Photonic Orbital Angular Momentum for quantum inter-playing with atoms and entanglement

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Abstract. Photonic Orbital Angular Momentum (OAM) is becoming a pertinent quantum variable for atom-light interaction, in particular for non-linear interaction which leads to photon entanglement and OAM-entanglement. With two 4-levels atomic schemes, we show that Four Wave Mixing addressed by vortex beams leads to very different OAM-entanglement especially for large OAM values.

1 Introduction

The photon carries several quantum variables, among them, the Orbital Angular Momentum (OAM) [1]. Atom-light interaction involving OAM can lead to entanglement between OAM [3] and, because the OAM explores a wide ensemble (the signed integer one) it permits multiple entanglement. Such possibility is of interest for quantum technologies.

The OAM is associated to an helical shape of the phase. An optical vortex carries such a phase [2]. An image of the vortex beam is the endless screw if the OAM equals one, or a fusilli pasta if the an OAM equals 2. The topological point located at the centre of the vortex beam is crucial and the related question is to understand its role in the interaction with matter and how it generates OAM-entanglement.

Vortex beams are not too difficult to prepare, for example by phase shaping a Gaussian beam by using spatial light modulators. So, we are able to generate vortex beams like Laguerre-Gaussian (LG) modes, carrying large OAM.

Creating entanglement relies in general on non-linear processes. For our purpose we use Four Wave Mixing (FWM) in an atomic vapor addressed with two vortex beams and which produces a photon pair as output. Phase-matching imposes OAM conservation and contributes to OAM entanglement at the output. But it depends also of the chosen 4-levels atomic schemes.

2 Four Wave Mixing in rubidium with OAM beams

We consider the two 4-levels schemes of Fig.1 where Rb atom is excited from its fundamental level to the 5D one with two lasers (780 and 776 *nm*). Then, it decays to its ground state by emitting a photon pair, whose colors depend on the chosen 4-level scheme, either an infrared photon and a blue one (5320 and 420 *nm*) or two NIR photons (762 and 795 *nm*).

The model and the experiment [4, 5] allow us to examine how the total input OAM, $L = \ell_1 + \ell_2$, is distributed in the pair and how the output OAMs , ℓ_3, ℓ_4 are correlated. We examine the excitation by two collinear input vortex beams as shown in Fig.1(c).

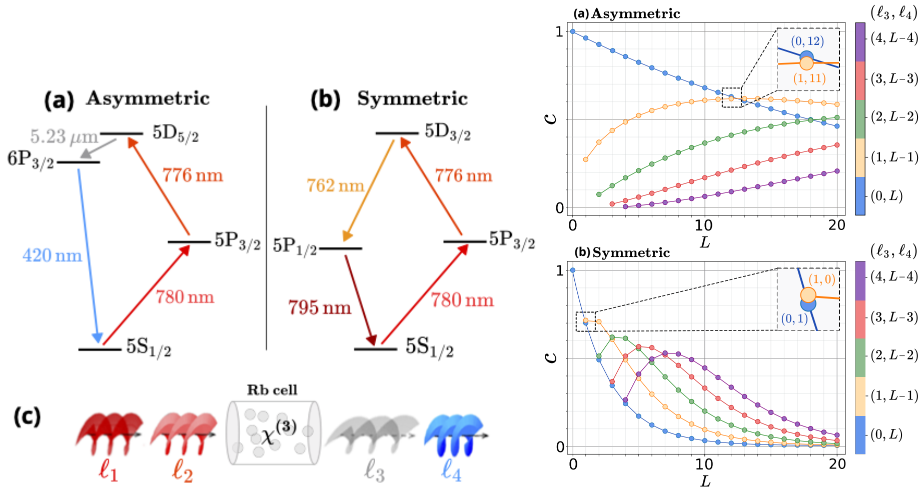

Figure 1. On the left : (a) asymmetric (a) and (b) symmetric Rb 4-levels schemes for FWM for pair generation, (c) principle of the experiment. On the right : (a) probability amplitude OAM of the blue (420 *nm*) in the output pair, and (b) of the NIR (795 *nm*).

3 OAMs in the output pair

The probability to produce OAM-pair is computed versus the total OAM input L, in the case of vortex beams same handedness OAMs ($\ell_1.\ell_2 > 0$). We use a decomposition of the output waves over a LG mode basis, to evaluate the overlap of the four modes involved in the FWM. In addition, phase-matching about OAM and Gouy phase provides selection rules so limiting the number of allowed OAM pairs.

Our results show that L is shared by the two outputs, with sharing rules strongly dependent on the 4-levels scheme (Fig.1). In particular a superposition with equal amplitude probabilities appears for $L = 12$ in the asymmetric case while it occurs at $L = 1$ in the symmetric one. This indicates that the entanglement concerns many modes in the symmetric case and so a multiple entanglement. The study for opposite handedness OAMs ($\ell_1.\ell_2 < 0$) is in progress.

4 Conclusion

FWM is known to generate photon pairs. If addressed by vortex beams it creates OAM pairs and entanglement between them. Our study shows that the OAM pairs depend on the chosen atomic scheme, leads to examine entanglement in other atomic schemes and could open to Bell states with OAM.

References

[1] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, J. P. Woerdman, Phys. Rev. A 45, 8185 (1992)
[2] P. Coullet, L. Gil, F. Rocca, Opt. Com. 73, 403, (1989)
[3] A. Mair, A. Vaziri, G. Welhs, and A. Zeilinger, Nature 412, 313 (2001)
[4] A. Chopinaud, M. Jacquey, B. Viaris de Lesegno, L. Pruvost, Phys. Rev. A. 97, 063806 (2018)
[5] M. Baker-Rasooli, L. Pruvost, submitted