Remote creation of hybrid entanglement between particle-like and wave-like optical qubits

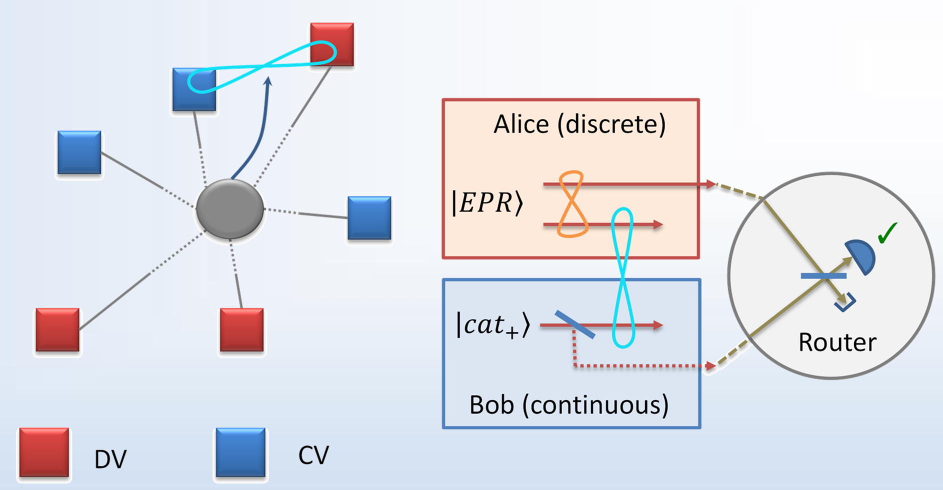
Olivier Morin, Kun Huang, Jianli Liu, Hanna Le Jeannic, Claude Fabre, Julien Laurat
Laboratoire Kastler Brossel, Université P. et M. Curie, ENS, CNRS, 4 Place Jussieu, 75005 Paris, France

Laboratoire Kastler Brossel
Physique quantique et applications

Introduction

The wave-particle duality of light has led to two different encodings for optical quantum information processing. Several approaches have emerged based either on particle-like discrete-variable states [1], e.g. finite-dimensional quantum systems, or on wave-like continuous-variable states [2], e.g. infinite-dimensional systems. Here, we demonstrate the first measurement-induced generation of hybrid entanglement between optical quantum bits of these different types [3], located at distant places and connected by a lossy channel.

Beyond its fundamental significance for the exploration of entanglement and its possible instantiations, our optical circuit opens the promises for heterogeneous network implementations, where discrete and continuous-variable operations and techniques can be efficiently combined [2].



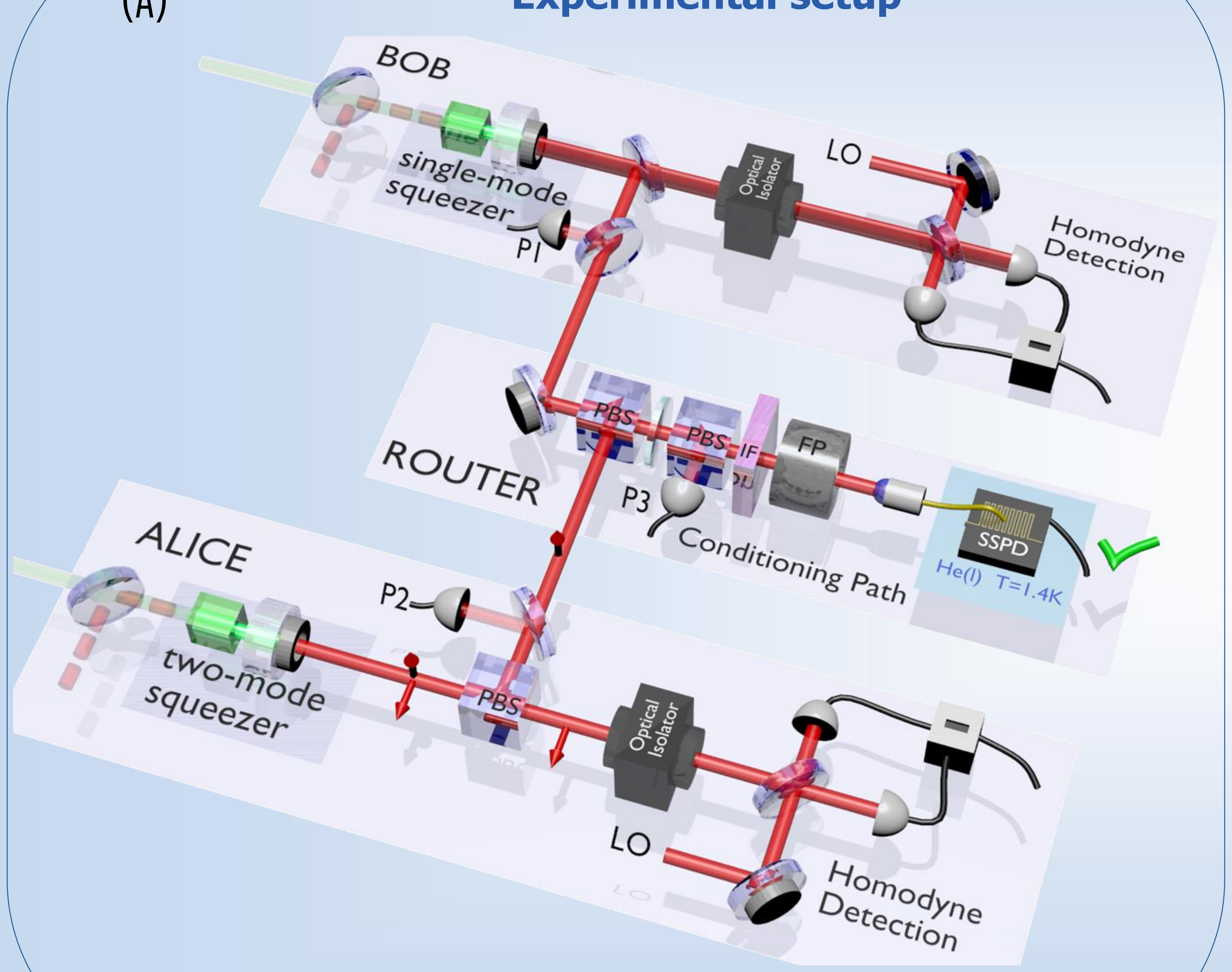
Heterogeneous network

	Qubit	Qumode
Degree of freedom	Discrete	Continuous
Hilbert space	Finite dimension	Infinite dimension
Encoding	Photon number	Quadrature components
Representation	Matrix density	Wigner function
Measuring	Photon counter	Homodyne detector
Features	✗ Low efficiencies ✗ Probabilistic ✓ Easy to process ✓ High fidelities	✓ High efficiencies ✓ Deterministic ✗ Difficult to process ✗ Limited fidelities

Hybrid Optical Approach
- The best of both sides for further capabilities -

Measurement-induced generation of hybrid entanglement

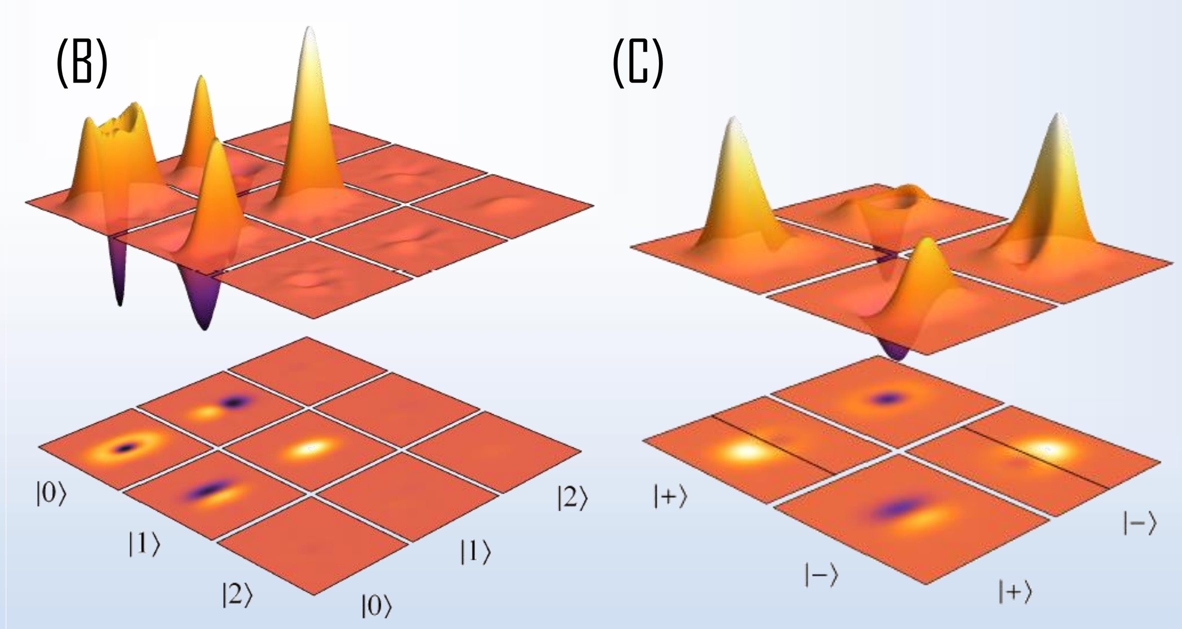
(A) Experimental setup



$|1\rangle_A|\mathrm{cat}_+\rangle_B + e^{i\phi}|0\rangle_A|\mathrm{cat}_-\rangle_B$

(A) Alice and Bob locally generate the required resources by using continuous-wave optical parametric oscillators operated below threshold [4]. A two-mode squeezer and a single-mode squeezer are used respectively on Alice's and Bob's node. A small fraction of Bob's squeezed vacuum is tapped (3%) and mixed at a central station to the idler beam generated by Alice. The resulting beam is then frequency filtered and detected by a superconducting single photon detector (SSPD). Given a detection event, which heralds the generation, the entangled state is characterized by two high-efficiency homodyne detections in the optimal temporal modes [5].

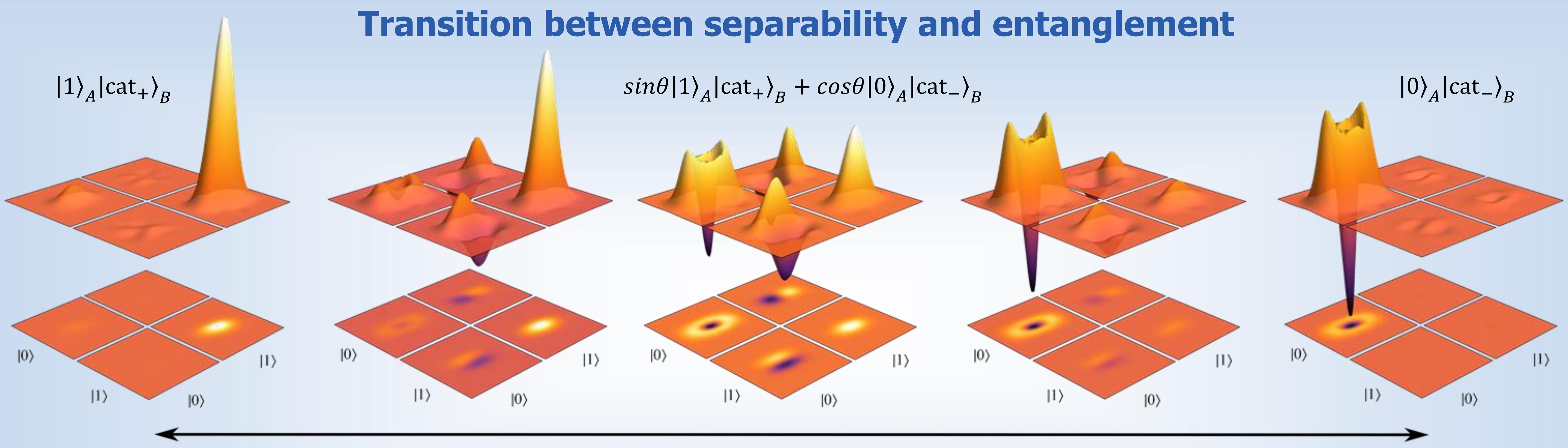
Two-mode quantum state tomography



$|0\rangle_A|\mathrm{cat}_-\rangle_B - |1\rangle_A|\mathrm{cat}_+\rangle_B$ $\quad$ $|-\rangle_A|\alpha\rangle_B - |+\rangle_A|-\alpha\rangle_B$

(B) The relative phase is set to $\varphi = \pi$ and the beam splitter ratio in the central station is adjusted to generate a maximally entangled state. The figure gives Wigner functions associated with the reduced density matrices $\langle k|\hat{\rho}|l\rangle$ with $k, l \in \{0,1,2\}$ after correction for detection losses ($\eta = 85\%$). For components with $k \neq l$, the plots give the real part of $\langle k|\hat{\rho}|l\rangle$ (back corner) and the imaginary part of $\langle l|\hat{\rho}|k\rangle$ (front corner). **(C)** Wigner functions associated with the reduced density matrices $\langle k|\hat{\rho}|l\rangle$ with $k, l \in \{+,-\}$, where $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$. A fidelity $77 \pm 3\%$ is obtained with the target state with $|\alpha| = 0.9$.

Transition between separability and entanglement



The relative phase is set to $\varphi = 0$ and the beam splitter ratio at the central station is tuned. For each generated state, the negativity $\mathcal{N}$ is computed, showing the transition from separable to maximally entangled state and back to separable. The two extreme states result indeed from heralding events coming only from Alice's node or Bob's node. The figure in the middle provides the balanced case, which is very similar to the one provided in previous block (figure B) but with an opposite phase, as can be seen in the off-diagonal terms. The two other blocks give examples of intermediate ratios, showing the building up of the coherences.

QScale
chist-era
erc HybridNet

References:

1. P. Kok et al., "Linear optical quantum computing with photonic qubits", Rev. Mod. Phys. **79**, 135-174 (2007).
2. P. van Loock, "Optical hybrid approaches to quantum information", Laser Photon. Rev. **5**, 167-200 (2011).
3. O. Morin et al., "Remote creation of hybrid entanglement between particle-like and wave-like optical qubits", arXiv: 1309.6191 (2013).
4. O. Morin et al., "A high-fidelity single-photon source based on a type-II optical parametric oscillator", Opt. Lett. **37**, 3738 (2012).
5. O. Morin et al., "Experimentally accessing the optimal temporal mode of traveling quantum light states", Phys. Rev. Lett. **111**, 213602 (2013).

UPMC SORBONNE UNIVERSITÉS
IUF
CNRS