Making correlations between photonic orbital angular momenta by interaction of optical vortices in a vapor

Project supervised by Laurence Pruvost

vortex+light in the style of Klimt (AI generated)

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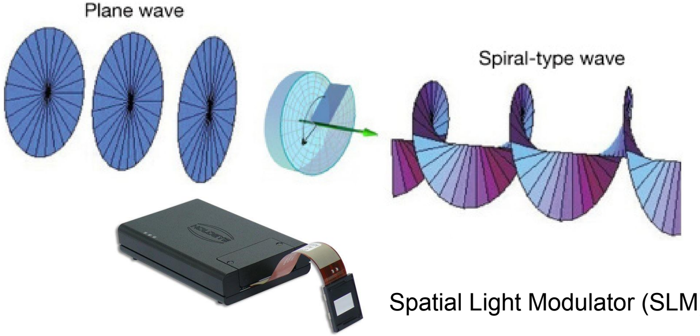
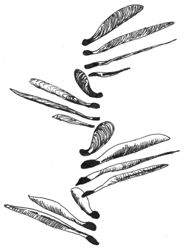
Orbital Angular Momentum of the optical vortex

- Optical vortices are laser beams with an helical wavefront. They carry a quantum variable, the **OAM**[1] ℓ, being a relative integer. It is related to the phase and the handedness

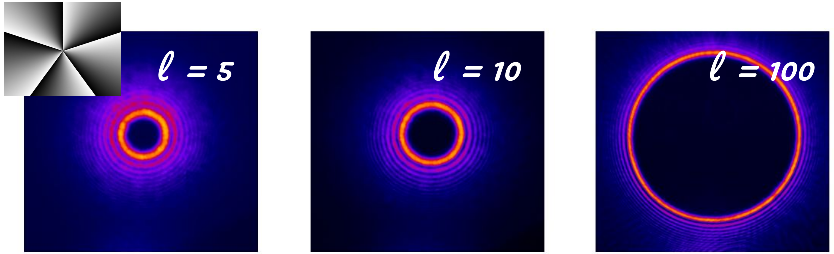
- To generate one, a laser beam propagates through an object that has an helical singularity



Spatial Light Modulator (SLM)



- Anular intensity of a vortex images[2] recorded with a CCD camera



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[1] L. Allen et al., Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes, Phys.Rev. A **45**, 8185, 1992

[2] A. Chopinaud. Atomes et vortex optiques, Physique Atomique.Université Paris Saclay (2018)

OAMs correlations study

The OAM is used in several applications such as for quantum memories[1] or entanglement[2]…

We use this variable to make and study OAMs entanglement
→ Thanks to a non-linear effect, it is possible to build correlations between pairs of OAMs

Plan

- **The non-linear effect: Spontaneous Four Wave Mixing**
- **Principle of the model**
- **Comparison to experimental data**
- **Prediction for next experiment**

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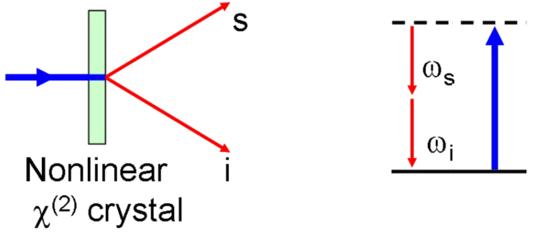
1 : A. J. F. de Almeida et al., Storage of orbital angular momenta of light via coherent population oscillation, Opt. Lett. **40**, 2545 (2015)
2 : Mair A, Vaziri A, Weihs G, Zeilinger A. Entanglement of the orbital angular momentum states of photons. Nature. **19**, 412 (2001)

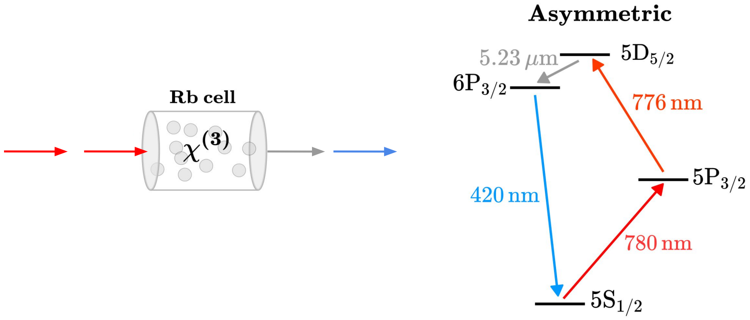
Entangled photon sources

Emission of photons pairs

- **Spontaneous Down Conversion (SPDC)**
  - In crystals
  - One input laser (continuous or pulsed)
  - To be spectrally selective, the crystal must be well prepared



- **Spontaneous Four Wave Mixing (SFWM)**
  - In vapors
  - Two input lasers (continuous or pulsed)
  - Realizable with different atomic schemes



We realize SFWM with vortex beams to study both:

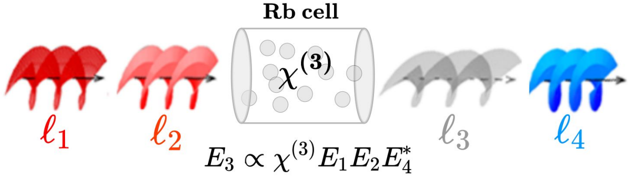
- colors entanglement
- OAMs entanglement

ℓ = OAM

OAMs and Spontaneous Four Wave Mixing

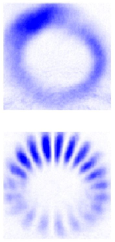
- If the two input colors carry an OAM, the output vortices have **correlated OAMs**
- SFWM allows an unambiguous study of the output OAMs
- The blue light intensity and phase have been measured in experiments done in Glasgow^1, Williamsburg^2 and Paris^3

Develop a model to study the output



$$E_3 \propto \chi^{(3)} E_1 E_2 E_4^*$$

1



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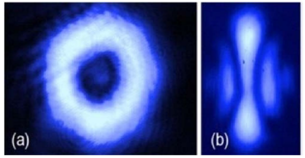
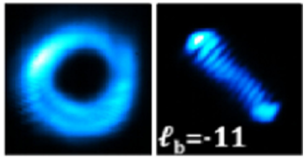


3



1: G. Walker, A. S. Arnold, and S. Franke-Arnold, Trans-Spectral Orbital Angular Momentum Transfer via Four-Wave Mixing in Rb Vapor, Phys. Rev. Lett.**108**, 243601 (2012)
2: A.M. Akulshin, I. Novikova, E.E. Mikhailov, S.A. Suslov, and R.J. McLean. "Arithmetic with optical topological charges in stepwise-excited Rb vapor, Opt. Lett.**41**, 1146 (2016)
3 : A. Chopinaud, M. Jacquey, B. Viaris de Lesegno, and L.Pruvost. High helicity vortex conversion in a rubidium vapor. Phys. Rev. A **97**, 063806 (2018)

The output is expressed as $\sum_{\ell_3,\ell_4} c(\ell_3,\ell_4)\times LG_{p_3}^{\ell_3}\times LG_{p_4}^{\ell_4}$

How the total OAM is distributed?

Laguerre-Gauss basis

Hypothesis: $\ell_1 \geq 0$, $\ell_2 \geq 0$ and $p_1 = p_2 = 0$

Conservation of the total **OAM** and the **Gouy phase**

$$\left.\begin{aligned} L &= \ell_3 + \ell_4 = \ell_1 + \ell_2 \\ |\ell_3| + |\ell_4| + 2p_3 + 2p_4 &= |\ell_1| + |\ell_2| \end{aligned}\right\}$$

All radial number ***p*** are null

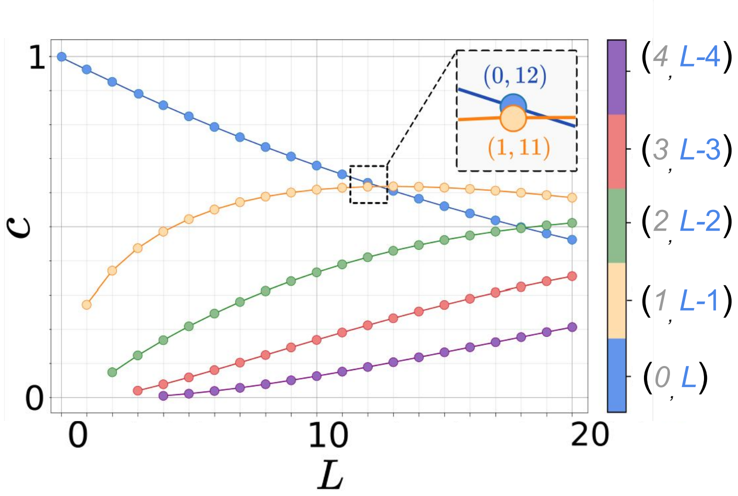
***L*+1** pairs (ℓ_3, ℓ_4) at the output:

(0,*L*), (1,*L*-1), (2,L-2) … (L-1,1), (*L*,0)

Boyd's criterion assumption: beams have same Rayleigh range

$$c(\ell_3, \underbrace{L-\ell_3}_{\ell_4}) \propto \iint LG^{\ell_1} LG^{\ell_2} LG^{\ell_3} LG^{\ell_4} r dr d\theta$$

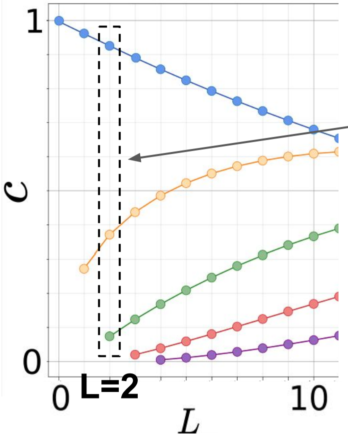
(overlap of 4 modes)



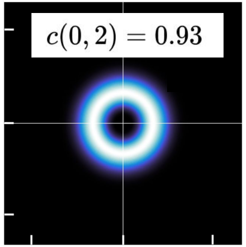
- Each curve represents a family of pairs (ℓ_3, ℓ_4)
- With ***L*** increasing**,** there is more than one pair at the output

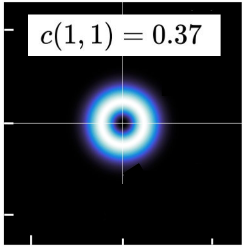
Blue output for L=2

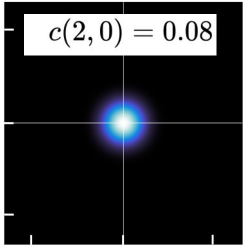
$$E_4 = \sum_{\ell_4}^{2} c(L-\ell_4,\ell_4) \times LG^{\ell_4}$$



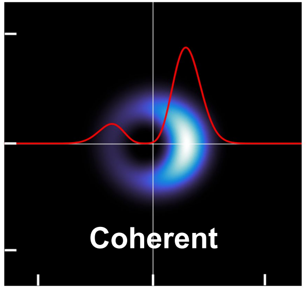
Three modes at the output, one predominant



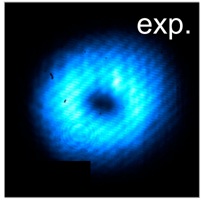


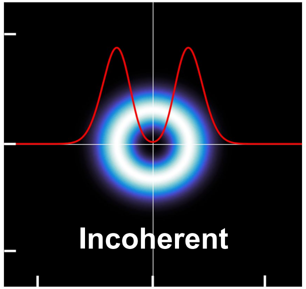


The **coherent** sum gives a crescent moon intensity



Annular intensity if **incoherent**

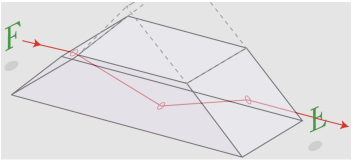




Comparison to experiment for L=2

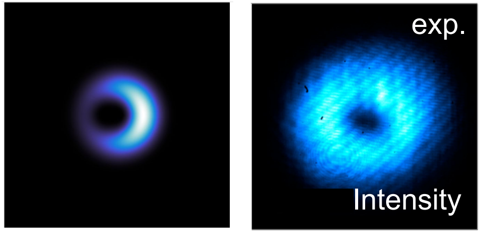
Does information on the OAM remains?

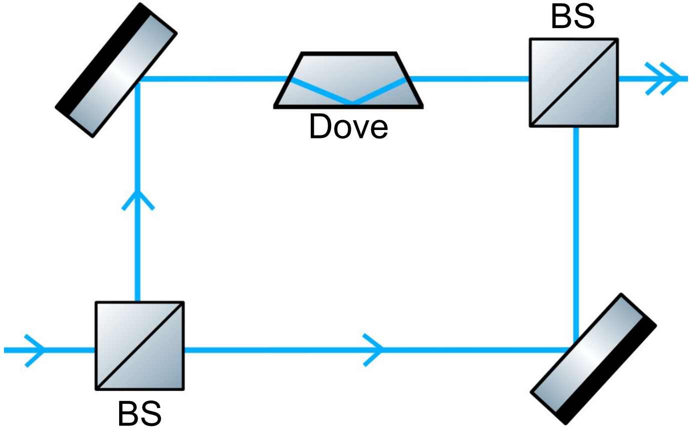
A Dove prism return the field

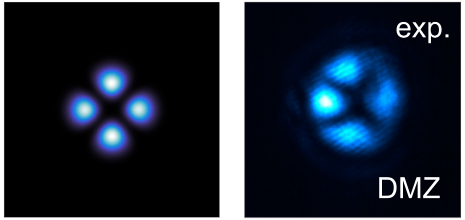


For single OAM beams, we use a Mach-Zehnder interferometer added by a Dove prism (DMZ)

The number of radial interference fringes is equal to twice the OAM



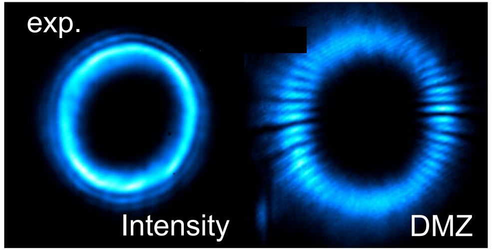




4 fringes → ℓ_4 **= 2**

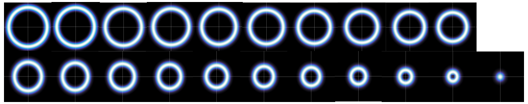
Experimental data from A. Chopinaud. Atomes et vortex optiques, Physique Atomique.Université Paris Saclay (2018)

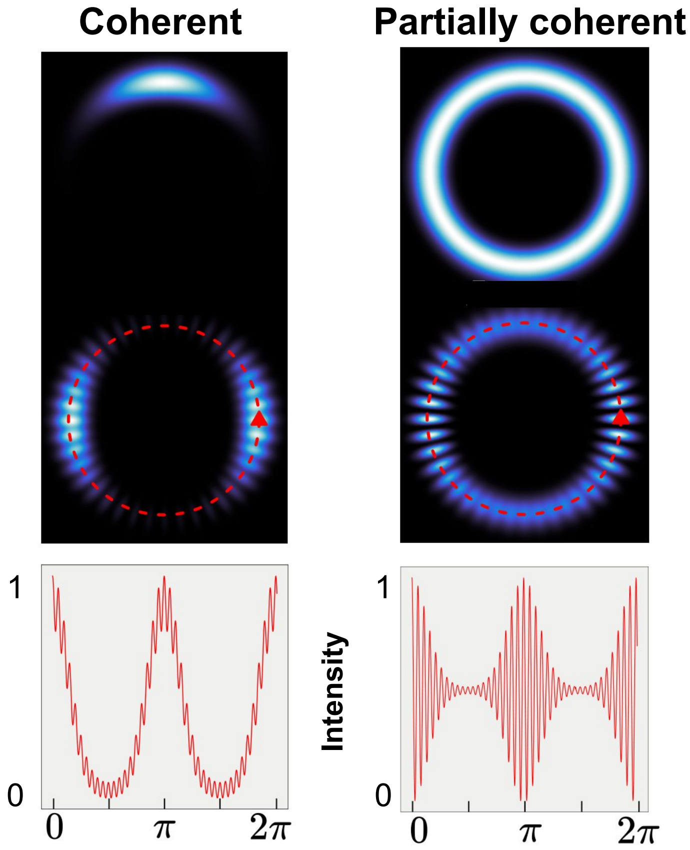
If L=20 at input: 21 modes in output



- It becomes hard to count the fringes
- Theory-experiment agreement
- **Explained by a partially coherent superposition of modes?** Work in progress

Intensity of the 21 modes involved

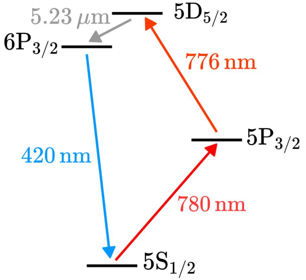


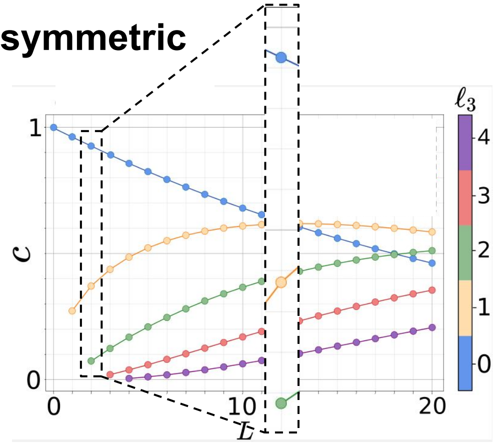


Prediction for the symmetric scheme

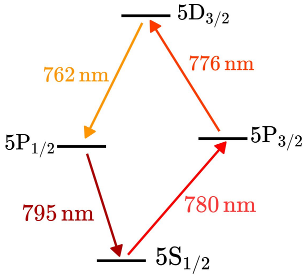
The distribution of the OAM is equiprobable

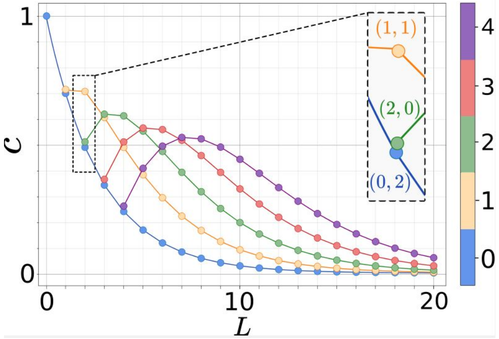
Asymmetric

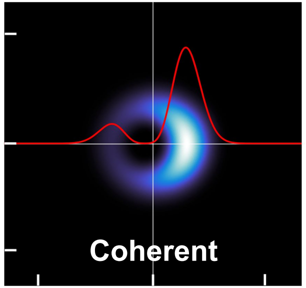


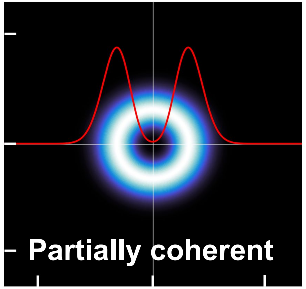


Symmetric (Strong correlations)

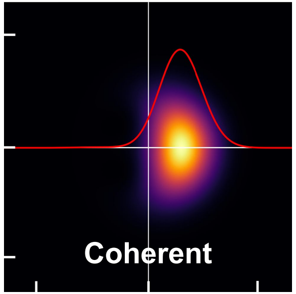


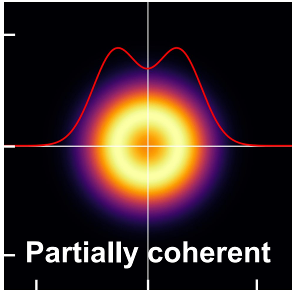



Coherent


Partially coherent

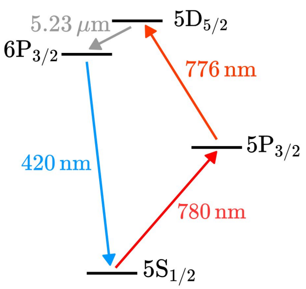
L=2

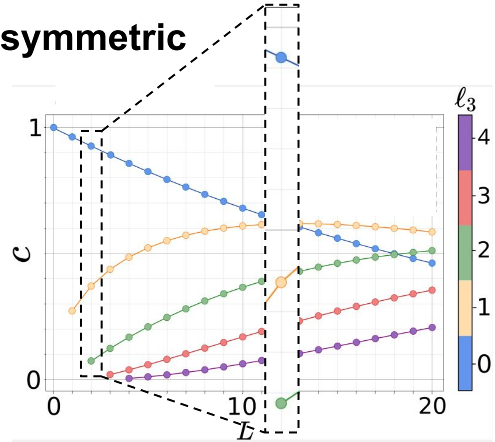

Coherent

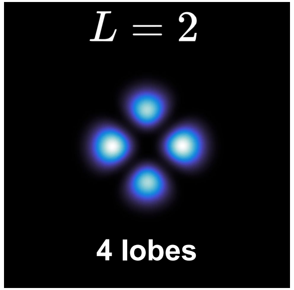

Partially coherent

Different expected signatures

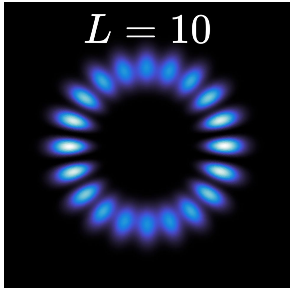
Asymmetric



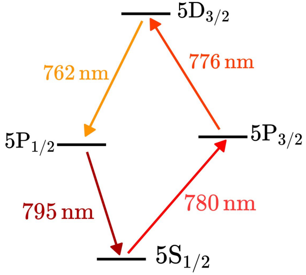


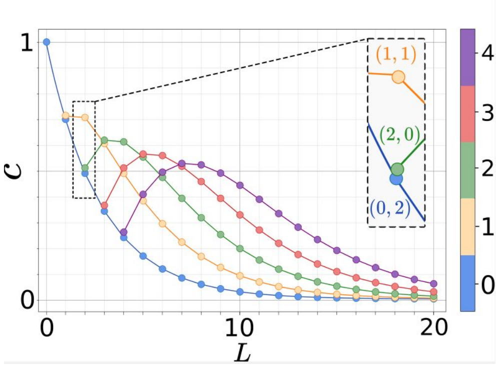


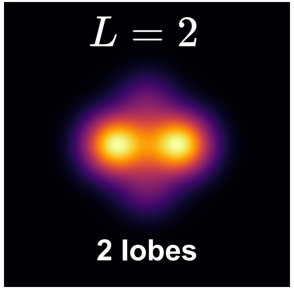
4 lobes



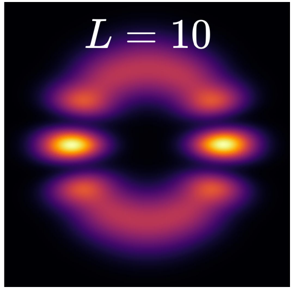
Symmetric (Strong correlations)







2 lobes



Conclusion

- Even with partially coherence, signature of OAM correlations between the pairs (ℓ_3, ℓ_4) remain (in progress)
- The model explains the experimental results
- And also for prediction !

Outlook

- About the experiment:
  - detect the infrared beam
  - apply multimode inputs
  - realize the symmetric scheme
- To try configurations where ℓ_1 *and* ℓ_2 have opposite handedness

Merci beaucoup :)


Myrann Abobaker


Laurence Pruvost