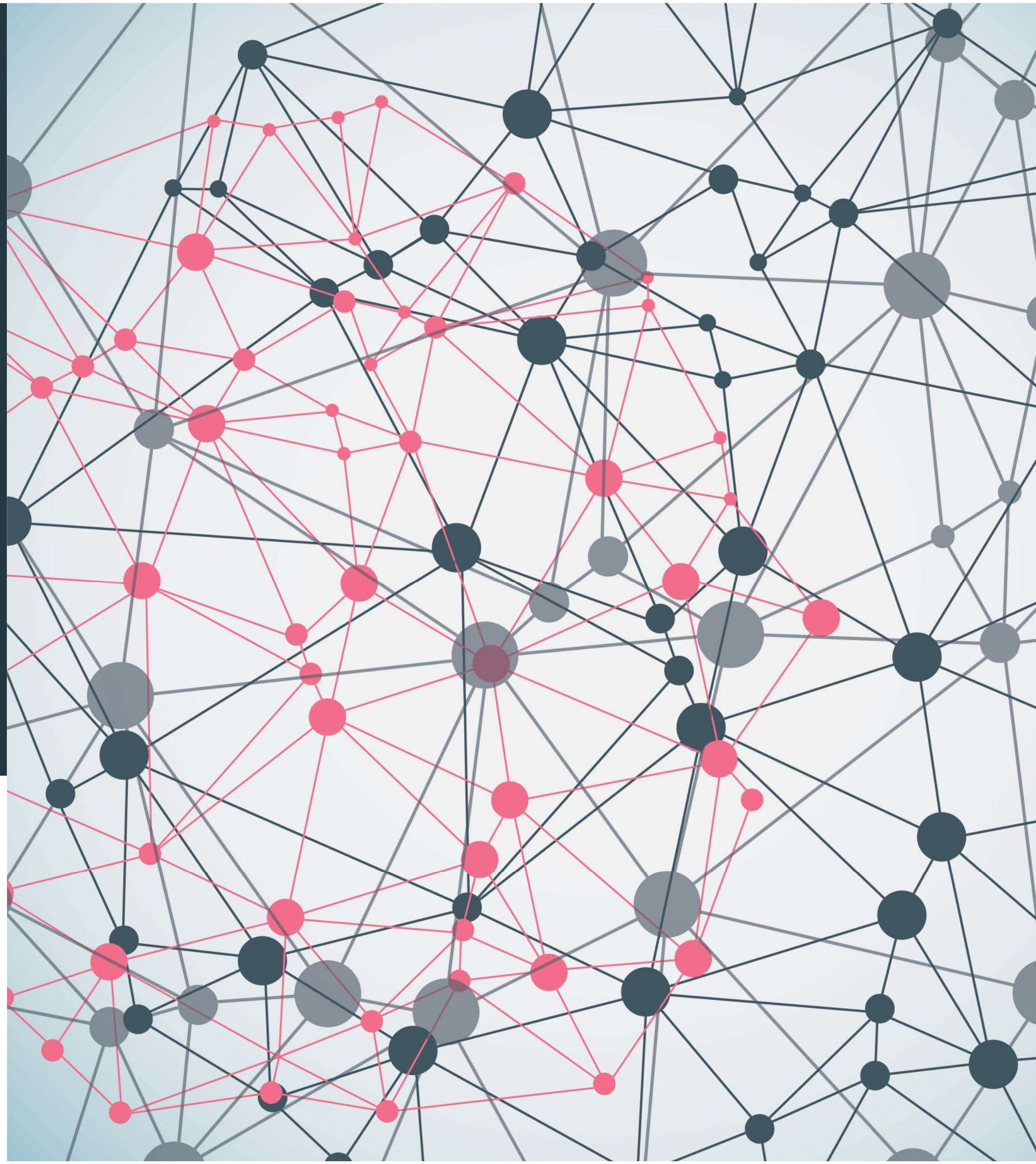
Холодные нейтроны с орбитальным угловым моментом: новый инструмент для исследования вещества и ядерных сил

Дмитрий Карловец

Физический факультет, Университет ИТМО

ПИЯФ, 21.06.22

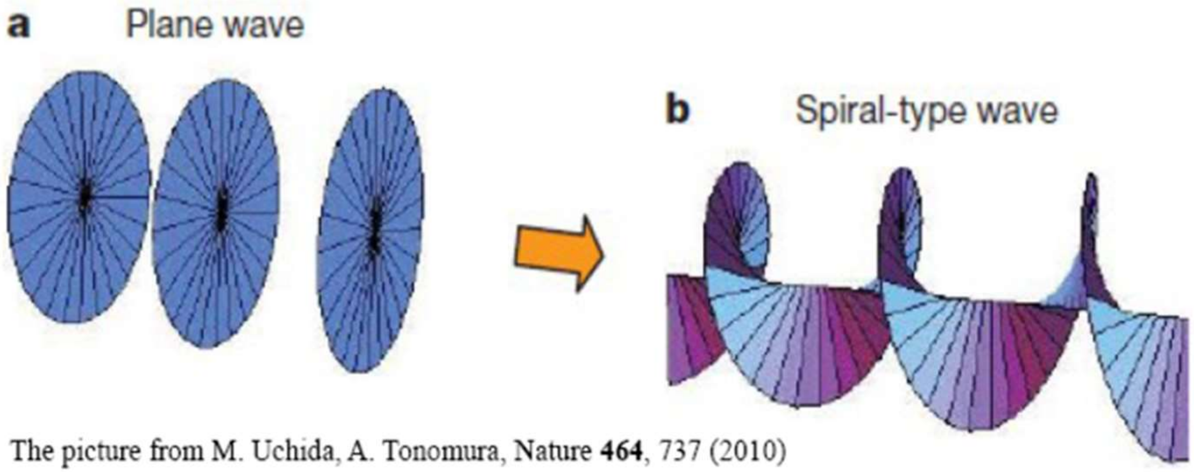


Even the macroscopic systems can be twisted!

https://static.dezeen.com/uploads/2019/05/camp-adventure-tower-effekt-denmark_dezeen_2364_sq.jpg

As predicted theoretically and demonstrated experimentally in 1990s,
light can carry orbital angular momentum (OAM)

[L. Allen, et al., Phys. Rev. A 45, 8185 (1992)]



The picture from M. Uchida, A. Tonomura, Nature **464**, 737 (2010)

A phase vortex on the propagation axis:
the wave intensity vanishes, the phase is undetermined

See e.g. B.A. Knyazev, V.G. Serbo, Phys.-Usp. **61**, 449 (2018)

Beams with quantized angular momentum

Basic exact solutions to the wave equations

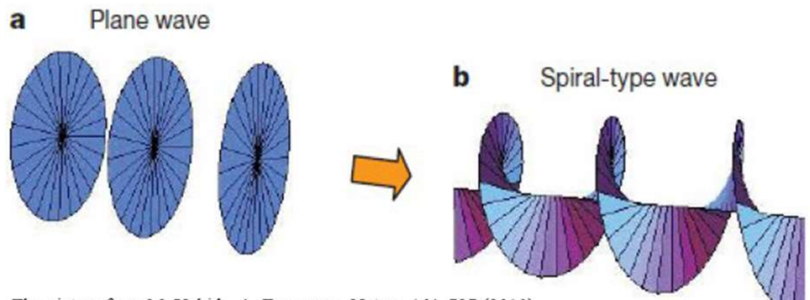
$$\psi_{\mathbf{k}}(\mathbf{r}) = \exp(\mathrm{i}\mathbf{k}\mathbf{r}),$$ – plane waves

$$\psi_{klm}(\mathbf{r}) = \sqrt{\frac{2\pi}{kr}}\, J_{l+1/2}(kr)\, Y_{lm}(\theta_r, \varphi_r),$$ – spherical waves

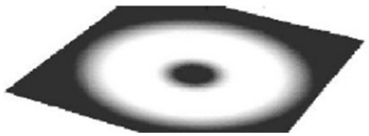
$$\psi_{\varkappa m k_z}(\mathbf{r}) = J_m(\varkappa\rho)\exp\left[\mathrm{i}(m\varphi_r + k_z z)\right]$$ – cylindrical waves (Bessel beams)

$$\hat{l}_z = [\hat{\boldsymbol{r}} \times \hat{\boldsymbol{p}}]_z = -i\frac{\partial}{\partial\phi_r}$$

K.Y. Bliokh, et al.,
PRL 99 (2007) 190404



The picture from M. Uchida, A. Tonomura, Nature **464**, 737 (2010)



Generalizations for relativistic bosons and fermions
are straightforward!

Twisted photons

- Optical tweezers for trapping and moving micro- and nano-objects for biology, condensed matter physics, etc.
- Focused laser beams and photons in waveguides and optical fibers were shown to carry OAM
- They enable quadrupole transitions in atoms, prohibited for plane-wave photons
- They can be generated in a vicinity of rotating black holes
- X-ray twisted photons can be generated via inverse Compton scattering by relativistic electrons
- Entangled pairs of twisted photons can be created, for instance, via the parametric down conversion
- Can be used to increase transmission capacity of radio signals

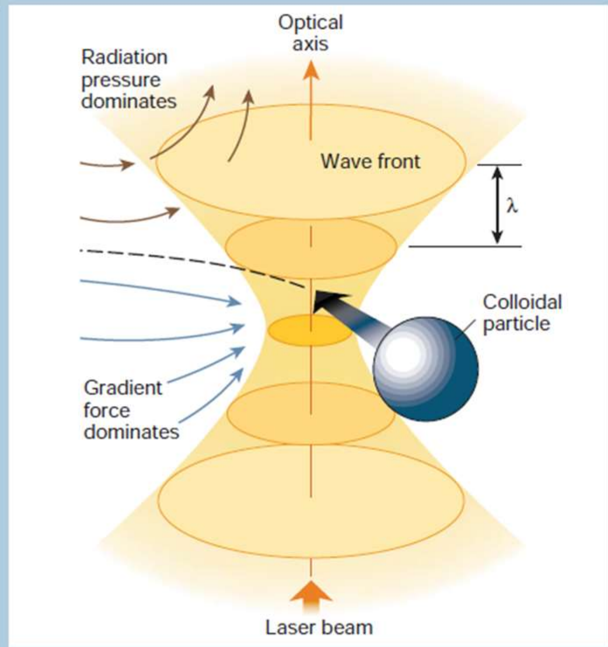
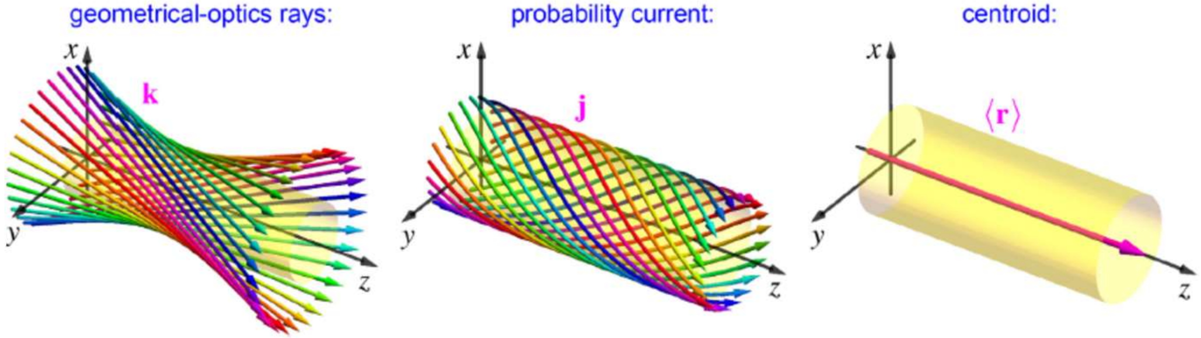


Figure 1 Optical tweezers use a strongly focused beam of light to trap objects. Intensity gradients in the converging beam draw small objects, such as a colloidal particle, toward the focus, whereas the radiation pressure of the beam tends to blow them down the optical axis. Under conditions where the gradient force dominates, a particle can be trapped, in three dimensions, near the focal point.

Grier, Nature 424, 810 (2003)

Beams with quantized angular momentum

Vortex electrons: the probability current has an azimuthal component



K.Y. Bliokh et al. / Physics Reports 690 (2017) 1–70

The electron magnetic moment can be huge!

$$\mathbf{M} = \frac{1}{2c}\frac{\int \mathbf{r}\times\mathbf{j}_e\, d^3\mathbf{r}}{\int \rho\, d^3\mathbf{r}} = \frac{e}{2m_e c}\langle \mathbf{L}\rangle$$

$$\mu \propto \mu_B(\mathbf{l} + 2\mathbf{s})$$

If the OAM is large, $l_z \equiv m \gg \hbar$, then $\mu \gg \mu_B$!

Beams with quantized angular momentum

The first generation of vortex electrons:

- M. Uchida and A. Tonomura, Nature 464, 737 (2010),
- J. Verbeeck, et al., Nature 467 (2010) 301–304,
- B. J. McMorran, et al., Science 331, 192 (2011)

- The highest electron energy is 300 keV
- The highest angular momentum so far is ~ 1000!
- The smallest spot size is 0.1 nm!

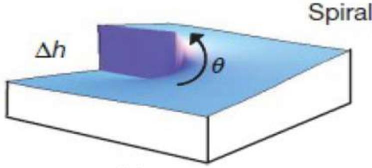
Atomic scale!

Two main methods:

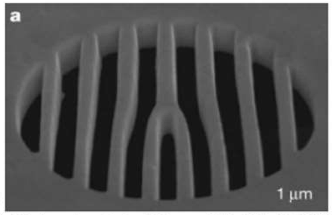
Spiral phase plates

Gratings with a fork dislocation

Spiral phase plate

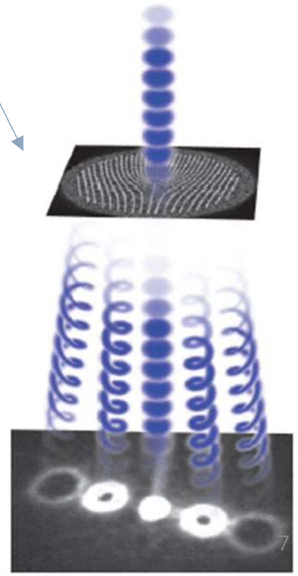


M. Uchida, A. Tonomura, Nature **464**, 737 (2010)



Diffraction grating with an edge dislocation made of Pt foil

J. Verbeeck, et al., Nature **467**, 301 (2010)



Beams with quantized angular momentum

RESEARCH

RESEARCH ARTICLE

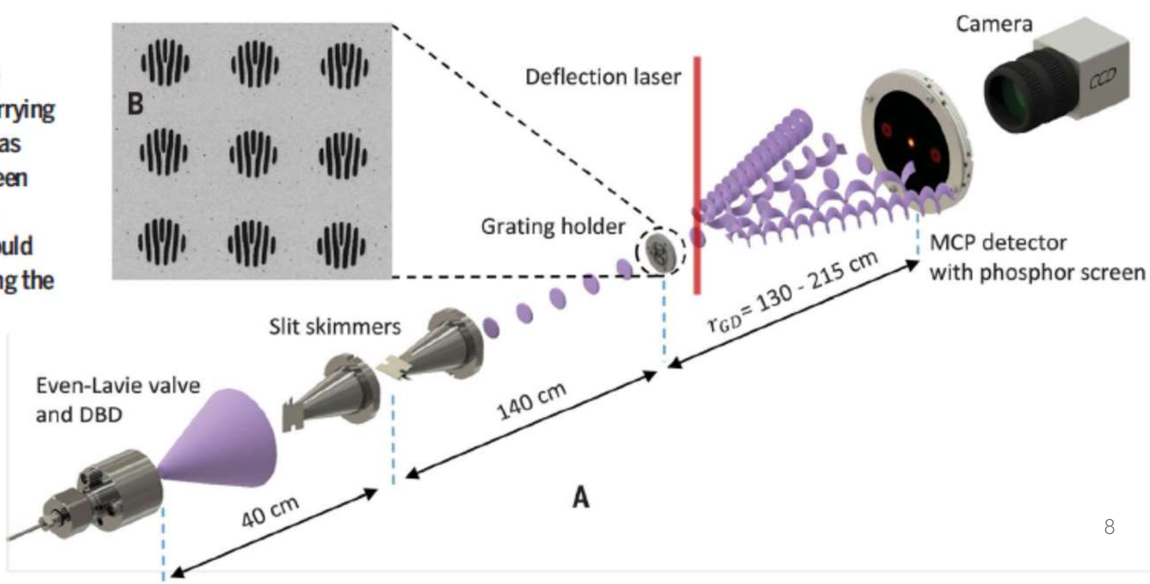
August 2021!

QUANTUM PHYSICS

Vortex beams of atoms and molecules

Alon Luski[1]†, Yair Segev[1]†‡, Rea David[1], Ora Bitton[1], Hila Nadler[1], A. Ronny Barnea[2], Alexey Gorlach[3], Ori Cheshnovsky[2], Ido Kaminer[3], Edvardas Narevicius[1]*

Angular momentum plays a central role in quantum mechanics, recurring in every length scale from the microscopic interactions of light and matter to the macroscopic behavior of superfluids. Vortex beams, carrying intrinsic orbital angular momentum (OAM), are now regularly generated with elementary particles such as photons and electrons. Thus far, the creation of a vortex beam of a nonelementary particle has never been demonstrated experimentally. We present vortex beams of atoms and molecules, formed by diffracting supersonic beams of helium atoms and dimers off transmission gratings. This method is general and could be applied to most atomic and molecular gases. Our results may open new frontiers in atomic physics, using the additional degree of freedom of OAM to probe collisions and alter fundamental interactions.



No theory of vortex atoms!

Beams with quantized angular momentum

Bessel beams → Laguerre-Gaussian beams

$$\psi_{\ell,n}(r,t) = \sqrt{\frac{n}{(n+|\ell|)}}\frac{i^{2n+\ell}}{\pi^{3/4}}\frac{\rho^{|\ell|}}{(\sigma_\perp(t))^{|\ell|+3/2}} L_n^{|\ell|}\left(\frac{\rho^2}{(\sigma_\perp(t))^2}\right)\exp\Big\{-it\langle p\rangle^2/2m + i\langle p\rangle z + i\ell\phi_r - i(2n+|\ell|+3/2)\arctan(t/t_d) - \frac{1}{2(\sigma_\perp(t))^2}(1-it/t_d)(\rho^2+(z-\langle u\rangle t)^2)\Big\},$$

$$\langle\rho^2\rangle = \sigma_\perp^2(t)\,(n+|\ell|+1)$$

$$[\sigma_\perp(t)]^2 = [\sigma_\perp(0)]^2 + \left(\frac{\lambda_c}{\sigma_\perp(0)}\right)^2 t^2,$$

D. Karlovets, PRA **99**, 043824 (2019)

Landau states in magnetic field

$$\Psi(r,t) = \text{const}\,\left(\frac{\rho}{\rho_H}\right)^{|\ell|} L_{n_H}^{|\ell|}\left(\frac{2\rho^2}{\rho_H^2}\right)\exp\left\{-\frac{\rho^2}{\rho_H^2} + i\ell\phi + ip_z z - i\varepsilon t\right\}$$

$$\langle\rho^2\rangle_{\text{LG}} = \frac{\rho_H^2}{2}(2n_H+|\ell|+1) \geq \frac{\rho_H^2}{2} \qquad \rho_H = \sqrt{\frac{4}{|e|H}}$$

$$\langle\hat{L}_z^{\text{can}}\rangle = \ell,\ \ \ell = 0, \pm1, \pm2, \ldots \qquad n_H = 0, 1, 2, \ldots,$$

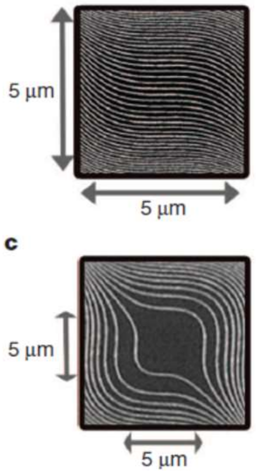
$$\boldsymbol{H} = \{0, 0, H\}$$

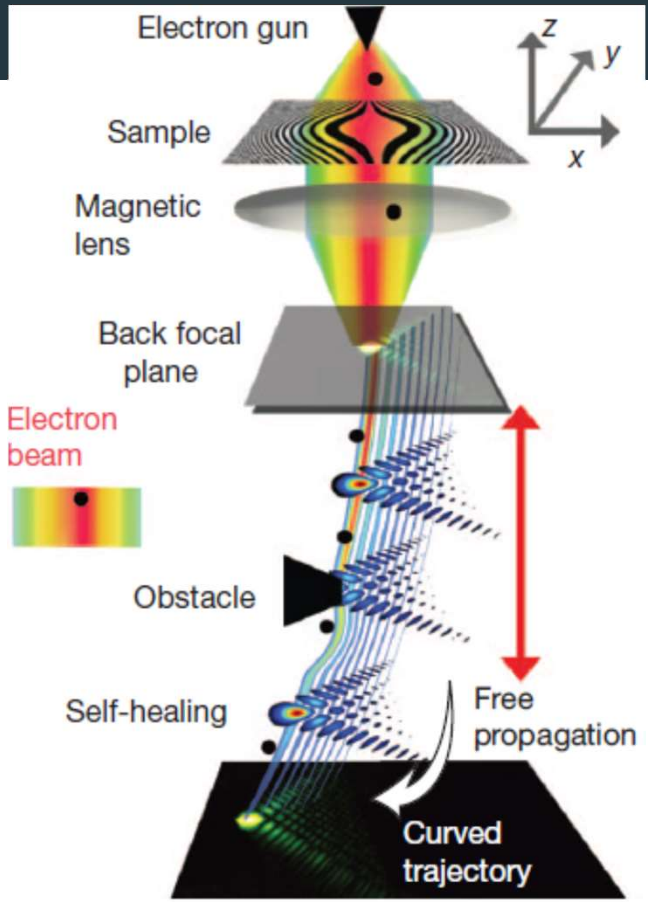
For free vortex electrons, the angular momentum is still quantized!

Airy beams

Solution to the wave equation
[Berry & Balazs, Am. J. Phys. 47, 264 (1979)]:

$$\Psi(x,y,z) = \mathrm{Ai}\left(\frac{x}{x_0} - \frac{z^2}{4k_B^2 x_0^4}\right)\mathrm{Ai}\left(\frac{y}{y_0} - \frac{z^2}{4k_B^2 y_0^4}\right) \times \exp\left(i\frac{xz}{2k_B x_0^3} - i\frac{z^3}{12k_B^3 x_0^6}\right) \times \exp\left(i\frac{yz}{2k_B y_0^3} - i\frac{z^3}{12k_B^3 y_0^6}\right)$$





- The electron energy is 200 keV
- No spreading
- Self heals

Voloch-Bloch, et al., Nature 494, 331 (2013)

Vortex neutrons

LETTER

doi:10.1038/nature15265

Controlling neutron orbital angular momentum

Charles W. Clark[1], Roman Barankov[2], Michael G. Huber[3], Muhammad Arif[3], David G. Cory[4,5,6,7] & Dmitry A. Pushin

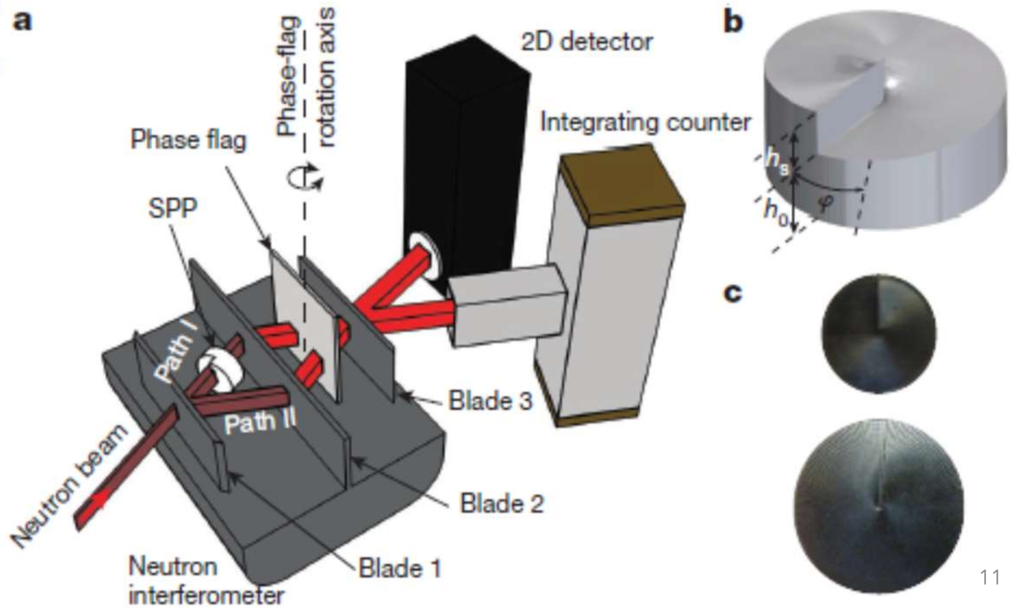
E = 11 meV, wavelength = 0.271 nm

At the National Institute of Standards and Technology (NIST), USA:
Created in a 20 MW reactor, cooled in a cryogenic moderator to 20K,
and transported through 30 m of neutron guides.

Neutron transverse coherence length: 60 nm – 1 µm

Beam diameter: 15 mm

New means for neutron optics and low-energy nuclear physics:
imaging, tomography, magnetic material studies, skyrmions, etc.



Vortex neutrons

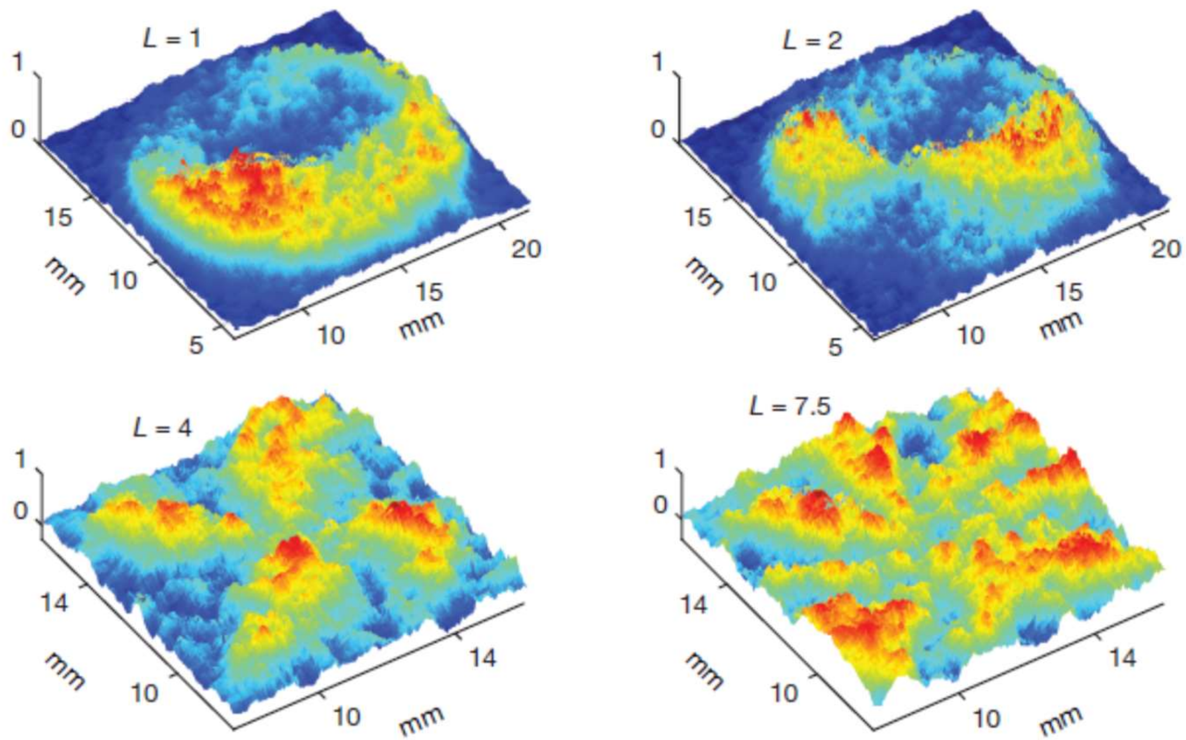


Figure 2 | OAM interferograms. Spatial distribution of the neutron counts in the 2D detector[30] of the neutron interferometer for four SPPs, with values of $L = 1, 2, 4$ and 7.5, as labelled. The horizontal and vertical positions on the 2D neutron detector are shown in millimetres. For the integer values of L these distributions display the simple OAM interference pattern expressed in equation (2); for $L = 7.5$ we have the superposition of OAM modes given by equation (4) in Methods. The 2D detector is a centroid-type event-counting detector with a spatial resolution of 100 μm and an 18% quantum efficiency (that is, counts registered per neutron incident on the detector). Its operation is shot-noise (Poisson-noise) limited in this regime. The neutron counts were collected over 3.5 days and normalized by the maximal pixel count, which is about 45.

Vortex neutrons

Research Article | Vol. 24, No. 20 | 3 Oct 2016 | OPTICS EXPRESS 22528

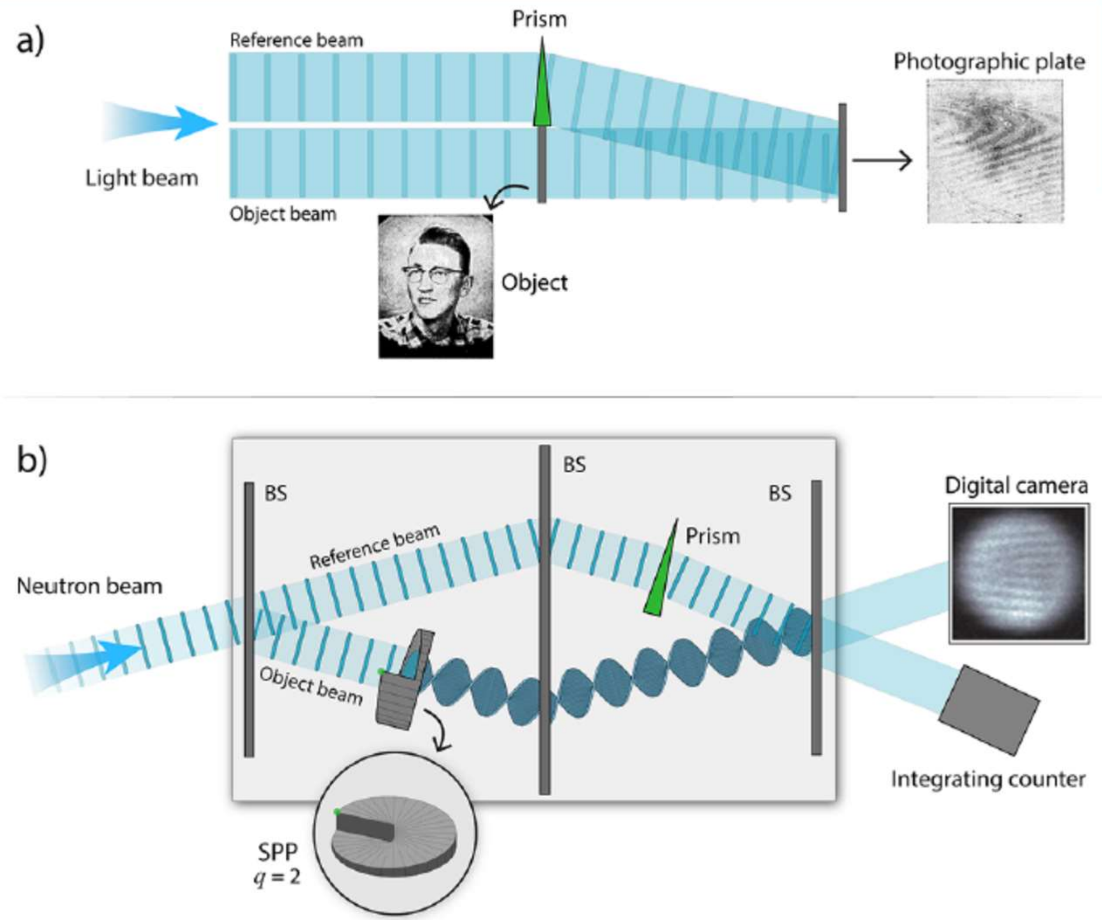
Optics EXPRESS

Holography with a neutron interferometer

DUSAN SARENAC,[1,2,*] MICHAEL G. HUBER,[3] BENJAMIN HEACOCK,[4,5] MUHAMMAD ARIF,[3] CHARLES W. CLARK,[3,6] DAVID G. CORY,[2,7,8,9] CHANDRA B. SHAHI,[6,10] AND DMITRY A. PUSHIN[1,2]

[1] *Department of Physics, University of Waterloo, Waterloo, ON, N2L3G1, Canada*
[2] *Institute for Quantum Computing, University of Waterloo, Waterloo, ON, N2L3G1, Canada*
[3] *National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*
[4] *North Carolina State University, Raleigh, North Carolina 27695, USA*
[5] *Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[6] *Joint Quantum Institute, College Park, MD 20742, USA*
[7] *Department of Chemistry, University of Waterloo, Waterloo, ON, N2L3G1, Canada*
[8] *Perimeter Institute for Theoretical Physics, Waterloo, ON, N2L2Y5, Canada*
[9] *Canadian Institute for Advanced Research, Toronto, Ontario, M5G 1Z8, Canada*
[10] *Physics and Engineering Physics Department, Tulane University, New Orleans, LA 70188, USA*
[*] *dsarenac@uwaterloo.ca*

Abstract: We use a Mach-Zehnder interferometer to perform neutron holography of a spiral phase plate. The object beam passes through a spiral phase plate, acquiring the phase twist characteristic of orbital angular momentum states. The reference beam passes through a fused silica prism, acquiring a linear phase gradient. The resulting hologram is a fork dislocation image, which could be used to reconstruct neutron beams with various orbital angular momenta. This work paves the way for novel applications of neutron holography, diffraction and imaging.



"Note that the experiment is an expectation valued measurement over many events, each of which involves only a single neutron. That is, there is one neutron at a time in the NI and the hologram is build up from an incoherent superposition of many events"

Vortex neutrons

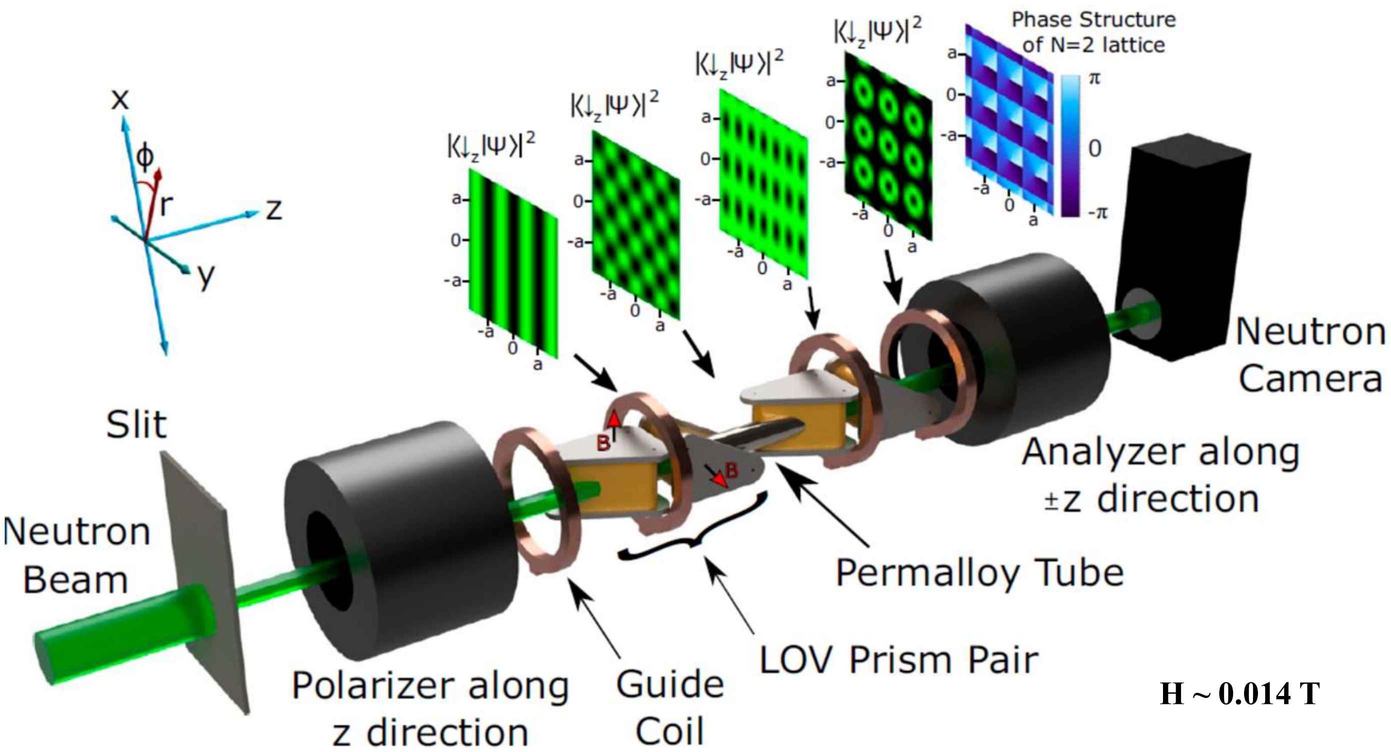
Generation and detection of spin-orbit coupled neutron beams

Dusan Sarenac[a,1], Connor Kapahi[a,b], Wangchun Chen[c,d], Charles W. Clark[e], David G. Cory[a,f,g,h], Michael G. Huber[i], Ivar Taminiau[a], Kirill Zhernenkov[a,j,k], and Dmitry A. Pushin[a,b]

Spin-orbit coupling of light has come to the fore in nanooptics and plasmonics, and is a key ingredient of topological photonics and chiral quantum optics. We demonstrate a basic tool for incorporating analogous effects into neutron optics: the generation and detection of neutron beams with coupled spin and orbital angular momentum. The ^{3}He neutron spin filters are used in conjunction with specifically oriented triangular coils to prepare neutron beams with lattices of spin-orbit correlations, as demonstrated by their spin-dependent intensity profiles. These correlations can be tailored to particular applications, such as neutron studies of topological materials.

20328–20332 | PNAS | October 8, 2019 | vol. 116 | no. 41

" The triangular coils induce perpendicular phase gradients along the directions that are also perpendicular to the direction of the incoming spin state. Pairs of triangular coils then effectively act as LOV prism pairs."



H ~ 0.014 T

Vortex neutrons

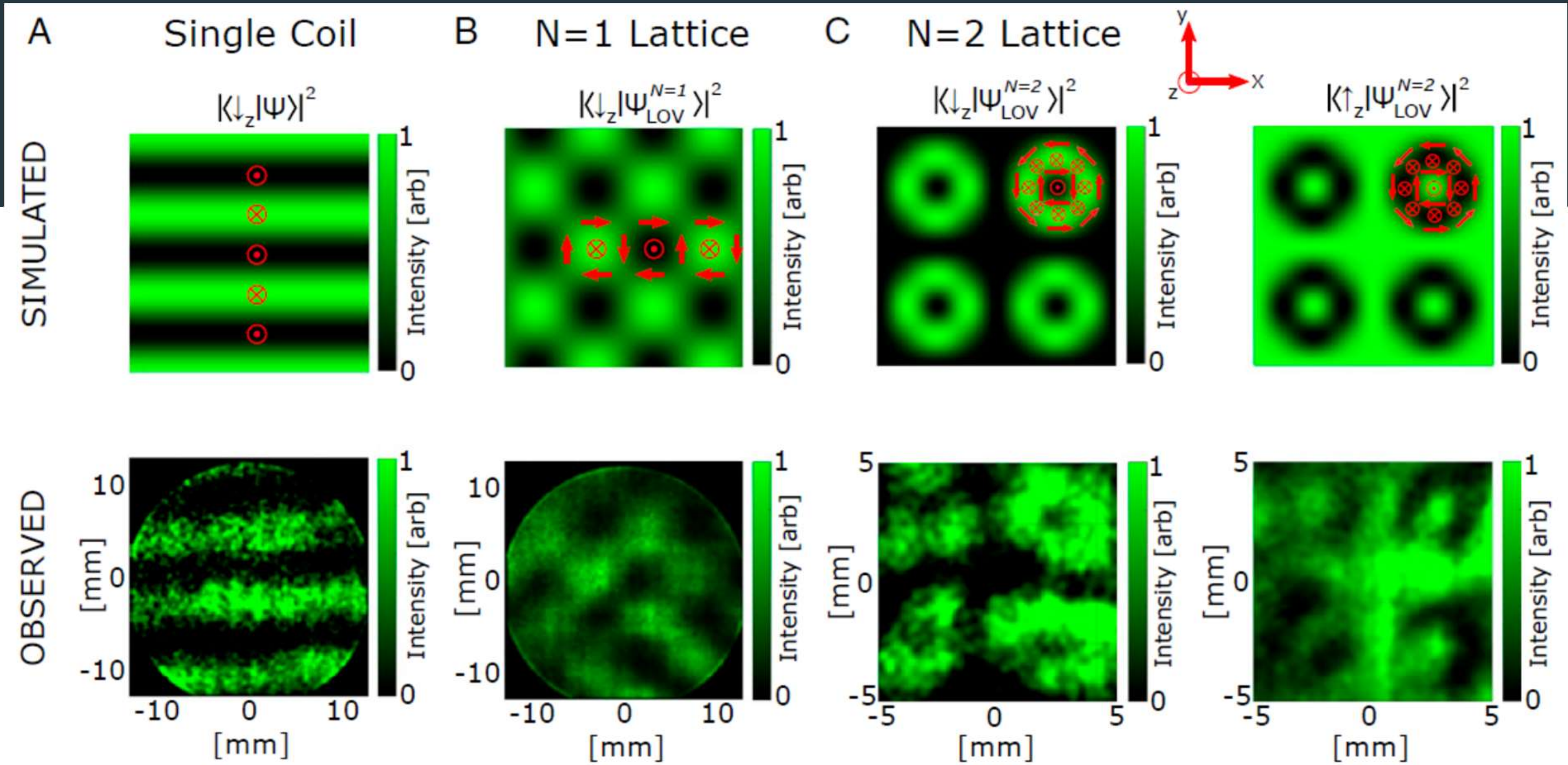


Fig. 2. The simulated and observed spin-dependent intensity profiles. A Gaussian filter as well as an intensity gradient was added to each observed image, to highlight the features of interest. The currents on the (first, second, third, and fourth) triangular coil were set to (*A*) (0, 0, 0, and 2.5 A), (*B*) (2.5, 2.5, 0, and 0 A), and (*C*) (5, 5, 5, and 4 A). The spatially varying spin direction (before the spin filtering) is overlaid on the simulated intensity profiles via the red arrows. The N = 1 lattice exhibits a vortex antivortex structure, and its spin-dependent intensity profile resembles a checkerboard pattern. The N = 2 lattice appears as a lattice of doughnut/ring shapes. Good qualitative agreement is shown between the simulated and observed intensity profiles.

20328–20332 | PNAS | October 8, 2019 | vol. 116 | no. 41

Vortex neutrons

New J. Phys. 20 (2018) 103012 https://doi.org/10.1088/1367-2630/aae3ac

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

PAPER

Methods for preparation and detection of neutron spin-orbit states

D Sarenac[1,2], J Nsofini[1,2], I Hincks[2,3], M Arif[4], Charles W Clark[5], D G Cory[2,6,7,8], M G Huber[4] and D A Pushin[1,2]

$$|n, \ell, s\rangle = \mathcal{N}\xi^{|\ell|}e^{-\frac{\xi^2}{2}}\mathcal{L}_n^{|\ell|}(\xi^2)e^{i\ell\phi}|s\rangle$$

$$|\Psi_{SO}\rangle = \frac{1}{\sqrt{2}}(|n_\uparrow, \ell_\uparrow, \uparrow\rangle + e^{i\beta}|n_\downarrow, \ell_\downarrow, \downarrow\rangle)$$

Various alloys can be engineered to have $b_c \sim b_m$, for instance a 50:50 Fe:Co alloy posses $(b_c - b_m)$ $(b_c + b_m) = -0.047$. Such materials are routinely used for neutron optics [32, 33]. For example, widel

«Recent interest in complex topological and quantum materials suggests a need for a tool with unique penetrating abilities and magnetic sensitivity. Analysis of material properties could be performed using a neutron spin-orbit lattice where the lattice constants are matched to the characteristic length scales of materials"

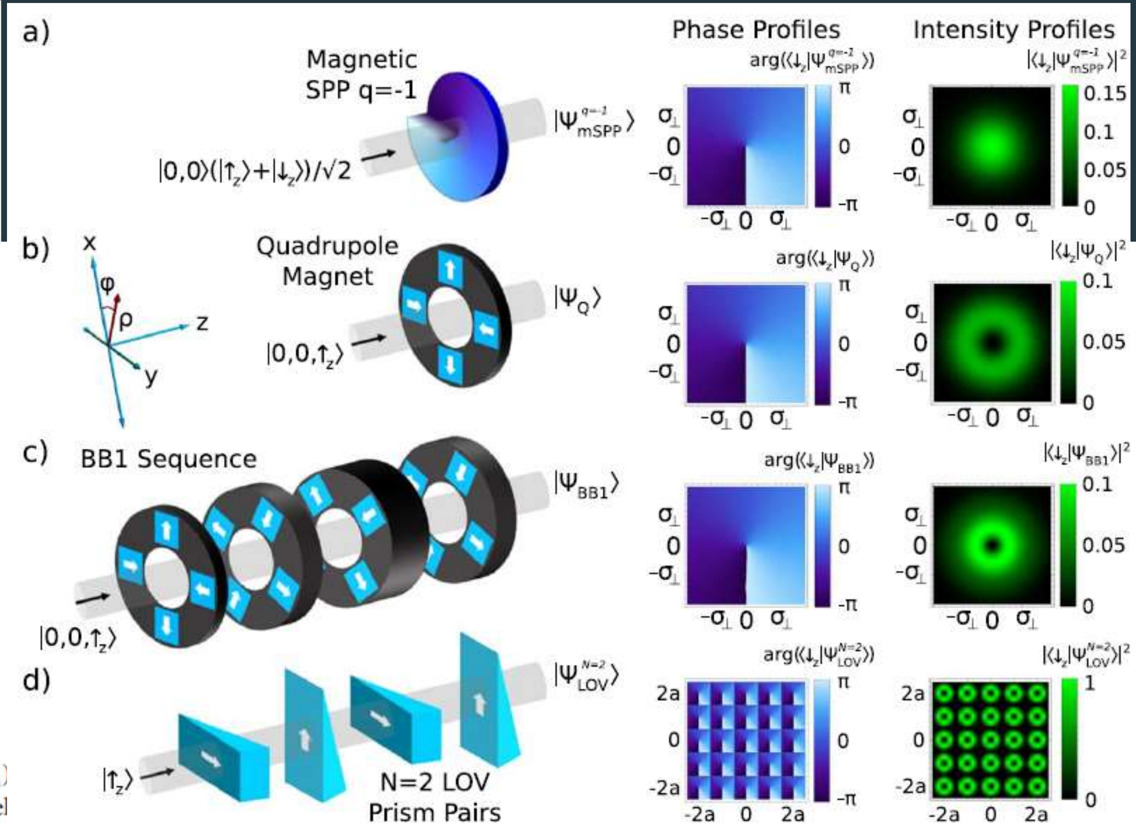
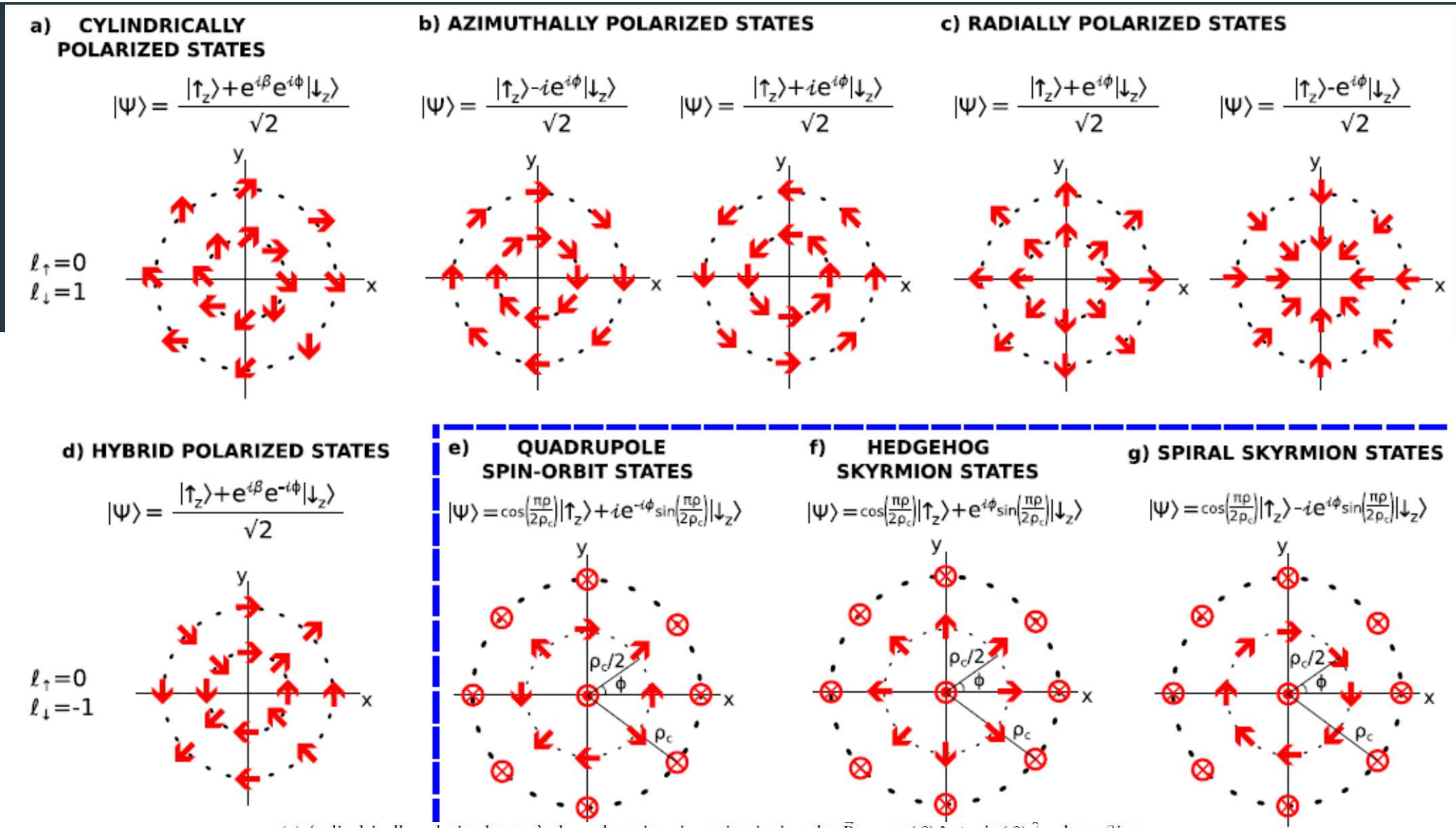


Figure 1. Four methods of producing neutron spin-orbit states. The phase and intensity profiles of the output states, post-selected on the spin state correlated to the OAM, are shown on the right. (a) An incoming neutron wavepacket in a coherent superposition of the two spin eigenstates passes through a magnetic SPP which is made out of a material with equal magnetic and nuclear scattering lengths, thereby inducing an azimuthally varying phase for only one spin state. (b) A spin-polarized neutron wavepacket passes through a quadrupole magnetic field which induces the spin-orbit state [18]. After transversing the quadrupole field, the intensity profile of the spin state correlated to the OAM has a ring shape. (c) A sequence of quadrupoles with appropriate length and orientation acts as a BB1 pulse which increases the radii at which the spin and OAM are maximally entangled. (d) In analogy to the LOV prism pairs capable of generating lattices of optical spin-orbit states [34], a sequence of magnetic prisms can be used to approximate the quadrupole operator and produce a lattice of neutron spin-orbit states.



(a) ‘cylindrically polarized states’ where the spin orientation is given by $\vec{P} = \cos(\beta)\hat{\rho} + \sin(\beta)\hat{\phi}$, where β is an arbitrary phase;

(b) ‘azimuthally polarized states’ which are a subset of cylindrically polarized states where $\vec{P} = \pm\hat{\phi}$;

(c) ‘radially polarized states’ which are a subset of cylindrically polarized states where $\vec{P} = \pm\hat{r}$; and

(d) ‘hybrid polarization states’ where $\vec{P} = \sin(2\phi + \beta)\hat{r} + \cos(2\phi + \beta)\hat{\phi}$, where β is an arbitrary phase.

Vortex neutrons

PHYSICAL REVIEW C **100**, 051601(R) (2019)

Rapid Communications

Schwinger scattering of twisted neutrons by nuclei

Andrei V. Afanasev,[1] D. V. Karlovets,[2] and V. G. Serbo[3,4]

[1]*Department of Physics, The George Washington University, Washington, D.C. 20052, USA*

[2]*Tomsk State University, Lenina Avenue 36, 634050 Tomsk, Russia*

[3]*Novosibirsk State University, RUS-630090 Novosibirsk, Russia*

[4]*Sobolev Institute of Mathematics, RUS-630090 Novosibirsk, Russia*

(Received 28 March 2019; revised manuscript received 5 September 2019; published 25 November 2019)

Standard Schwinger cross section (plane waves):

$$\frac{d\sigma^{(\mathrm{st})}(\mathbf{e}_3, \mathbf{n}', \zeta)}{d\Omega'} = |a|^2 + \frac{1}{4}[\beta\ \cot(\theta'/2)]^2 - \beta\zeta_\perp(\mathrm{Im}\, a)\cot(\theta'/2)\sin(\varphi' - \varphi_\zeta).$$

$\mathbf{n} = \mathbf{p}/p$ and $\mathbf{n}' = \mathbf{p}'/p$ $\qquad$ $\zeta_\perp = \zeta_\perp(\cos\ \varphi_\zeta, \sin\ \varphi_\zeta, 0)$

Scattering amplitude:

$$f_{\lambda\lambda'}(\mathbf{n}, \mathbf{n}') = w'^{\dagger}_{\lambda'}(a + i\mathbf{B}\sigma)w_\lambda, \quad \mathbf{B} = \beta\frac{\mathbf{n}\times\mathbf{n}'}{(\mathbf{n}-\mathbf{n}')^2},$$

$$\beta = \frac{\mu_n Z e^2}{m_p c^2} = -Z \times 2.94 \times 10^{-16}\ \mathrm{cm},$$

a nucleus. For thermal neutrons with the energies near 25 meV and an $^{197}_{79}$Au nuclear target ($a = 7.63$ fm [19]), the relevant parameters are

$$\varepsilon \equiv |\beta/a| \approx 0.03, \quad |(\mathrm{Im}\, a)/a| \approx 2 \times 10^{-4}$$

Vortex neutrons

$$\psi_{\varkappa m p_z \lambda}(\mathbf{r}) = \int \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} a_{\varkappa m}(\mathbf{p}_\perp) i^\lambda w^{(\lambda)}(\mathbf{n}) e^{i\mathbf{pr}/\hbar} .$$

$$a_{\varkappa m}(\mathbf{p}_\perp) = i^{-m} e^{im\varphi} \frac{2\pi}{p_\perp} \delta(p_\perp - \hbar\varkappa). \qquad \mathbf{p} = (\mathbf{p}_\perp, p_z) = (\hbar\varkappa \cos\varphi, \hbar\varkappa \sin\varphi, p_z).$$

Macroscopic target (incoherent superposition of many nuclei):

$$\frac{d\bar\sigma(\theta, \theta', \varphi', \zeta)}{d\Omega'} = \frac{1}{\cos\theta} \int_0^{2\pi} \frac{d\sigma^{(\mathrm{st})}(\mathbf{n}, \mathbf{n}', \zeta)}{d\Omega'} \frac{d\varphi}{2\pi} = \frac{1}{\cos\theta} [|a|^2 + \beta^2 G(\theta, \theta') - \beta(\mathrm{Im}\, a)\zeta_\perp g(\theta, \theta') \sin(\varphi' - \varphi_\zeta)],$$

$$G(\theta, \theta') = \frac{1}{2|\cos\theta - \cos\theta'|} - \frac{1}{4},$$

$$g(\theta, \theta') = \begin{cases} \cot(\theta'/2), & \text{at } \theta' > \theta, \\ -\tan(\theta'/2) & \text{at } \theta' < \theta. \end{cases}$$

Angular singularity at $1/|\theta' - \theta|$ instead of 0!

Vortex neutrons

PHYSICAL REVIEW C **103**, 054612 (2021)

Elastic scattering of twisted neutrons by nuclei

A. V. Afanasev,[1] D. V. Karlovets,[2,3] and V. G. Serbo[4,5]
[1]Department of Physics, The George Washington University, Washington, DC 20052, USA
[2]Faculty of Physics, Tomsk State University, Lenina Avenue 36, 634050 Tomsk, Russia
[3]School of Physics and Engineering, ITMO University, Lomonosova 9, 191002 St. Petersburg, Russia
[4]Novosibirsk State University, 630090 Novosibirsk, Russia
[5]Sobolev Institute of Mathematics, 630090 Novosibirsk, Russia

(Received 19 February 2021; accepted 10 May 2021; published 20 May 2021)

$$W_{\lambda}^{(m)}(\theta,\theta',\mathbf{b}) = \sum_{\lambda'} \left\langle \left| F_{\lambda\lambda'}^{(m)}(\theta,\theta',\varphi',\mathbf{b}) \right|^2 \right\rangle = \frac{1}{2}\Sigma^{(m)} + \lambda\Delta^{(m)},$$

$$A_{\lambda} = \frac{W_{\lambda=1/2}^{(m)} - W_{\lambda=-1/2}^{(m)}}{W_{\lambda=1/2}^{(m)} + W_{\lambda=-1/2}^{(m)}} = \frac{\Delta^{(\mathrm{m})}}{\Sigma^{(\mathrm{m})}}$$

The amplitude with a lateral shift:

$$F_{\lambda\lambda'}^{(m)}(\theta,\theta',\varphi',\mathbf{b}) = i^{\lambda-m} e^{-i\mathbf{p}'_{\perp}\mathbf{b}} \sum_{\sigma=\pm 1/2} d_{\sigma\lambda}^{1/2}(\theta)\, w^{(\lambda')\dagger}(\mathbf{n}')[A^{(\sigma)} + i\mathbf{B}^{(\sigma)}\boldsymbol{\sigma}] \times w^{(\sigma)}(\mathbf{e}_z). \quad (36)$$

Averaging the cross section with a density:

$$n(\mathbf{b}-\mathbf{b}_t) = \frac{1}{2\pi\sigma_t^2} e^{-(\mathbf{b}-\mathbf{b}_t)^2/(2\sigma_t^2)}.$$

Vortex neutrons

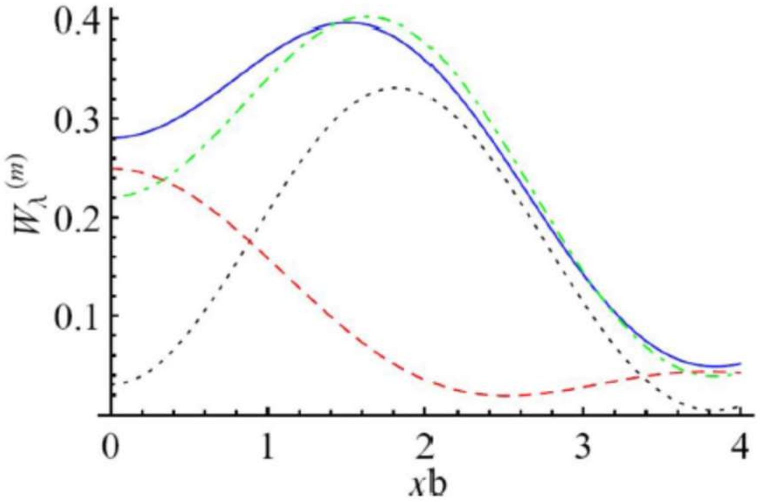


FIG. 3. The probability (17) as a function of the $^{197}_{79}$Au nucleus position $\varkappa b$ for $m = 1/2,\ \lambda = -1/2,\ \theta' = 0.03,\ \theta = 0.06$ rad, and $\varepsilon = 0.03$. The separate contributions from the nuclear amplitude (black dotted line) from the electromagnetic one (dashed red line), and the full result (solid blue line) are shown. The full result with an opposite sign of the strong amplitude (green dot-dashed line) demonstrates the role of its real part.

Within the momentum cone

$$\theta' < \theta \approx 1^\circ\text{–}10^\circ$$

the asymmetry reaches the values

$$|A_\lambda| \approx 10^{-3}\text{–}10^{-1}$$

$^{197}_{79}$Au nucleus $\quad a = 7.63$ fm

$$\varepsilon \equiv |\beta/a| \approx 0.03, \quad |(\mathrm{Im}\, a)/a| \approx 2 \times 10^{-4}$$

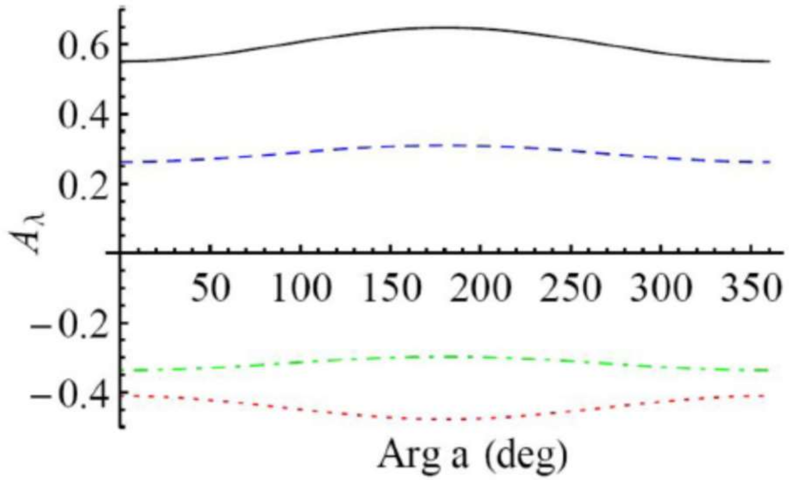


FIG. 4. The helicity asymmetry (18) for $\theta' = 0.03,\ \theta = 0.06$ rad, and $\varepsilon = 0.03$. Black line: $m = 1/2,\ \varkappa b = 0$, blue dashed line: $m = 1/2,\ \varkappa b = 1$, red dotted line: $m = 1/2,\ \varkappa b = 2$, green dot-dashed line: $m = 5/2,\ \varkappa b = 1$.

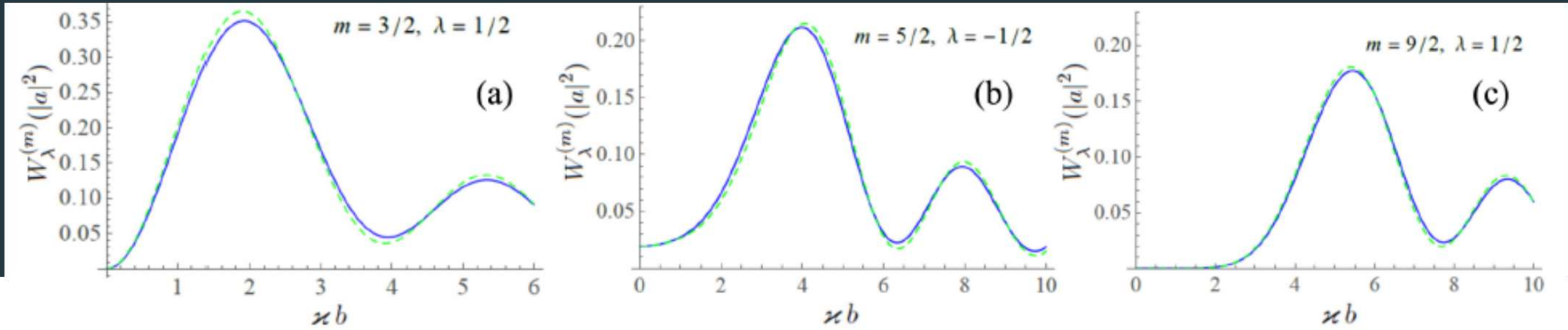


FIG. 7. The distribution (38) in units $|a|^2$ as a function of the ${}^{197}_{79}$Au nucleus position b for $\theta' = 0.04$ rad, $\theta = 0.07$ rad, and $\varepsilon = 0.03$. The case Im $a > 0$ is shown by blue solid lines, while the case Im $a < 0$ is shown by green dashed lines.

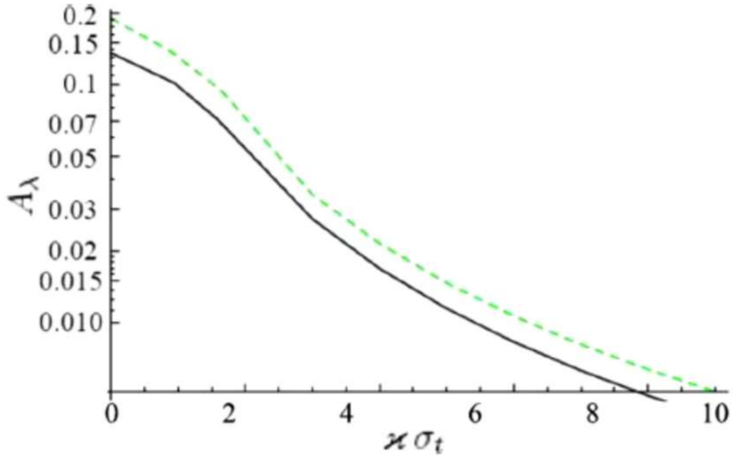


FIG. 9. The helicity asymmetry as a function of $\varkappa\sigma_t$ where σ_t is a width of the ${}^{197}_{79}$Au mesoscopic target for $m = 5/2$, $\theta' = 0.04$ rad, $\theta = 0.07$ rad, and $\varepsilon = 0.03$, $b_t = \varphi_t = 0$. The case Im $a > 0$ is shown by the black solid line, while the case Im $a < 0$ is shown by the green dashed line.

New physics with vortex neutrons

Total angular momentum = orbital AM + spin

Vortex particles instead of the spin-polarized ones!

PHYSICAL REVIEW LETTERS **124,** 192001 (2020)

Featured in Physics

Doing Spin Physics with Unpolarized Particles

Igor P. Ivanov*
CFTP, Instituto Superior Tecnico, Universidade de Lisboa, Lisbon 1049-001, Portugal

Nikolai Korchagin†
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

Alexandr Pimikov‡
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
and Research Institute of Physics, Southern Federal University, Rostov-na-Donu 344090, Russia

Pengming Zhang§
School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, China

(Received 4 December 2019; accepted 8 April 2020; published 13 May 2020)

Twisted, or vortex, particles refer to freely propagating non-plane-wave states with helicoidal wave fronts. In this state, the particle possesses a nonzero orbital angular momentum with respect to its average propagation direction. Twisted photons and electrons have been experimentally demonstrated, and creation of other particles in twisted states can be anticipated. If brought in collisions, twisted states offer a new degree of freedom to particle physics, and it is timely to analyze what new insights may follow. Here, we theoretically investigate resonance production in twisted photon collisions and twisted e^+e^- annihilation and show that these processes emerge as a completely novel probe of spin and parity-sensitive observables in fully inclusive cross sections with unpolarized initial particles. This is possible because the initial state with a nonzero angular momentum explicitly breaks the left-right symmetry even when averaging over helicities. In particular, we show how one can produce almost 100% polarized vector mesons in unpolarized twisted e^+e^- annihilation and how to control its polarization state.

DOI: 10.1103/PhysRevLett.124.192001

New physics with vortex neutrons

1. Potentially huge angular momentum: new means for neutron tomography, holography, and material studies: different interactions with spin waves and other quasi-particles in materials

2. More effective testing of the nuclear forces at low energies where the QCD does not work

3. Finite transverse and longitudinal coherence phenomena: going beyond the Born approximation, fundamentals of quantum mechanics, testing its different interpretations

4. For charged vortex particles, the magnetic moments increases, so does the cyclotron frequency in magnetic field. No similar effects for vortex neutrons?

5. Precision tests of the Standard model and search for New physics

6. Unwanted systematics in high-precision experiments due to accidental twisting

Acknowledgements

I am grateful to Valery Serbo, Andrei Afanasev, Igor Ivanov, Klaus Floettmann, Stanislav Baturin, Andrey Surzhykov, Andrey Pupasov-Maksimov, Andrey Volotka, and many other colleagues and friends

The study is supported by the Russian Science Foundation, Projects No. 17-72-20013, 21-42-04412, and by the Government of the Russian Federation through the ITMO Fellowship and Professorship Program