



King's Research Portal

Document Version Peer reviewed version

Link to publication record in King's Research Portal

Citation for published version (APA):

Eismann, J., Nicholls, L., Roth, D., Alonso, M. A., Banzer, P., Rodriguez Fortuno, F., Zayats, A., Nori, F., & Bliokh, K. (2020). Transverse spinning of unpolarized light. *Nature Photonics*. Advance online publication.

Citing this paper

Please note that where the full-text provided on King's Research Portal is the Author Accepted Manuscript or Post-Print version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version for pagination, volume/issue, and date of publication details. And where the final published version is provided on the Research Portal, if citing you are again advised to check the publisher's website for any subsequent corrections.

General rights

Copyright and moral rights for the publications made accessible in the Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognize and abide by the legal requirements associated with these rights.

•Users may download and print one copy of any publication from the Research Portal for the purpose of private study or research. •You may not further distribute the material or use it for any profit-making activity or commercial gain •You may freely distribute the URL identifying the publication in the Research Portal

Take down policy

If you believe that this document breaches copyright please contact librarypure@kcl.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

1

Transverse spinning of unpolarized light

2	J. S. Eismann ^{1,2,*} , L. H. Nicholls ^{3,*} , D. J. Roth ^{3,*} , M. A. Alonso ^{4,5} , P. Banzer ^{1,2,6,#} ,
3	F. J. Rodríguez-Fortuño ³ , A. V. Zayats ^{3,#} , F. Nori ^{7,8} , and K. Y. Bliokh ^{7,#}
4	¹ Max Planck Institute for the Science of Light, Staudtstrasse 2,
5	D-91058 Erlangen, Germany
6	² Institute of Optics, Information, and Photonics, University Erlangen-Nuremberg,
7	Staudtstrasse 7/B2, D-91058 Erlangen, Germany
8	³ Department of Physics and London Centre for Nanotechnology, King's College London,
9	Strand, London WC2R 2LS, UK
10	⁴ CNRS, Centrale Marseille, Institut Fresnel, Aix Marseille Univ,
11	UMR 7249, 13397 Marseille CEDEX 20, France
12	⁵ The Institute of Optics, University of Rochester, Rochester, NY 14627, USA
13	⁶ Institute of Physics, University of Graz, NAWI Graz, Universitätsplatz 5, Graz, 8010
14	Austria ⁷ Theoretical Quantum Physics Laboratory, RIKEN Cluster for Pioneering Research,
15	Wako-shi, Saitama 351-0198, Japan
16	⁸ Physics Department, University of Michigan, Ann Arbor, Michigan 48109-1040, USA
17	*These authors contributed equally to this work
18	[#] Corresponding authors
19	
20	It is well known that the spin angular momentum of light, and therefore that of
21	photons, is directly related to their circular polarization. Naturally, for totally
22	unpolarized light, polarization is undefined and the spin vanishes. However, for
23	nonparaxial light, the recently discovered transverse spin component, orthogonal to
24	the main propagation direction, is largely independent of the polarization state of the
25	wave. Here we demonstrate, both theoretically and experimentally, that this
26	transverse spin survives even in nonparaxial fields (e.g., focused or evanescent)
27	generated from totally unpolarized paraxial light. This counterintuitive phenomenon
28	is closely related to the fundamental difference between the meanings of 'full
29	depolarization' for 2D paraxial and 3D nonparaxial fields. Our results open an
30	avenue for studies of spin-related phenomena and optical manipulation using
31	unpolarized light.

32 1. Introduction

33 Classical polarization optics usually regards paraxial light and its 2D polarization states 34 [1]. Similarly, the spin of photons in quantum electrodynamics textbooks is also described by 2D 35 circular polarizations of plane electromagnetic waves [2]. However, modern nano-optics is based 36 on the use of structured nonparaxial fields, where all three spatial components of the field vector 37 generically play a role [3]. This has required extending the existing polarization theory to the 3D 38 case [4–12]. This extension is by no means trivial: the four Stokes parameters describing generic 39 2D polarization are now substituted by *nine* polarization parameters characterizing generic 3D 40 polarization.

Simultaneously, the notion of spin has to be augmented to 3D structured fields [13–17], where the local spin density is well-defined for monochromatic waves and can be associated with the radiation torque on small dipole particles [17]. This resulted in the discovery of the unusual *transverse spin* in inhomogeneous fields with several remarkable properties [18–32] (for reviews, see [17,33–35]). This spin, orthogonal to the main propagation direction and wavevectors, is a very robust phenomenon that has found applications for spin-direction 47 coupling using evanescent waves, which is highly efficient and largely independent of the details
48 of the system [22–25,27–29,33–35]. Moreover, it was recently found that the transverse spin is
49 equally present in inhomogeneous sound waves [36–38], which are traditionally considered as
50 scalar (i.e., spinless), quantum electron waves [29], and even gravitational waves [39].

51 In this work, we demonstrate, both theoretically and experimentally, that the transverse 52 spin is essentially a 2D-polarization-independent phenomenon, which survives even in 3D fields 53 generated from *totally unpolarized* paraxial light, Fig. 1. This is in sharp contrast to the usual 54 longitudinal spin, which is directly related to the 2D polarization and vanishes in unpolarized 55 fields. We show that this phenomenon is intimately related to the difference between the 2D and 56 3D polarization descriptions. Namely, the totally unpolarized 2D field is at the same time *half*-57 *polarized* in the 3D sense (according to the definition [5]). Indeed, 2D depolarization implies a 58 single random phase between the two orthogonal field components (with equal amplitudes), 59 while complete 3D depolarization requires two random phases between the three mutually-60 orthogonal field components. Therefore, any regular optical transformation producing a 61 nonparaxial 3D field from a 2D-unpolarized far-field source will have partial 3D polarization, 62 with the degree of polarization not less than 1/2. In particular, the local increase of the degree of 63 polarization up to almost 1 was demonstrated for the tight focusing of an unpolarized paraxial 64 beam [40,41]. Below we show that the transverse spin appears in any paraxial-to-nonparaxial 65 transformation (see Fig. 1), even without a change in the degree of polarization; the minimal 66 value of 1/2 allows for nonzero spin in such fields. The origin of this phenomenon lies in 67 intrinsic spin-orbit interaction of light [34], where any transformation in the wavevector 68 direction produces spin-related phenomena, even for 2D-unpolarized light.

69 Since spin is a fundamental dynamical property of light, which is very important in both 70 quantum and classical, theoretical and applied optics (e.g., for optical manipulation of micro- and 71 nano-particles), our findings provide a novel opportunity to use polarization-independent spin 72 from unpolarized sources.

73 2. Theoretical background

Nonparaxial optical fields are usually generated from far-field sources of paraxial light via some optical transformations (see Fig. 1): focusing, diffraction, scattering, etc. In this work, we consider two of the most common examples of nonparaxial fields: (i) tightly focused Gaussianlike beams and (ii) evanescent waves. These are generated via high-NA focusing and total internal reflection of the incident paraxial light, respectively.

79 The incident paraxial light can be approximated by a plane wave, so its 2D polarization state can be described by the 2×2 polarization (density) matrix $\hat{\Phi}^{2D}$ or, equivalently, by 4 real 80 Stokes parameters $\vec{s} = (s_0, s_1, s_2, s_3)$: $\hat{\Phi}^{2D} = \frac{1}{2} \sum_{l=0}^{3} s_l \hat{\sigma}_l$, with $\hat{\sigma}_l$ being the basic Pauli matrices 81 [1]. Here, the normalized parameter s_3 corresponds to the normalized spin angular momentum 82 density of the wave (*z*-directed along the wave propagation): $S_z / I = s_3 / s_0 \in [-1,1]$ [17], where 83 $I = W / \omega$ is the wave intensity expressed via the energy density W and frequency ω . The 84 degree of paraxial 2D polarization is defined as $P^{2D} = \sqrt{\sum_{i=1}^{3} s_i^2} / s_0 \in [0,1]$. For totally 2D-85 unpolarized light, $\vec{s} \propto (1,0,0,0)$, $P^{2D} = 0$, and the spin vanishes: $S_z = 0$ (see Fig. 1). 86

For the generated nonparaxial field, all three components are significant, and its polarization state at a point is described by a 3×3 Hermitian polarization (density) matrix $\hat{\Phi}^{3D}$, or equivalently by 9 real parameters $\vec{\Lambda} = (\Lambda_0, \Lambda_1, ..., \Lambda_8)$: $\hat{\Phi}^{3D} = \frac{1}{3} \sum_{l=0}^8 \Lambda_l \hat{\lambda}_l$, with $\hat{\lambda}_l$ being the basic Gell-Mann matrices [4–12] [see Supplementary Information (SI)]. In such fields, the polarization ellipsoid can have an arbitrary orientation, and the spin angular momentum density (orthogonal to it) involves all three components [14,17]. Its normalized value can be expressed via the properly normalized parameters A = A and A (see SI):

93 via the properly normalized parameters
$$\Lambda_2$$
, Λ_5 , and Λ_7 (see SI):

94
$$\frac{\mathbf{S}}{I} = \frac{1}{I} \left(S_x, S_y, S_z \right) = \frac{2}{3\Lambda_0} \left(-\Lambda_7, \Lambda_5, -\Lambda_2 \right). \tag{1}$$

There are several quantities characterizing the degree of polarization of a 3D field, which can be more or less relevant to the particular problem [4–12]. In our case, one of the most common definitions of the 3D degree of polarization is useful: $P^{3D} = \sqrt{\sum_{i=1}^{8} \Lambda_i^2} / \sqrt{3} \Lambda_0 \in [0,1]$ [5,10– 12,40,41], because it explicitly involves the norm of the spin given by Eq. (1), so that $\overline{000}$ is a sum of spin-dependent and spin-independent parts. For a totally unpolarized 3D field, $\overline{\Lambda} \propto (1,0,0,...,0), P^{3D} = 0$, and the corresponding vanishing $\mathbf{S} = \mathbf{0}$.

One remarkable feature of the above definitions of the degree of polarization is that totally 101 2D-unpolarized paraxial light, $P^{2D} = 0$, is *partially* polarized in the 3D sense: $P^{3D} = 1/2$ 102 [5,11,12] (see SI). This is because total 3D depolarization requires total mutual decoherence of 103 104 all of the three field components with equal amplitudes, while in paraxial light the longitudinal zcomponent vanishes. As a result, $\Lambda_8 = (\sqrt{3}/2) \Lambda_0 \neq 0$ even for a totally 2D-unpolarized paraxial 105 field. This "discrepancy" between the 2D and 3D polarization degrees naturally manifests itself 106 107 as a nonzero transverse spin in a nonparaxial field generated from a 2D-unpolarized paraxial 108 source, Fig. 1. 109 We first consider the case of a focused polarized field. Both the incident paraxial and 110 focused nonparaxial fields can be modeled by the post-paraxial description of a Gaussian beam

110 rocused holparaxial fields can be modeled by the post-paraxial description of a Gaussian beam 111 [17] with the infinite and finite Rayleigh range z_R , respectively. Using the natural cylindrical 112 coordinates (r, φ, z) , the normalized spin density in the focal plane of a polarized Gaussian beam 113 can be written as (see SI):

114
$$\frac{\mathbf{S}}{I} \simeq \frac{1}{1 + \tilde{r}^2 / 2} \left[\frac{\mathbf{S}_0}{I_0} + \tilde{r} \,\overline{\mathbf{\phi}} \right] \equiv \frac{\mathbf{S}_{\parallel}}{I} + \frac{\mathbf{S}_{\perp}}{I}.$$
(2)

Here $\mathbf{S}_0 / I_0 = (s_3 / s_0) \overline{\mathbf{z}}$ is the spin density in the plane-wave limit, $I \propto (1 + \tilde{r}^2 / 2) e^{-kr^2/z_R}$ is the intensity distribution, *k* is the wavenumber, $\tilde{r} = r / z_R$, and the overbars indicate the unit vectors of the corresponding axes. Equation (2) exhibits the usual polarization-dependent longitudinal spin, as well as the transverse spin component [17,26,32,33] which is totally independent of the polarization (Stokes parameters) of the incident plane wave.

120 The totally 2D-unpolarized Gaussian beam can be considered as an *incoherent* 121 superposition of two Gaussian beams with mutually orthogonal polarization states (e.g., with 122 $\vec{s} \propto (1,1,0,0)$ and $\vec{s} \propto (1,-1,0,0)$). The corresponding 3×3 polarization matrix and parameters $\vec{\Lambda}$ 123 in the focal plane of such unpolarized Gaussian field become (see SI): 124 $\Lambda_1 = \Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_6 = 0$,

125
$$\frac{\Lambda_8}{\Lambda_0} \simeq \frac{\sqrt{3}}{2} \frac{1 - \tilde{r}^2}{1 + \tilde{r}^2/2}, \quad \frac{\Lambda_5}{\Lambda_0} \simeq \frac{3}{2} \frac{\tilde{x}}{1 + \tilde{r}^2/2}, \quad \frac{\Lambda_7}{\Lambda_0} \simeq \frac{3}{2} \frac{\tilde{y}}{1 + \tilde{r}^2/2}, \quad (3)$$

where $\tilde{x} = x/z_R$ and $\tilde{y} = y/z_R$. In the paraxial limit $z_R \to \infty$, only the Λ_8/Λ_0 ratio survives, providing the 3D degree of polarization $P^{3D} = 1/2$ [5,11,12]. In the nonparaxial case, the 128 nonzero parameters Λ_5 and Λ_7 appear. These parameters exactly describe the transverse part of

spin (2) in agreement with Eq. (1): $\frac{\mathbf{S}_{\perp}}{I} = \frac{2}{3\Lambda_0} \left(-\Lambda_7, \Lambda_5, 0\right)$, while the longitudinal spin naturally

130 vanishes: $\mathbf{S}_{\parallel} = \mathbf{0}$ (see Fig. 1).

Second, we consider an evanescent wave, which can be generated via total internal reflection of a paraxial incident field (plane wave). Such z-propagating and x-decaying wave is characterized by the propagation constant $k_z > k \equiv \omega/c$ and the decay constant $\kappa = \sqrt{k_z^2 - k^2}$. Assuming, for simplicity, that the transmission coefficients of the total internal reflection are polarization-independent, the generation of the evanescent field can be regarded as a transition from the plane-wave limit $\kappa = 0$, $k_z = k$, to a given finite $\kappa > 0$. The normalized spin density of the polarized evanescent wave is [17,20]:

138
$$\frac{\mathbf{S}}{I} = \frac{k}{k_z} \frac{\mathbf{S}_0}{I_0} + \frac{\kappa}{k_z} \overline{\mathbf{y}} \equiv \frac{\mathbf{S}_{\parallel}}{I} + \frac{\mathbf{S}_{\perp}}{I}.$$
(4)

Here, as before, $\mathbf{S}_0 / I_0 = (s_3 / s_0) \overline{\mathbf{z}}$ is the spin density in the plane-wave limit, and the intensity distribution is $I \propto e^{-2\kappa x}$. As for the focused field, the spin (4) consists of the longitudinal polarization-dependent component and the transverse (*y*-directed) polarization-independent term [17,20,29,33,34].

143 The totally 2D-unpolarized evanescent field is obtained as an incoherent superposition of 144 evanescent waves with orthogonal polarization states. The corresponding parameters $\vec{\Lambda}$ for such 145 evanescent field are (see SI): $\Lambda_1 = \Lambda_2 = \Lambda_4 = \Lambda_6 = \Lambda_7 = 0$,

146
$$\frac{\Lambda_8}{\Lambda_0} = \frac{\sqrt{3}}{2} \frac{k^2 - \kappa^2 / 2}{k_z^2}, \quad \frac{\Lambda_3}{\Lambda_0} = \frac{3}{4} \frac{\kappa^2}{k_z^2}, \quad \frac{\Lambda_5}{\Lambda_0} = \frac{3}{2} \frac{\kappa}{k_z}.$$
 (5)

147 In the plane-wave limit $\kappa = 0$, only the ratio Λ_8 / Λ_0 survives, yielding $P^{3D} = 1/2$. In the 148 evanescent-wave case, both Λ_3 and Λ_5 are different from zero, the latter corresponding 149 precisely to the transverse part of the spin (4) in agreement with Eq. (1): 150 $\frac{\mathbf{S}_{\perp}}{I} = \frac{2}{3\Lambda_0} \left(-\Lambda_7, \Lambda_5, -\Lambda_2 \right)$, whereas the longitudinal spin vanishes: $\mathbf{S}_{\parallel} = \mathbf{0}$ (see Fig. 1).

Importantly, considering r/z_{R} and κ/k as a small parameter ε in the above two 151 152 problems, the 3D degree of polarization of the 2D-unpolarized focused and evanescent fields has the form $P^{3D} = \frac{1}{2} + \delta P^{3D}$, with $\delta P^{3D} \square \varepsilon^2$ and $\delta P^{3D} \square \varepsilon^4$, respectively (see SI), while the 153 transverse spin is of order ε . This means that, to first order, focusing or total-reflection 154 155 processes (with polarization-independent transmission amplitudes) do not change the 3D degree 156 of polarization of the incident 2D-unpolarized light [40,41], while the spin changes from zero in 157 the incident wave to the nonzero transverse spin in the nonparaxial field. This appearance of spin 158 without polarization originates from the intrinsic *spin-orbit interaction* of light [34]. The plane-159 wave transversality condition $\mathbf{k} \cdot \mathbf{E} = \mathbf{k} \cdot \mathbf{H} = 0$ imposes constraints on the relations between 160 longitudinal and transverse field components, which therefore have some intrinsic mutual 161 coherence even for fields generated from 2D-unpolarized sources. Transformations from 162 paraxial to nonparaxial fields can be approximated by \mathbf{k} -vector transformations (re-directions), 163 which do not affect the degree of polarization but inevitably generate the transverse spin, as 164 schematized in Fig. 1.

165 Another important point is that in our calculations we considered both *electric* and *magnetic* field contributions to all quadratic quantities (see SI): spin $\mathbf{S} = \mathbf{S}^{(e)} + \mathbf{S}^{(m)}$, intensity 166 $I = I^{(e)} + I^{(m)}$, polarization parameters $\vec{\Lambda} = \vec{\Lambda}^{(e)} + \vec{\Lambda}^{(m)}$, etc. For polarized fields, the electric and 167 magnetic contributions are not equal to each other, and additional terms generally appear when 168 169 considering only the electric or the magnetic fields [17,20,26,32]. In contrast, for 2D-unpolarized 170 fields, these contributions are always equal to each other, so that one can only consider the 171 electric (or magnetic) field contributions. One can say that unpolarized light and its transverse 172 spin have a *dual-symmetric* nature [16,42], similarly to circularly-polarized fields with well-173 defined helicity [15].

174 In what follows, we present experimental measurements of the nonzero transverse spin 175 from Eqs. (2) and (4) in tightly focused and evanescent fields generated from 2D-unpolarized 176 sources. The two experiments use different types of unpolarized sources and measure both the 177 electric and magnetic contributions to the spin.

178 3. Focused-beam experiment

179 In order to measure the transverse spin of a 2D-unpolarized tightly focused beam, we first prepared a suitable input field. We sent a Gaussian beam (wavelength $\lambda = 2\pi / k = 620 \text{ nm}$, 180 linewidth $\Delta \lambda_{\text{FWHM}} \approx 5 \text{ nm}$) through a linear polarizer and two liquid-crystal variable retarders 181 (LCs) oriented at 45° and 90° with respect to the axis of the linear polarizer, respectively. The 182 183 experimental setup is schematically shown in Fig. 2a [32,43]. With this arrangement, the polarization state of the generated beam can span the whole Poincaré sphere $(\sum_{i=1}^{3} s_i^2 = s_0^2)$ with 184 185 the position on the sphere depending on the settings of the LCs. These LCs were controlled via a 186 voltage applied to the corresponding devices to induce a voltage-dependent birefringence. For 187 the applied voltage, we used two random numbers in a range spanning multiple wavelengths of 188 retardance, updated 10 times per second. This produced a beam that is fully and homogeneously 189 polarized over its cross-section for a fixed instance in time. However, the beam appears totally

2D-unpolarized ($P^{2D} = \sum_{i=1}^{3} s_i^2 = 0$) when averaged over a certain time frame. 190

191 For tight focusing and subsequent collimation of the light beam, we used two confocally aligned microscope objectives (MOs) with numerical apertures $NA_1 = 0.9$ and $NA_2 = 1.3$, 192 193 respectively (see Fig. 2a). Following a scheme developed recently [32] for the reconstruction of the electric and magnetic parts of the transverse spin, we used a spherical silicon nanoparticle of 194 diameter d = 168 nm as a local probe in the focal volume. The NA of the collection MO₂ was 195 considerably larger than 1 in order to access the angular range above the critical angle, which is 196 197 required for the applied reconstruction technique. Then, we performed a polarization analysis in 198 the back focal plane (BFP) of MO, imaged onto a camera, which allowed us to access the far 199 field of the scattered light. This polarization analysis involved a LC, a linear polarizer and an 200 imaging lens (see Fig. 2a). At this stage of the setup, a single LC was sufficient because for the 201 reconstruction of the transverse spin we only need to distinguish between the x- and y-202 polarizations. According to the method in Ref. [32], intensities of the x- and y-components of the scattered field, dependent on the transverse wavevectors, $I_{x,y}^{sc}(\mathbf{k}_{\perp})$, allowed unambiguous 203 reconstruction of both the electric and magnetic field contributions to the transverse spin density, 204 $\mathbf{S}_{\perp}^{(e)}$ and $\mathbf{S}_{\perp}^{(m)}$, in the focused field at the location of the particle. 205

In order to provide a full map of the transverse electric and magnetic spin densities, $\mathbf{S}_{\perp}^{\scriptscriptstyle(e)}$ 206 and $\mathbf{S}_{\perp}^{(m)}$, shown in Fig. 2b, we raster scan the nanoparticle across the focal plane (over the square 207

area of $1.5 \times 1.5 \,\mu\text{m}^2$ with a step size of 30 nm) and record the polarization-resolved BFP 208 images for each particle position. For each position and polarization, the data is averaged over a 209 time frame of 40s. The distributions of the transverse spin obtained experimentally are in good 210 agreement with simple theoretical expression (2) with the fitted Rayleigh range $z_R \simeq 527 \,\mathrm{nm}$. 211 We also performed more accurate numerical calculations of the transverse spin densities using 212 213 vectorial diffraction theory [44] (which takes into account the finite aperture of the focused 214 beam) and plotted these as insets in Fig. 2b. In doing so, we adjusted all parameters of the 215 focusing system and the incoming beam to the experimental case. One can see that the 216 experimental results are in excellent agreement with the numerical data.

Importantly, the electric and magnetic spin densities in Fig. 2b exhibit very similar spatial 217 218 distributions, in agreement with the dual-symmetric nature of the transverse spin for 2Dunpolarized light: $\mathbf{S}_{\perp}^{(e)} = \mathbf{S}_{\perp}^{(m)} = \mathbf{S}_{\perp} / 2$ (see SI). The same feature is present in nonparaxial fields 219 with well-defined helicity [15], such as fields obtained by focusing circularly polarized input 220 221 light [45]. However, in our case of an unpolarized source, the helicity and longitudinal spin 222 vanish. Note also that the change in the 3D degree of polarization upon focusing [40,41] is small: $\delta P^{3D} \simeq \tilde{r}^2 / 4 \simeq 0.036$, where we used $r \simeq 200$ nm corresponding to the maximum of the spin 223 224 density in Fig. 2b (see SI).

225 **4. Evanescent-wave experiment**

226 In order to measure the transverse spin of a 2D-unpolarized evanescent wave, the total 227 internal reflection of collimated far-field light coming from an unpolarized tungsten lamp was 228 employed. To generate the evanescent wave, a BK7 glass prism (Thorlabs, refractive index 229 n = 1.51 at the wavelength $\lambda = 600$ nm) was illuminated by an unpolarized tungsten lamp of 230 wavelength 500-800 nm. The angle of incidence was measured to be 49°, which changes to 47° 231 upon refraction entering the right-angle prism. This is above the critical angle of 41°, producing 232 total internal reflection and an evanescent wave with $\kappa / k_z \simeq 0.43$ above the glass. Such an evanescent wave has noticeable transverse spin (4) and negligible change in the 3D degree of 233 polarization: $\delta P^{3D} \simeq 0.75 (\kappa / k_{\perp})^4 \simeq 0.026$ (neglecting the anisotropy of the Fresnel coefficients, 234 235 see SI). Akin to the focused-beam experiment, a small nanoparticle acting as a probe for the 236 local field polarization – in this case a gold nanoparticle (diameter d = 150 nm, Sigma Aldrich) 237 - was placed in the evanescent field above the prism and the far-field scattered radiation was 238 analyzed (see Fig. 3a).

239 The scattered signal from the gold nanoparticle was collected by a $100 \times$ microscope 240 objective with a numerical aperture NA = 0.9, allowing us to analyze the scattered light within a very large solid angle. The BFP of the detection objective (Fourier plane) was then imaged onto 241 242 an imaging spectrometer using a set of relay lenses. The scattered signal was analyzed using a 243 linear polarizer and a quarter wave plate in order to reconstruct the full Stokes parameters of the 244 light scattered from the particle in all directions in the upper half-space (see SI). Figure 3b shows the results of these measurements, i.e., angular dependences of the normalized Stokes parameters 245 $s_{1,2,3}/s_0$, as well as the 2D degree of polarization, P^{2D} , for the far-field scattering from the 246 247 nanoparticle.

Note that the gold nanoparticle in this experiment behaves as an *electric* dipole, i.e., it is sensitive to the electric rather than magnetic field properties. However, we have already shown that the magnetic field shares the same features in 2D-unpolarized light, so we omit the superscript "(e)".

The degree of polarization P^{2D} and third Stokes parameter s_3 / s_0 in the scattered radiation 252 253 show that the scattered light becomes partially polarized and acquires opposite-sign spins in the 254 $\pm y$ directions. This is in perfect agreement with the y-directed transverse spin in Eq. (4) and the 255 well-established fact that this transverse spin in an evanescent field is converted to the usual far-256 field spin (i.e., the third Stokes parameter) upon transverse scattering by a dipole particle [23– 257 25,27–29,33–35]. The insets in Fig. 3b show the analytically calculated Stokes parameters of the 258 scattered light for an unpolarized $\lambda = 600$ nm source. (The patterns depend very weakly on 259 wavelength so that they are almost constant within the whole 500–800 nm range.) The analytical 260 calculation was performed by matching the experimental parameters (angle of incidence, type of 261 glass, particle diameter and material), including the total internal reflection of the incident beam, 262 the particle modeled as a point dipole, and the subsequent scattering of the particle (taking into 263 account the effects of the surface reflections; see SI). One can see a very good agreement 264 between the theory and the experiment.

265 **5. Conclusions**

266 We have shown that pure redirection of wavevectors can generate nonzero spin angular 267 momentum in initially completely 2D-unpolarized paraxial light. This surprising result 268 establishes an important link between two areas of research: (i) 3D polarization in nonparaxial 269 fields [4–12,40,41] and (ii) transverse spin [17–39]. The direct relation between the redirection 270 of wavevectors and the appearance of spin points to the fundamental spin-orbit interaction origin 271 of this phenomenon [34]. We have provided theoretical calculations and two sets of experimental 272 measurements for the transverse spin generated upon tight focusing and total internal reflection 273 (i.e., generation of an evanescent wave) of an unpolarized paraxial light. All these results use 274 well-established methods for spin calculations and measurements, and are in perfect mutual 275 agreement.

276 Thus, our work has revealed one more exceptional feature of transverse spin. Together 277 with other properties found previously, we can conclude that transverse spin is not just "one of 278 the components of spin angular momentum density", but rather a separate physical entity whose 279 main features are completely different from those of the usual polarization-controlled 280 longitudinal spin of paraxial light or photons. As such, the transverse spin can offer novel 281 phenomena and applications in angular-momentum and polarization optics. The remarkable 282 "spin-momentum locking" associated with the transverse spin has already found promising 283 applications for highly efficient spin-direction couplers [22–25,27–29,33–36]. The present study 284 opens an avenue for the use of spin from unpolarized and incoherent sources. It also sheds light 285 onto the appearance of nonzero local spin in nonparaxial sound waves [36–38], which do not 286 feature a polarization degree of freedom in the paraxial regime and correspond to spin-0 287 quantum particles (phonons).

288

289 Acknowledgements: We acknowledge help of Uwe Mick with the fabrication of samples. This 290 work was partially supported by European Research Council (Starting Grant ERC-2016-STG-291 714151-PSINFONI and iCOMM Project No. 789340), EPSRC (UK), Excellence Initiative of 292 Aix Marseille University — A*MIDEX, a French 'Investissements d'Avenir' programme, NTT 293 Research, Army Research Office (ARO) (Grant No. W911NF-18-1-0358), Japan Science and 294 Technology Agency (JST) (via the CREST Grant No. JPMJCR1676), Japan Society for the 295 Promotion of Science (JSPS) (JSPS-RFBR Grant No. 17-52-50023 and the KAKENHI Grant 296 No. JP20H00134), the Foundational Questions Institute Fund (FQXi, Grant No. FQXi-IAF19-297 06), and a donor advised fund of the Silicon Valley Community Foundation.

298

Author contributions: K.Y.B. conceived the idea of this research, made theoretical calculations

300 with input from M.A.A., and prepared the manuscript with input from all the authors.

Focused-beam experiment: P.B. and J.S.E. developed the idea of the experiment. J.S.E.
 performed the experiment. J.S.E. and P.B. performed the data processing. J.S.E. and P.B. wrote
 the corresponding part of the manuscript.

304 Evanescent-wave experiment: F.J.R.-F, D.J.R, L.H.N, and A.V.Z developed the idea of the

305 experiment. D.J.R and L.H.N designed and performed the experiment. F.J.R.-F performed

- 306 theoretical modeling. D.J.R and F.J.R.-F performed data processing. D.J.R. fabricated the
- 307 samples. F.J.R.-F, D.J.R, L.H.N and A.V.Z wrote the related part of the manuscript.

308 Data Availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

311 Code Availability

- 312 The codes that support the calculations and plots within this paper and other findings of this
- 313 study are available from the corresponding authors upon reasonable request.

314 **Competing Interests**

315 The authors declare no competing interests.

316 **References**

- Azzam, R. M. A. & Bashara, N. M. *Ellipsometry and Polarized Light*. (North-Holland, 1977).
- Berestetskii, V. B., Lifshitz, E. M. & Pitaevskii, L. P. *Quantum Electrodynamics*. (Pergamon, 1982).
- 321 3. Novotny, L. & Hecht, B. *Principles of Nano-Optics*. (Cambridge University Press, 2012).
- 4. Carozzi, T., Karlsson, R. & Bergman, J. Parameters characterizing electromagnetic wave polarization. *Phys. Rev. E* 61, 2024–2028 (2000).
- 5. Setälä, T., Shevchenko, A., Kaivola, M. & Friberg, A. T. Degree of polarization for optical near fields. *Phys. Rev. E* 66, 016615 (2002).
- 326 6. Dennis, M. R. Geometric interpretation of the three-dimensional coherence matrix for 327 nonparaxial polarization. *J. Opt. A Pure Appl. Opt.* 6, S26–S31 (2004).
- 328
 7. Ellis, J. & Dogariu, A. Optical Polarimetry of Random Fields. *Phys. Rev. Lett.* 95, 203905 (2005).
- 330 8. Gil, J. J. Polarimetric characterization of light and media. *Eur. Phys. J. Appl. Phys.* 40, 1–47
 331 (2007).
- 332 9. Sheppard, C. J. R. Jones and Stokes parameters for polarization in three dimensions. *Phys.*333 *Rev. A* 90, 023809 (2014).
- Brosseau, C. & Dogariu, A. Symmetry properties and polarization descriptors for an
 arbitrary electromagnetic wavefield. *Prog. Opt.* 49, 315–380 (2006).

- 336 11. Petruccelli, J. C., Moore, N. J. & Alonso, M. A. Two methods for modeling the propagation 337 of the coherence and polarization properties of nonparaxial fields. Opt. Commun. 283, 338 4457-4466 (2010). 339 12. Alonso, M. A. Geometric descriptions for the polarization for nonparaxial optical fields: a 340 tutorial. ArXiv:2008.02720 (2020). 341 13. Enk, S. J. van & Nienhuis, G. Spin and Orbital Angular Momentum of Photons. *Europhys.* 342 Lett. 25, 497–501 (1994). 343 14. M. V. & Dennis, M. R. Polarization singularities in isotropic random vector waves. Proc. R. 344 Soc. London. Ser. A Math. Phys. Eng. Sci. 457, 141–155 (2001). 345 15. Bliokh, K. Y., Alonso, M. A., Ostrovskaya, E. A. & Aiello, A. Angular momenta and spin-346 orbit interaction of nonparaxial light in free space. *Phys. Rev. A* 82, 063825 (2010). 347 16. Cameron, R. P., Barnett, S. M. & Yao, A. M. Optical helicity, optical spin and related 348 quantities in electromagnetic theory. New J. Phys. 14, 053050 (2012). 349 17. Bliokh, K. Y. & Nori, F. Transverse and longitudinal angular momenta of light. *Phys. Rep.* 350 **592**, 1–38 (2015). 351 18. Bliokh, K. Y. & Nori, F. Transverse spin of a surface polariton. Phys. Rev. A 85, 061801 352 (2012).353 19. Banzer, P. et al. The photonic wheel - Demonstration of a state of light with purely 354 transverse angular momentum. J. Eur. Opt. Soc. 8, 13032 (2013). 355 20. Bliokh, K. Y., Bekshaev, A. Y. & Nori, F. Extraordinary momentum and spin in evanescent 356 waves. Nat. Commun. 5, 3300 (2014). 357 21. Canaguier-Durand, A. & Genet, C. Transverse spinning of a sphere in a plasmonic field. 358 *Phys. Rev. A* 89, 033841 (2014). 359 22. Neugebauer, M., Bauer, T., Banzer, P. & Leuchs, G. Polarization Tailored Light Driven 360 Directional Optical Nanobeacon. Nano Lett. 14, 2546–2551 (2014). 361 23. Rodríguez-Fortuño, F. J. et al. Near-Field Interference for the Unidirectional Excitation of 362 Electromagnetic Guided Modes. Science 340, 328–330 (2013). 363 24. Petersen, J., Volz, J. & Rauschenbeutel, A. Chiral nanophotonic waveguide interface based 364 on spin-orbit interaction of light. Science 346, 67-71 (2014). 365 25. O'Connor, D. et al. Spin–orbit coupling in surface plasmon scattering by nanostructures. 366 Nat. Commun. 5, 5327 (2014). 367 26. Neugebauer, M., Bauer, T., Aiello, A. & Banzer, P. Measuring the Transverse Spin Density 368 of Light. Phys. Rev. Lett. 114, 063901 (2015). 27. le Feber, B., Rotenberg, N. & Kuipers, L. Nanophotonic control of circular dipole emission. 369 370 Nat. Commun. 6, 6695 (2015). 371 28. Lefier, Y. & Grosjean, T. Unidirectional sub-diffraction waveguiding based on optical spin-372 orbit coupling in subwavelength plasmonic waveguides. Opt. Lett. 40, 2890 (2015). 373 29. Bliokh, K. Y., Smirnova, D. & Nori, F. Quantum spin Hall effect of light. Science 348, 374 1448-1451 (2015). 375 30. Bekshaev, A. Y., Bliokh, K. Y. & Nori, F. Transverse Spin and Momentum in Two-Wave 376 Interference. Phys. Rev. X 5, 011039 (2015). 377 31. Bauer, T., Neugebauer, M., Leuchs, G. & Banzer, P. Optical Polarization Möbius Strips and 378 Points of Purely Transverse Spin Density. Phys. Rev. Lett. 117, 013601 (2016). 379 32. Neugebauer, M., Eismann, J. S., Bauer, T. & Banzer, P. Magnetic and Electric Transverse 380 Spin Density of Spatially Confined Light. *Phys. Rev. X* 8, 021042 (2018). 381 33. Aiello, A., Banzer, P., Neugebauer, M. & Leuchs, G. From transverse angular momentum to 382 photonic wheels. Nat. Photonics 9, 789–795 (2015). 383 34. Bliokh, K. Y., Rodríguez-Fortuño, F. J., Nori, F. & Zayats, A. V. Spin-orbit interactions of 384 light. Nat. Photonics 9, 796–808 (2015). 385 35. Lodahl, P. et al. Chiral quantum optics. Nature 541, 473–480 (2017).
- 386 36. Shi, C. *et al.* Observation of acoustic spin. *Natl. Sci. Rev.* **6**, 707–712 (2019).

- 387 37. Bliokh, K. Y. & Nori, F. Spin and orbital angular momenta of acoustic beams. *Phys. Rev. B*388 99, 174310 (2019).
- 38. Toftul, I. D., Bliokh, K. Y., Petrov, M. I. & Nori, F. Acoustic Radiation Force and Torque
 on Small Particles as Measures of the Canonical Momentum and Spin Densities. *Phys. Rev. Lett.* 123, 183901 (2019).
- 392 39. Golat, S., Lim, E. A. & Rodríguez-Fortuño, F. J. Evanescent gravitational waves. *Phys. Rev.*393 D 101, 084046 (2020).
- 40. Lindfors, K., Friberg, A. T., Setälä, T. & Kaivola, M. Degree of polarization in tightly
 focused optical fields. *J. Opt. Soc. Am. A* 22, 561 (2005).
- 41. Lindfors, K. *et al.* Local polarization of tightly focused unpolarized light. *Nat. Photonics* 1, 228–231 (2007).
- 398
 42. Bliokh, K. Y., Bekshaev, A. Y. & Nori, F. Dual electromagnetism: helicity, spin,
 399 momentum and angular momentum. *New J. Phys.* 15, 033026 (2013).
- 43. Banzer, P., Peschel, U., Quabis, S. & Leuchs, G. On the experimental investigation of the
 electric and magnetic response of a single nano-structure. *Opt. Express* 18, 10905 (2010).
- 402 44. Richards, B. & Wolf, E. Electromagnetic diffraction in optical systems, II. Structure of the
 403 image field in an aplanatic system. *Proc. R. Soc. London. Ser. A. Math. Phys. Sci.* 253, 358–
 404 379 (1959).
- 405 45. Eismann, J. S., Banzer, P. & Neugebauer, M. Spin-orbit coupling affecting the evolution of
 406 transverse spin. *Phys. Rev. Res.* 1, 033143 (2019).

407 **Figure captions**

- Figure 1. Spin and polarization in paraxial and nonparaxial fields. Schematic illustration of the longitudinal and transverse spin for the paraxial (plane-wave) and nonparaxial regimes for polarized and unpolarized (in the 2D sense) fields. Transverse spin S_{\perp} appears in nonparaxial
- 411 fields, while the depolarization of the paraxial source eliminates only the longitudinal spin S_{μ} .
- 412

413 Figure 2. Focused beam experiment. a, Experimental setup for the reconstruction of the 414 transverse spin in a tightly focused 2D-unpolarized field. A linear polarizer and two liquid 415 crystal variables retarders (LCs) are used to prepare a beam with randomly varied polarization. 416 Subsequently, two confocally aligned microscope objectives (MOs) focus and collimate the 417 beam. A spherical silicon nanoparticle is placed on a coverslip in the focal plane. It produces 418 scattered light with wavevectors outside of the aperture of the transmitted beam, which carries 419 information about the local transverse spin density in the beam [26,32]. Polarization-resolved 420 back focal plane images using the scattered light are recorded by using another LC, a linear polarizer and a lens. b, Experimental results of the reconstructed electric and magnetic transverse 421 spin, $S_{\perp}^{(e)}$ and $S_{\perp}^{(m)}$ (normalized to the maximum absolute value), which equal each other in the 422 2D-unpolarized field (see SI). The results of numerical calculations are shown as insets. 423

424

Figure 3. Evanescent wave experiment. a, Experimental setup used to detect the non-zero transverse spin in an evanescent wave from a 2D-unpolarized source. Light from an unpolarized source undergoes total internal reflection, generating an evanescent wave, which is then scattered by a nanoparticle. The scattering from this nanoparticle is collected via a microscope objective. The radiation diagram above the nanoparticle represents the measured P^{2D} (i.e., the degree of polarization in different directions), whereas the color represents the spin of the far-field radiation given by s_3/s_0 . b, Experimentally retrieved and analytically calculated (inset) maps of

- P^{2D} and normalized Stokes parameters $s_{1,2,3}/s_0$ of the scattered light in every direction of the
- 433 upper half-space.





