A Versatile Source of Polarization-Entangled photons

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Abstract:

We propose a method for the generation of a large variety of polarization-entangled photon states within the same experimental setup. Starting with N uncorrelated photons, emitted from N arbitrary single photon sources, and using linear optical tools only, we demonstrate the creation of all symmetric states, e.g., GHZ- and W-states, as well as all (symmetric and non-symmetric) total angular momentum eigenstates of the N-qubit compound [1].

References:

[1] A. Maser *et al.*, Phys. Rev. A **81**, 053842 (2010)

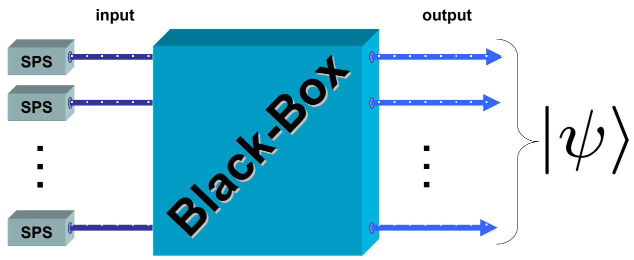
[2] T. Bastin *et al.*, Phys. Rev. Lett. **102**, 053601 (2009)

[3] C.Thiel *et al.*, Phys. Rev. Lett. **99**, 193602 (2007)

[4] A. Maser *et al.*, Phys. Rev. A **79**, 033833 (2009)

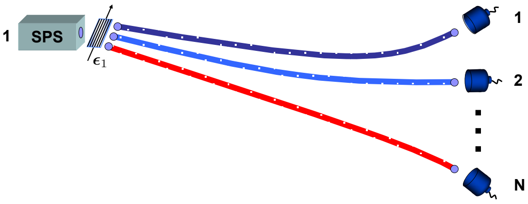
I. Idea: Source independent photon entanglement

A Black-Box which works with different single photon sources (SPS)



II. Distribution of a photon into several modes

Derivation of the mode population operator



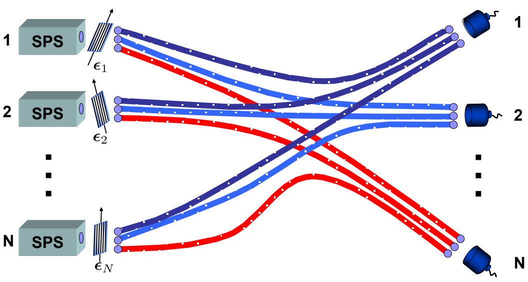
We consider a single photon emitted by source 1. Its wave function compatible with a successful measurement at any of N detectors is given by:

$$|\psi\rangle = \hat{\hat{P}}_1 |\mathrm{vac}\rangle$$
$$\hat{\hat{P}}_1 = \sum_{m=1}^{N} e^{i\phi_{1,m}} \left(\alpha_1 \hat{a}^{\dagger(m)}_{\boldsymbol{\sigma}^+} + \beta_1 \hat{a}^{\dagger(m)}_{\boldsymbol{\sigma}^-}\right),$$

with $\phi_{1,m}$ being the optical phase accumulated on the way from source 1 to detector m (m = 1,…, N), and α_1 and β_1 defined through the polarizer orientation $\boldsymbol{\epsilon}_1 = \alpha_1\boldsymbol{\sigma}^+ + \beta_1\boldsymbol{\sigma}^-$.

III. Generation of entangled multi photon states

Application of mode population operator in case of N sources



We consider only cases where one photon is registered at each detector. To ensure this condition we have to change the operator $\hat{\hat{P}}_1$ to $\hat{P}_1$, where $\hat{P}_1$ is given by:

$$\hat{P}_n = \sum_{m=1}^{N} e^{i\phi_{n,m}} \left(\alpha_n |\boldsymbol{\sigma}^+\rangle_m \langle 0| + \beta_n |\boldsymbol{\sigma}^-\rangle_m \langle 0|\right).$$

The state $|\psi\rangle$ compatible with a successful detection event of N photons is obtained by applying the N operators $\hat{P}_n,\ n \in 1,\dots,N$ onto the vacuum state:

$$|\psi\rangle = \hat{P}_N \dots \hat{P}_2\hat{P}_1 |\mathrm{vac}\rangle.$$

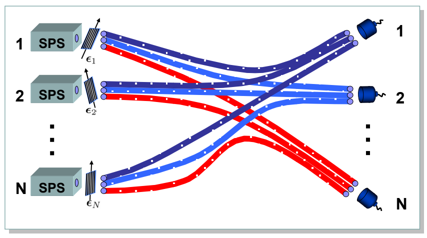
By adjusting the orientation of the polarizers, i.e. the coefficients α_n and β_n , and regulate the optical pathways $\phi_{n,m}$, a wide variety of entangled states can be realized:

- All symmetric states
- All (symmetric and non symmetric) total angular momentum eigenstates

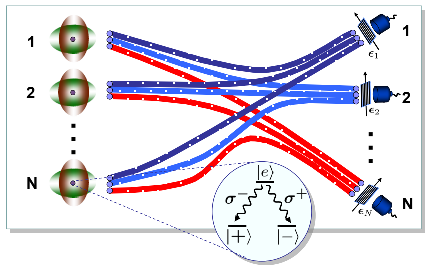
IV. Comparison with generation of entangled states in atomic qubits

Similarity of mode population operator and detection operator allows transfer of results

Photonic qubits



Atomic qubits



State $|\psi_{\mathrm{phot}}\rangle$ compatible with a successful detection event:

$$\hat{P}_n = \sum_{m=1}^{N} e^{i\phi_{n,m}} \left(\alpha_n |\boldsymbol{\sigma}^+\rangle_m \langle 0| + \beta_n |\boldsymbol{\sigma}^-\rangle_m \langle 0|\right)$$
$$|\psi_{\mathrm{phot}}\rangle = \hat{P}_N \dots \hat{P}_2\hat{P}_1 |0,0,\dots,0\rangle.$$

$$\cong$$

State $|\psi_{\mathrm{atom}}\rangle$ compatible with a successful detection event:

$$\hat{D}_m = \sum_{n=1}^{N} e^{i\phi_{n,m}} \left(\alpha_m |-\rangle_n \langle e| + \beta_m |+\rangle_n \langle e|\right)$$
$$|\psi_{\mathrm{atom}}\rangle = \hat{D}_N \dots \hat{D}_2\hat{D}_1 |e,e,\dots,e\rangle.$$

Moving the polarizers from the sources to the detectors allows to generate equivalent states, either encoded in the polarization degrees of freedom of photonic qubits or in the long living ground states of matter qubits.

➡ Direct transfer of results obtained for the generation of entangled states in matter qubits is possible.

V. Transfer of results from entanglement of matter qubits

Generation of all symmetric states and all total angular momentum eigenstates

All symmetric states:

By employing suitable oriented polarizers of elliptical polarization it is possible to generate all symmetric N-qubit states. The orientation of the polarizers is determined by the roots z_i of the polynomial $P(z)$, which is determined by the desired state $|\psi\rangle$ [2]:

$$|\psi\rangle = \sum_{k=0}^{N} c_k |D_N(k)\rangle$$
$$P(z) = \sum_{k=0}^{N} (-1)^{N-k} \binom{N}{k}^{\frac{1}{2}} c_k z^k$$
$$z_i = \frac{\alpha_i}{\beta_i}$$

Hereby, $|D_N(k)\rangle$ is the symmetric N-qubit Dicke state with *k* $|\sigma^-\rangle$ excitations.

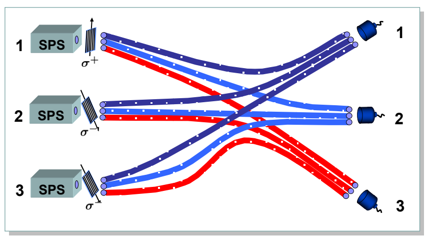
Example: 3-qubit Dicke states

$$|D_3(0)\rangle = |\sigma^+\sigma^+\sigma^+\rangle$$
$$|D_3(1)\rangle = \frac{1}{\sqrt{3}}\left(|\sigma^+\sigma^+\sigma^-\rangle + |\sigma^+\sigma^-\sigma^+\rangle + |\sigma^-\sigma^+\sigma^+\rangle\right)$$
$$|D_3(2)\rangle = \frac{1}{\sqrt{3}}\left(|\sigma^+\sigma^-\sigma^-\rangle + |\sigma^-\sigma^+\sigma^-\rangle + |\sigma^-\sigma^-\sigma^+\rangle\right)$$
$$|D_3(3)\rangle = |\sigma^-\sigma^-\sigma^-\rangle$$

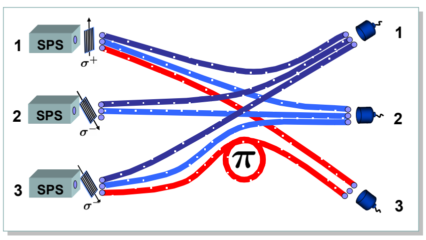
All total angular momentum eigenstates:

For the generation of total angular momentum eigenstates we have to use only circular polarizers. In contrast to the generation of symmetric states we have to make use of the phase degrees of freedom and allow certain photons not to enter certain modes, by removing the corresponding connection. By mimicking the quantum mechanical addition of angular momenta we can derive an algorithm which determines the number of σ^+ and σ^- polarizers, as well as which sources should be connected to which modes [3,4].

Examples:



$$\left|\frac{3}{2};+\frac{1}{2}\right\rangle = \frac{1}{\sqrt{3}}\left(|\sigma^+\sigma^-\sigma^-\rangle + |\sigma^-\sigma^+\sigma^-\rangle + |\sigma^-\sigma^-\sigma^+\rangle\right)$$



$$\left|\frac{1}{2};+\frac{1}{2}\right\rangle = \frac{1}{\sqrt{6}}\left(2|\sigma^-\sigma^-\sigma^+\rangle - |\sigma^-\sigma^+\sigma^-\rangle - |\sigma^+\sigma^-\sigma^-\rangle\right)$$