Non-separable States of Light: Classical and Quantum

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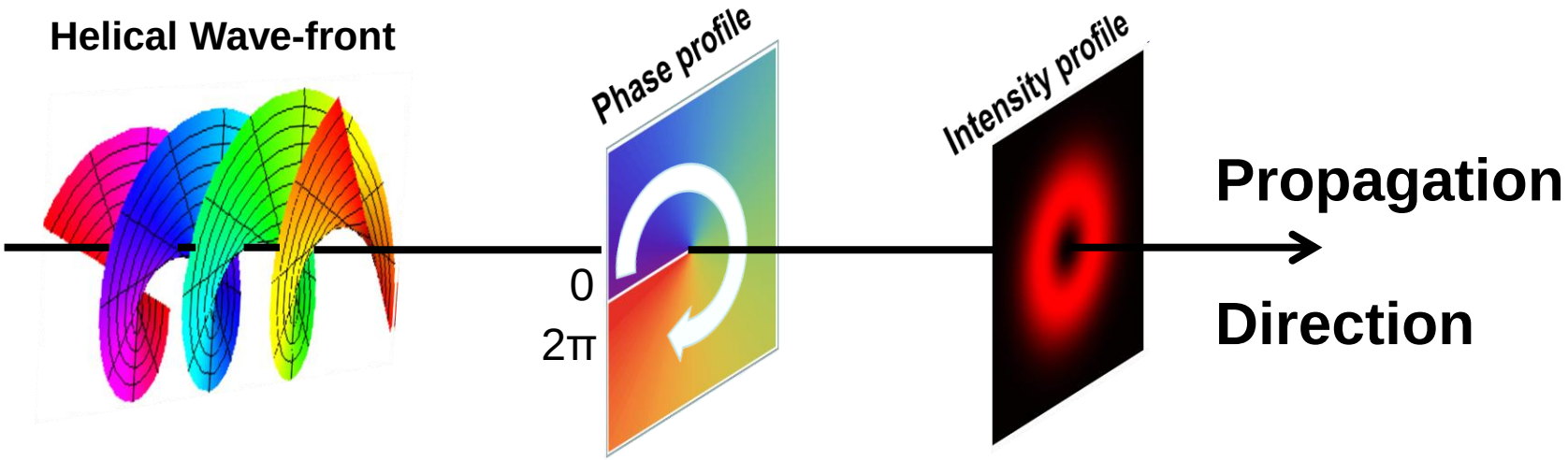
- **Introduction: Optical Vortices – Orbital Angular Momentum (OAM) states of light**
- **Non-separable states of light**
- **Confirmation of vorticity**
- **Transfer of classical non-separability to quantum domain**

Optical Vortex beams



Vortex order (topological charge)

- Helical wave fronts, dark core at the center due to the azimuthal phase.
- They carry an orbital angular momentum which is proportional to its order, defined as the number of helical paths completed in one wave length.

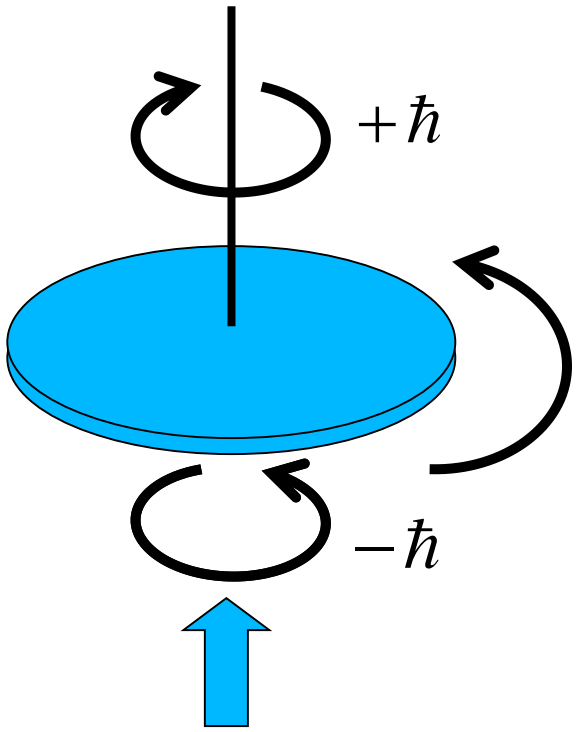
Spin Angular Momentum

Poynting showed classically for a beam of circularly polarized light

$$\frac{J_z}{W} = \frac{\text{Angular Momentum}}{\text{Energy}} = \pm\frac{1}{\omega}$$

Angular momentum

σ^+, σ^- Polarized: $\pm\hbar$ per photon



Beth
Phys. Rev. 50, 115, 1936

Orbital Angular Momentum

For a field amplitude distribution where

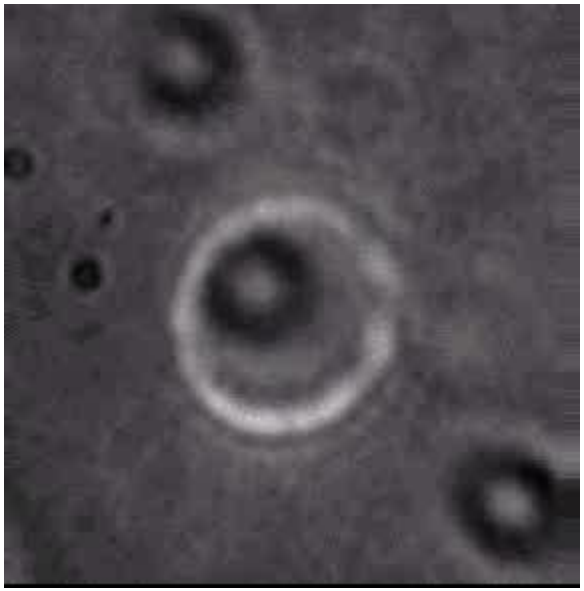
$$u(r,z) = u_0(r,z)\exp(-il\phi)$$

$$\frac{J_z}{W} = \frac{\text{Angular Momentum}}{\text{Energy}} = \pm\frac{l+\sigma_z}{\omega}$$

L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw and J. P. Woerdman

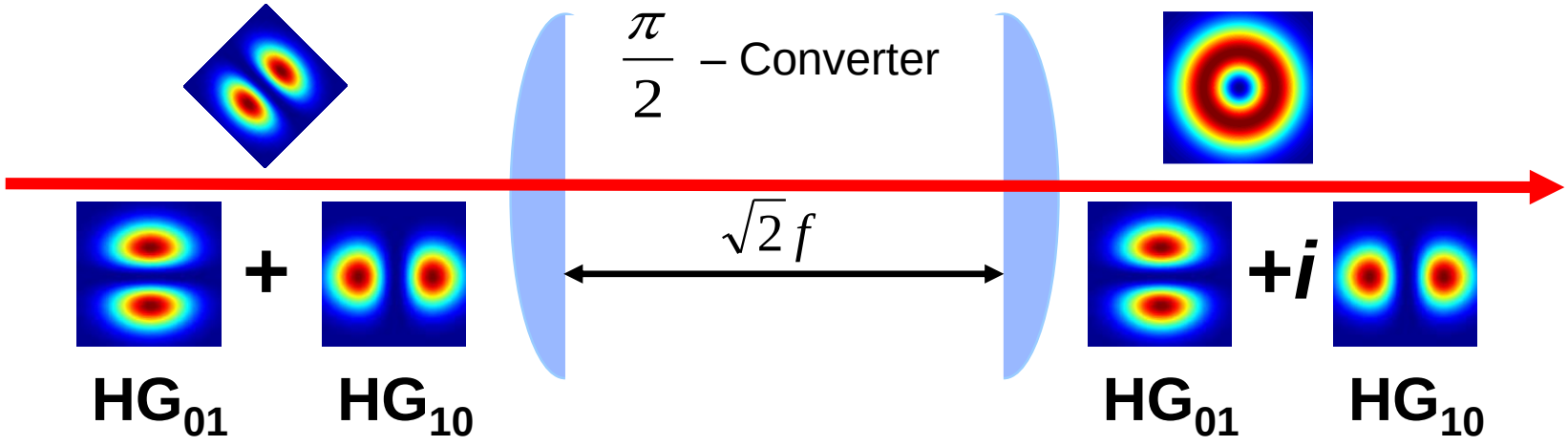
Phys. Rev. 45, 8185, 1992

Difference in SAM and OAM

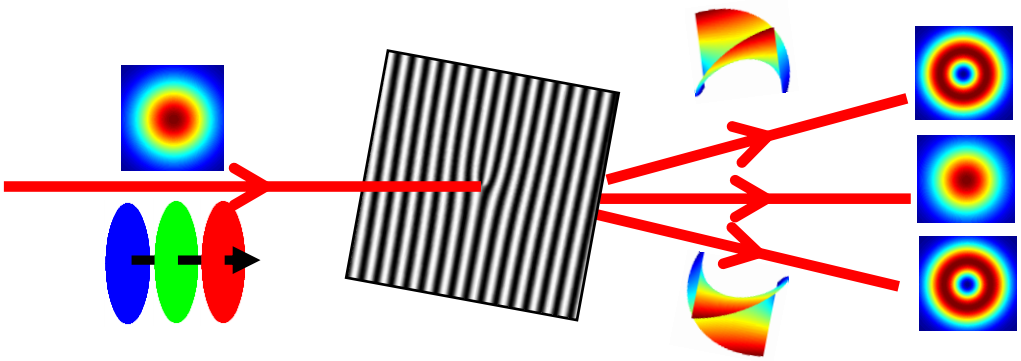


Optical Vortex beams – generation

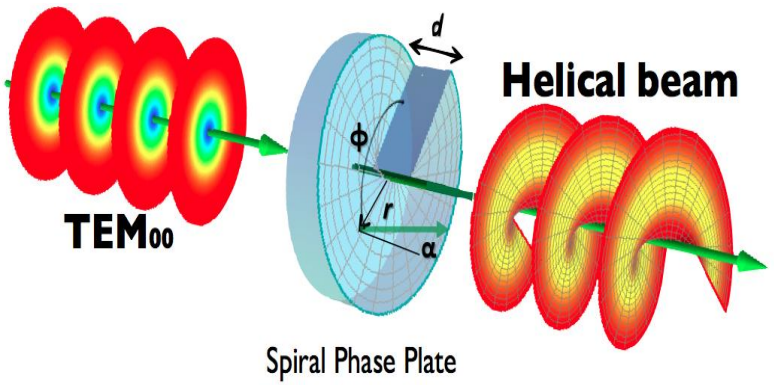
Astigmatic mode-converter



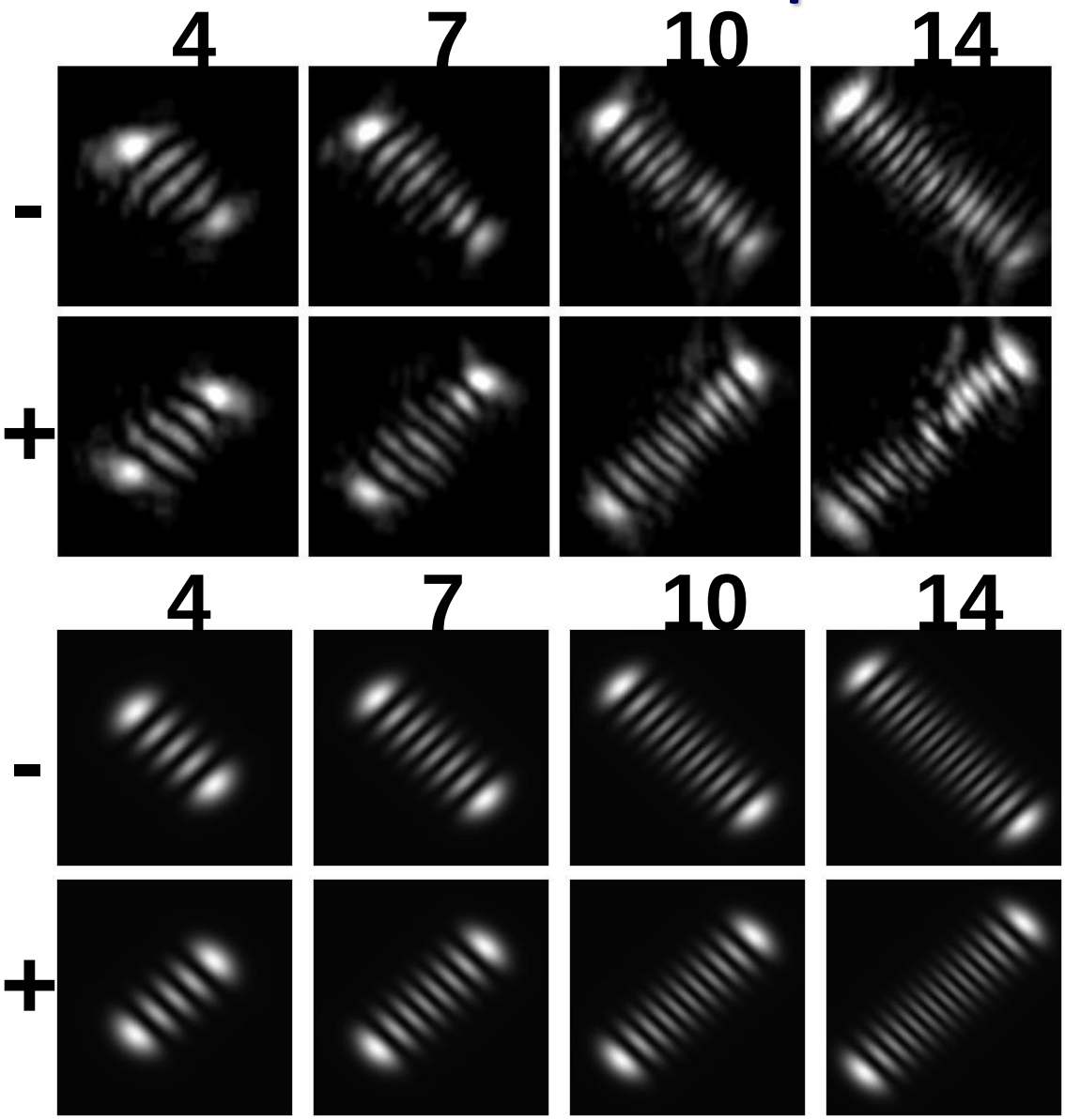
Computer Generated Holography



Spiral Phase plate



Using an ordinary tilted lens one can easily determine the order of an optical vortex



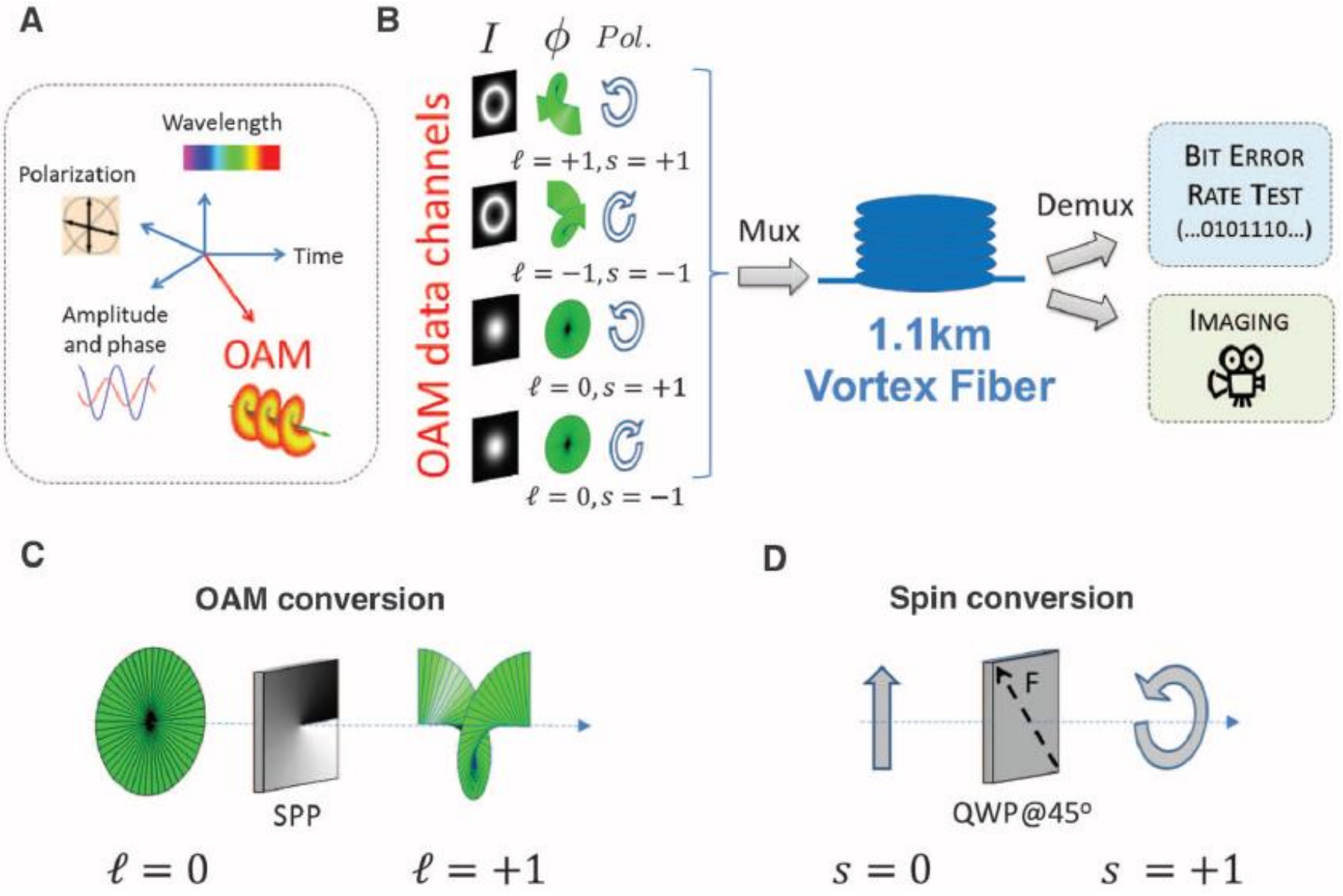
Vortex of charge *m* breaks into *m*+1 bright stripes

Expt.

Theory

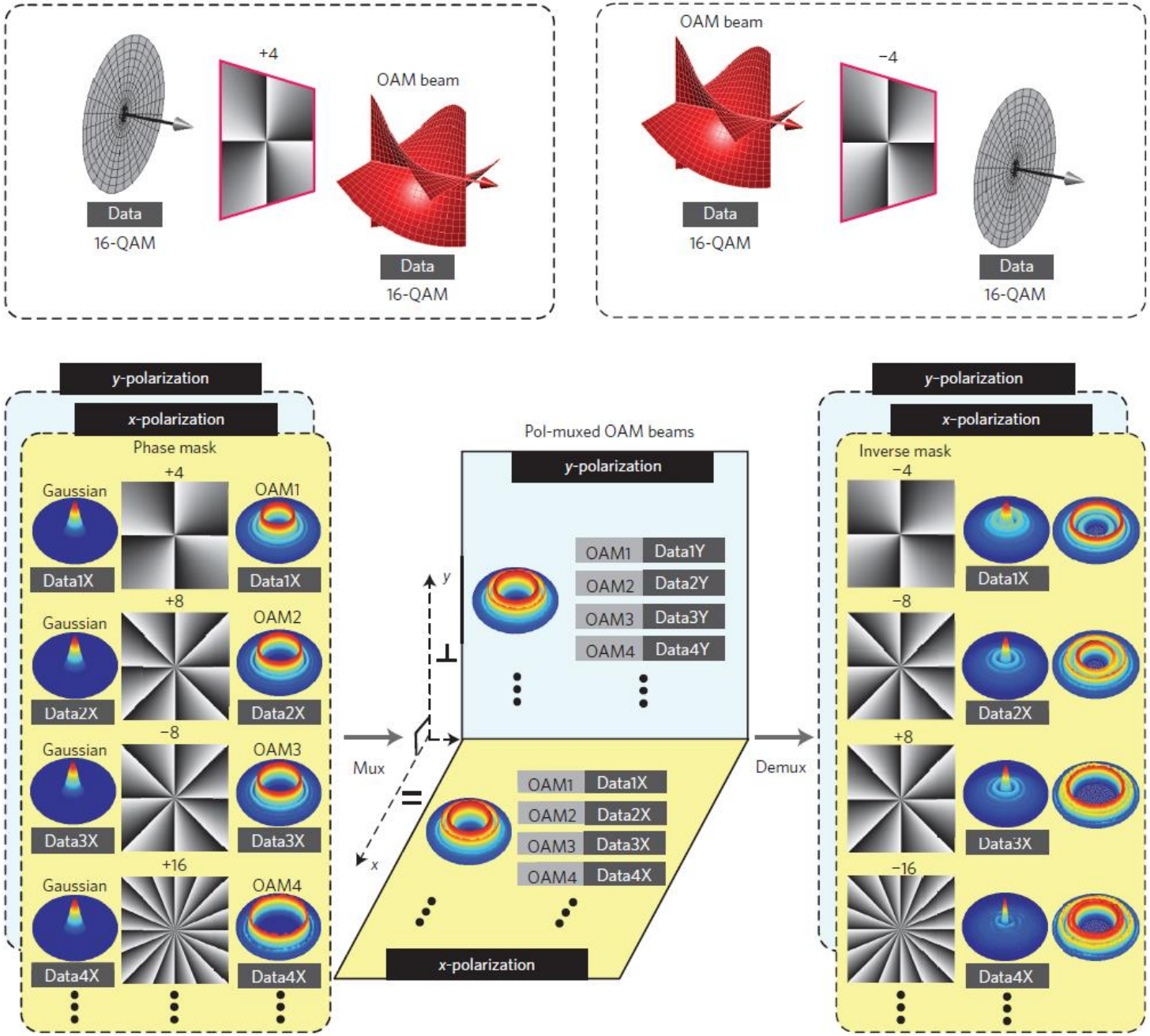
P. Vaity, J. Banerji, RPS, Phys. Lett A 377, 1154 (2013)

Terabit-Scale OAM Mode Division Multiplexing in Fibers



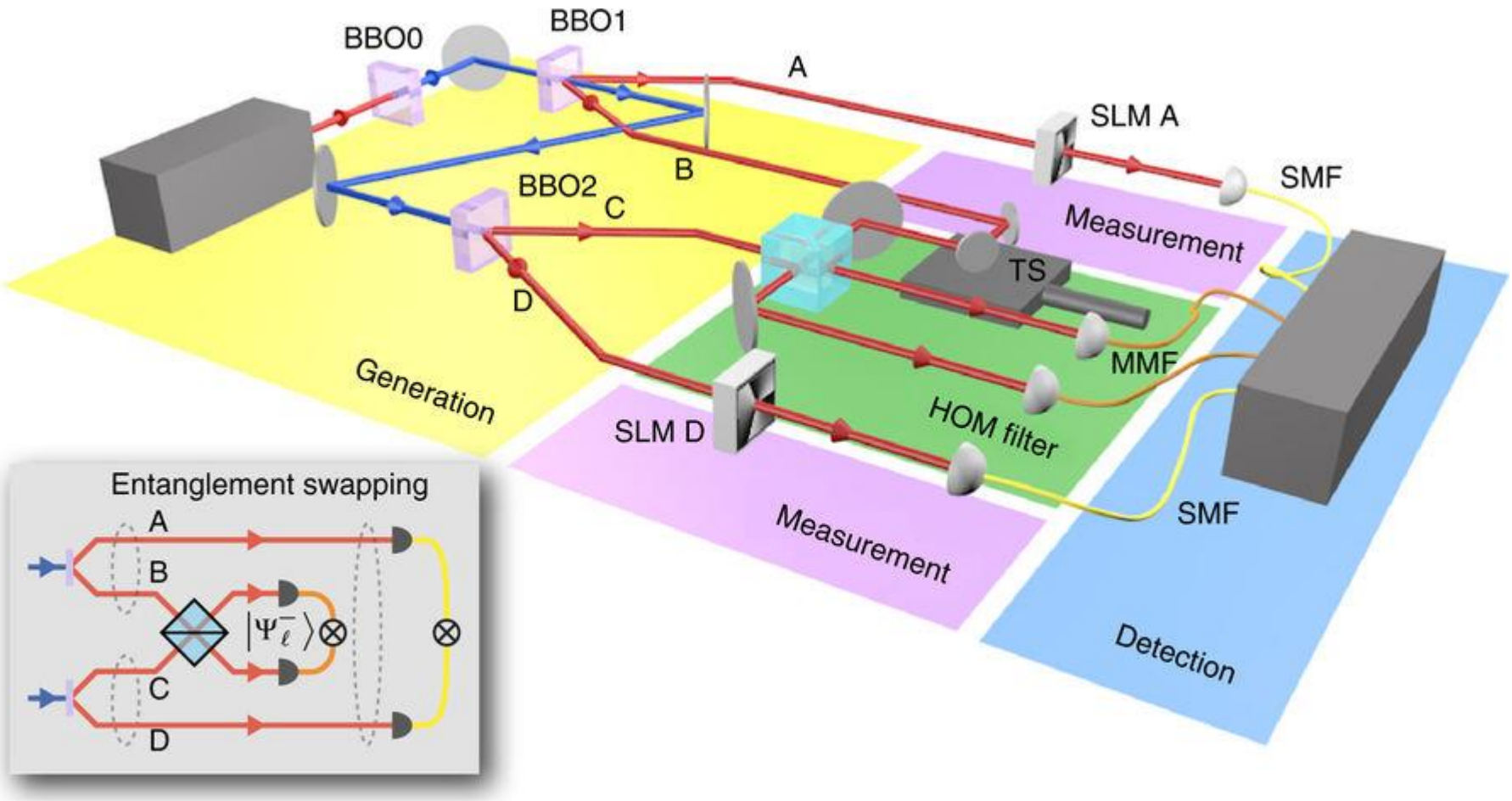
SCIENCE VOL 340 28 JUNE 2013 1545-1548

Terabit free-space data transmission employing OAM multiplexing



NATURE PHOTONICS
Vol. 6, 488-496 (2012)

Simultaneous entanglement swapping of multiple orbital angular momentum states of light, Zhang et al, *Nature Communications* 8, Article number: 632(2017)



Generation of non-separable state and scattering

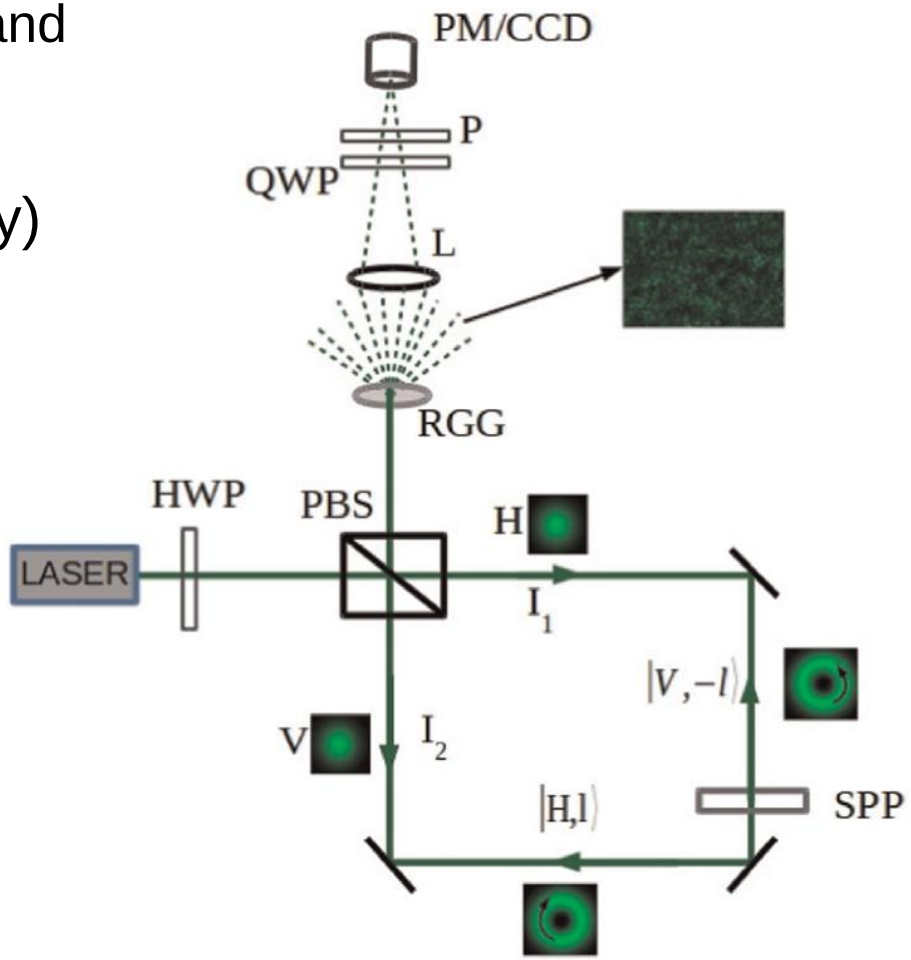
• A non-separable state of polarization and OAM for a light beam can be written as

$E(x, y) = \widehat{e_x}\, LG_0^m(x, y) + \widehat{e_y}\, LG_0^{-m}(x, y)$

$$|\Psi\rangle = |H\rangle|m\rangle + |V\rangle|-m\rangle$$

Optics Communications, 355 (2015) 301–305

Applied Physics Letters, 107, 021104 (2015)



Experimental setup for the generation and scattering of non-separable state of polarization and OAM. HWP – half wave plate, QWP – quarter wave plate, P – polarizer, L – lens with focal length 15 cm, CCD – charge coupled device (camera), PM – power meter, PBS – polarizing beam splitter

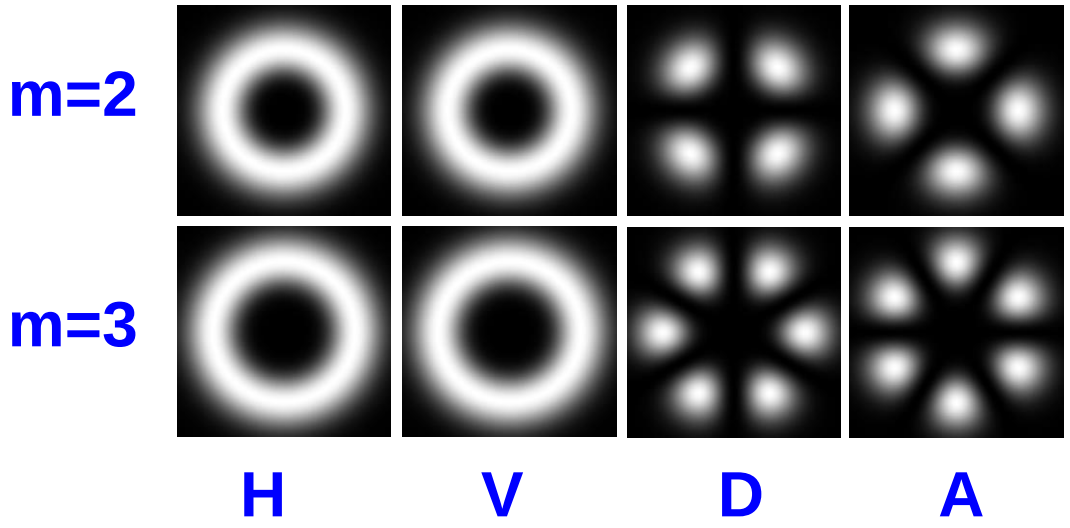
Non-separable states of light …..

•Projection of this non-separable state of light beam to an arbitrary polarization

$$\left|\Psi\right\rangle_P = \cos(\theta)\left|H\right\rangle + \sin(\theta)\, e^{i\phi}\left|V\right\rangle$$

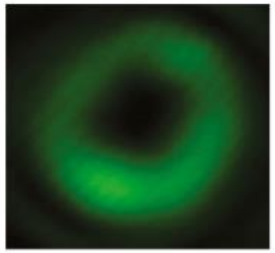
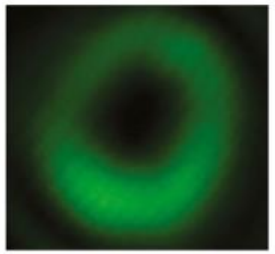
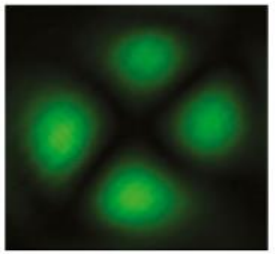
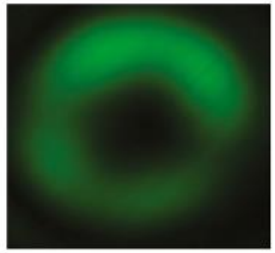
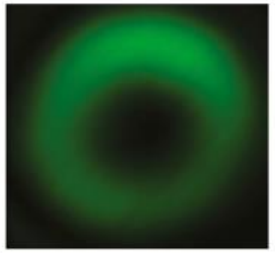
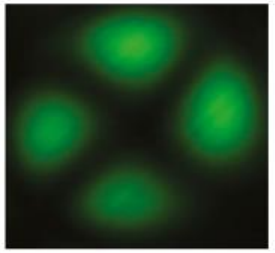
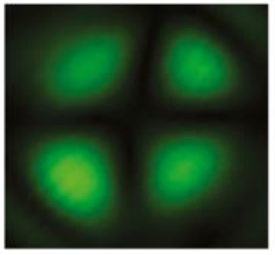
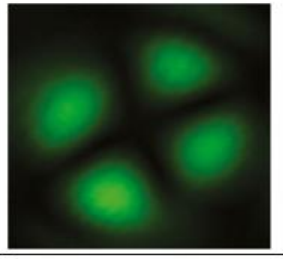
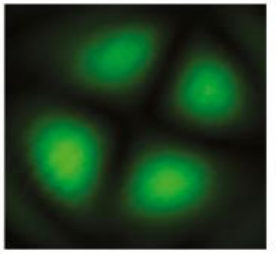
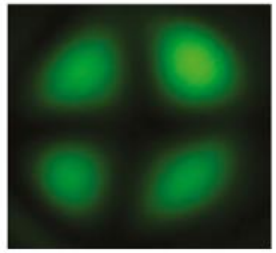
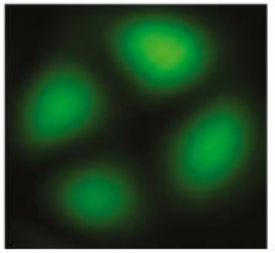
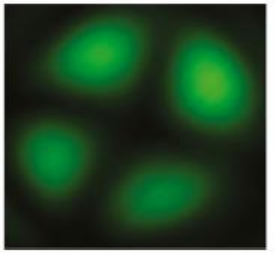
gives

$$\left|\Psi\right\rangle_{OAM} = \cos(\theta)\left|m\right\rangle + \sin(\theta)\, e^{i\phi}\left|-m\right\rangle$$



This system can successfully simulate most features of entanglement, but fails to simulate quantum nonlocality

Experimental results

Projections → / Beam ↓	$H \rightarrow \lvert 2\rangle$	$V \rightarrow \lvert -2\rangle$	$D \rightarrow \frac{1}{\sqrt{2}}\left(\lvert 2\rangle + \lvert -2\rangle\right)$
Coherent			
Scattered			
Projections → / Beam ↓	$A \rightarrow \frac{1}{\sqrt{2}}\left(\lvert 2\rangle - \lvert -2\rangle\right)$	$R \rightarrow \frac{1}{\sqrt{2}}\left(\lvert 2\rangle + i\lvert -2\rangle\right)$	$L \rightarrow \frac{1}{\sqrt{2}}\left(\lvert 2\rangle - i\lvert -2\rangle\right)$
Coherent			
Scattered			

Linear entropy and degree of polarization (DOP)

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|+l\rangle + |V\rangle|-l\rangle\right)$$

$$\rho_{ns} = |\psi\rangle\langle\psi|$$

$$\rho_p = \mathrm{Tr}_l\{\rho_{ns}\} = \sum_{i=l,-l} \langle i|\psi\rangle\langle\psi|i\rangle = \frac{I_p}{2}$$

$$S_L = \frac{d}{d-1}(1 - \mathrm{Tr}(\rho^2))$$

$$S_L = 2(1 - \mathrm{Tr}(\rho_p^2)) = 1 \;\rightarrow\; S_L = 1 - DOP^2$$

$$\rho_p = \frac{1}{2}\sum_{i=0}^{3} \sigma_i . \, s_i$$

$$\mathrm{Tr}\{\rho_p^2\} = \tfrac{1}{2}\left(1 + s_1^2 + s_2^2 + s_3^2\right) = \tfrac{1}{2}(1 + DOP^2)$$

$$s_1 = \frac{I_H - I_V}{I}$$

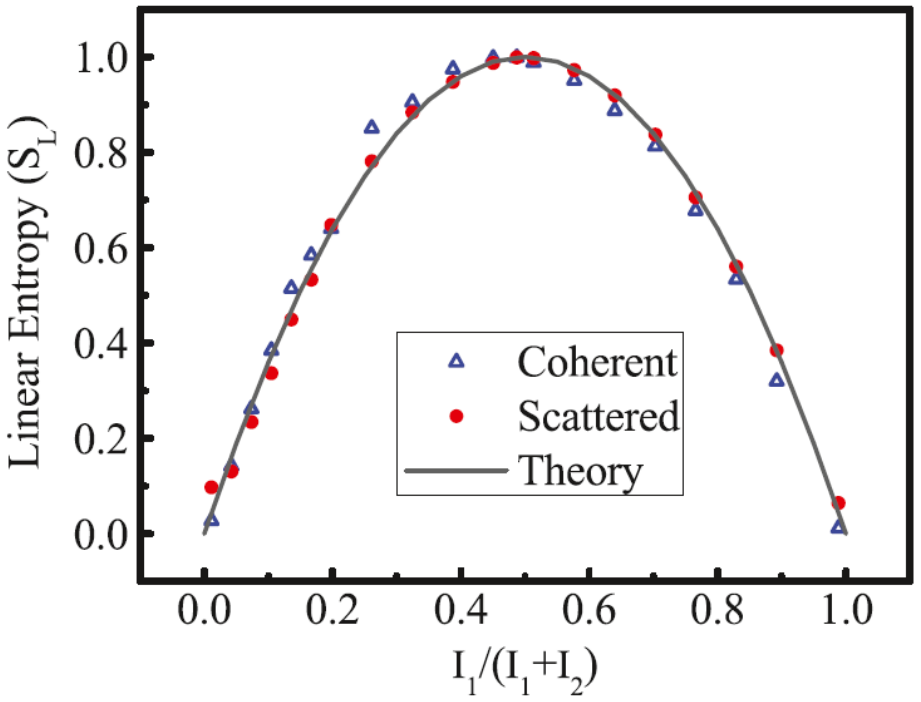
$$s_2 = \frac{I_D - I_A}{I}$$

$$s_3 = \frac{I_R - I_L}{I}$$

In experiment we produce:

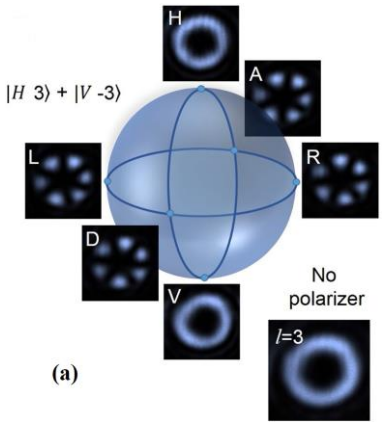
$$|\psi\rangle = \frac{1}{\sqrt{I_1 + I_2}}\left(\sqrt{I_1}|H\rangle|+2\rangle + \sqrt{I_2}|V\rangle|-2\rangle\right)$$

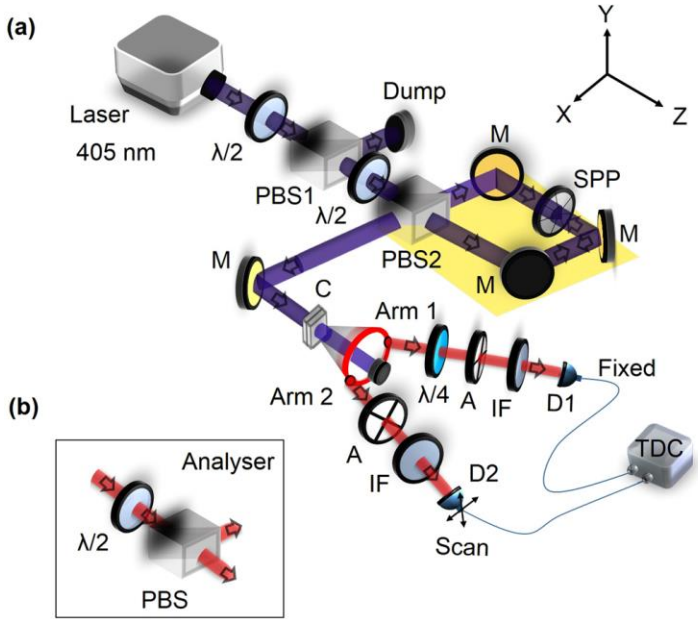
$$S_L = \frac{4I_1I_2}{(I_1 + I_2)^2}$$

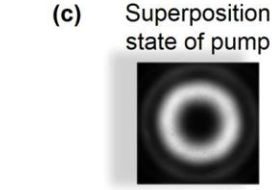


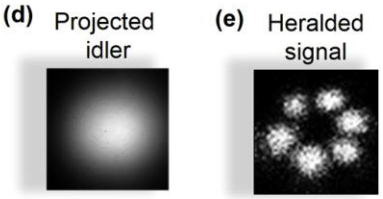
State	Before scattering			After scattering		
	Stokes vectors		DOP	Stoke's vectors		DOP
Separable state (without SPP)	s_1	0.044	0.957	s_1	0.056	0.924
	s_2	0.956		s_2	0.922	
	s_3	−0.02		s_3	−0.026	
Non-separable state (with SPP)	s_1	−0.03	0.001	s_1	0.01	0.001
	s_2	−0.01		s_2	−0.02	
	s_3	0.02		s_3	−0.02	

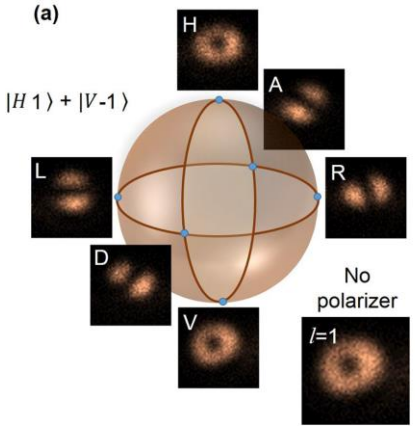
Hybrid entangled photon source

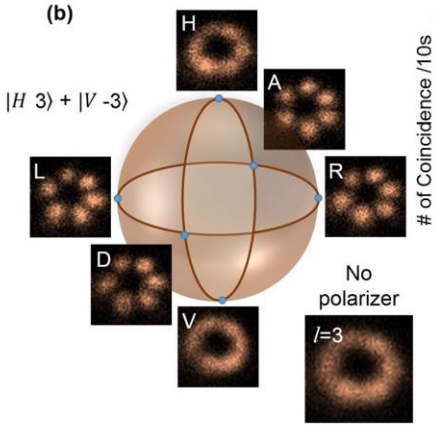


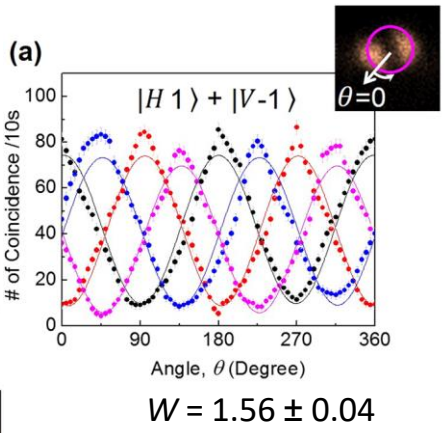




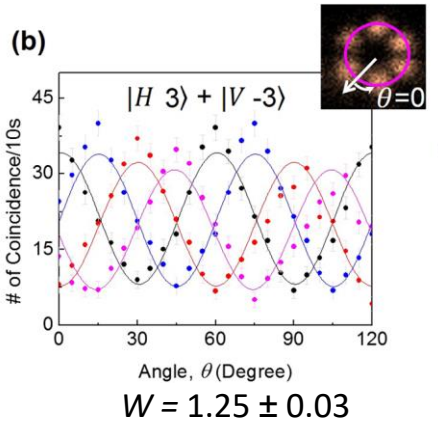




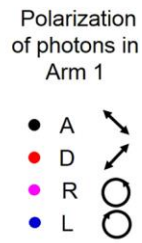




$W = 1.56 \pm 0.04$

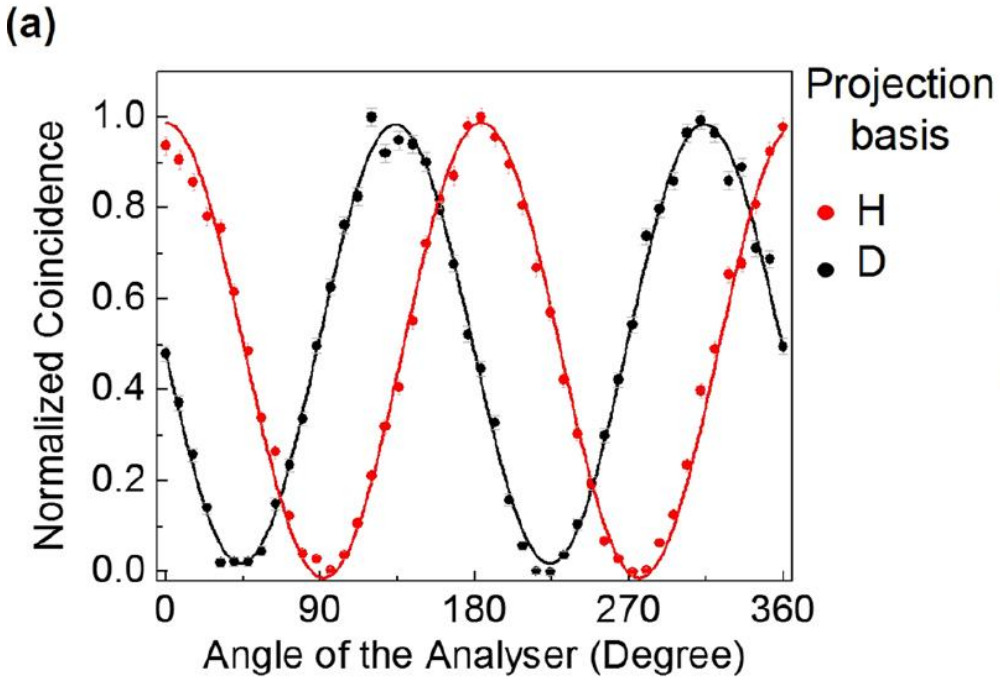


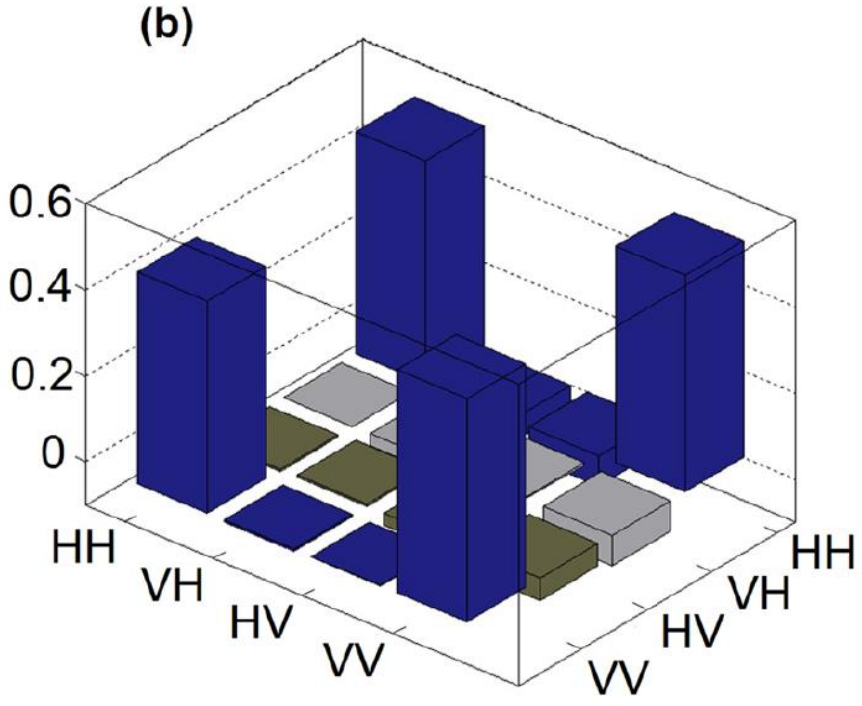
$W = 1.25 \pm 0.03$



Scientific Reports, 7, 7331 (2017)

Verifying polarization entanglement when SPP is not present





Visibility | H/V=99.70±0.03%
D/A=96.90±0.04%

Bell's parameter, S=2.73±0.04
State fidelity, F=0.992

Acknowledgements

All the members of the group:

Past and present