DARK AND BRIGHT STATES OF LIGHT IN CROSS-CAVITY SYSTEMS

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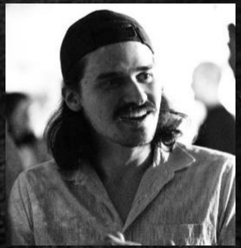
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INTRODUCTION

MATTER

- BRIGHT STATE → MATTER-RADIATION INTERACTION: ABSORBING AND EMITTING PHOTONS
- DARK STATE → INVISIBLE TO RADIATION: COHERENT POPULATION TRAPPING

INTRODUCTION

LIGHT

BRIGHT STATE → INTERACT WITH MATTER

DARK STATE → DOES NOT INTERACT WITH MATTER

INTRODUCTION

DARK STATES OF LIGHT

SINGLE-MODE CASE: UNIQUE DARK STATE

↓

VACUUM STATE

MULTIMODE CASE: INFINITE FAMILY OF DARK STATES

↓

ARBITRARY NUMBER OF PHOTONS

Introduction

Dark states of light (application)

Bright and dark states of light: The quantum origin of classical interference

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Classical theory asserts that several electromagnetic waves cannot interact with matter if they interfere destructively to zero, whereas quantum mechanics predicts a nontrivial light-matter dynamics even when the average electric field vanishes. Here we show that in quantum optics classical interference emerges from collective bright and dark states of light, *i.e.*, entangled superpositions of multi-mode photon-number states. This makes it possible to explain wave interference using the particle description of light and the superposition principle for linear systems.

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Universal quantum computation using atoms in cross-cavity systems

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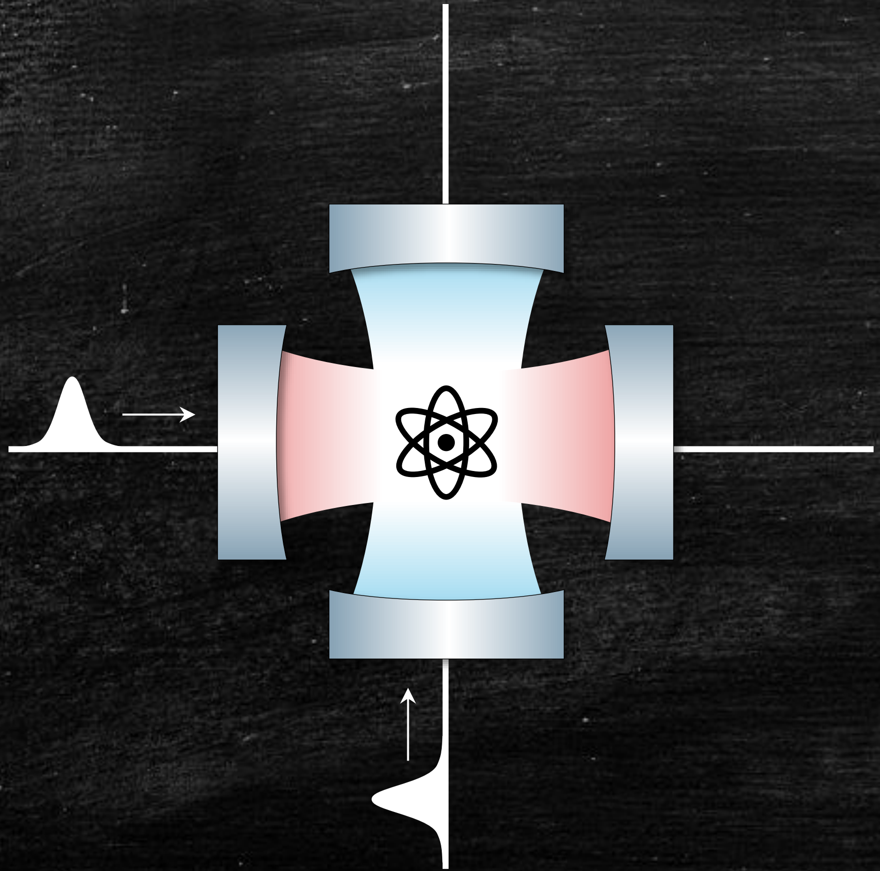
Quantum gates are the building blocks of quantum circuits, which in turn are the cornerstones of quantum information processing. In this work, we theoretically investigate a single-step implementation of both a universal two- (CNOT) and three-qubit (quantum Fredkin) gates in a cross-cavity setup coupled to a Λ-type three-level atom. Within a high-cooperativity regime, the system exhibits an atomic-state-dependent π-phase gate involving the two-mode single-photon bright and dark states of the input light pulses. This allows for the controlled manipulation of light states by the atom and vice versa. Our results indicate these quantum gates can be implemented with high probability of success using the state-of-the-art parameters, either for the weak- or strong-coupling regime, where the quantum interference is due to an electromagnetically induced transparencylike phenomenon and the Autler-Townes splitting, respectively. This work not only paves the way for implementing quantum gates in a single step using simple resources, thus avoiding the need to chain basic gates together in a circuit, but it also endorses the potential of cross-cavity systems for realizing universal quantum computation.

BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

CROSS-CAVITY SYSTEM



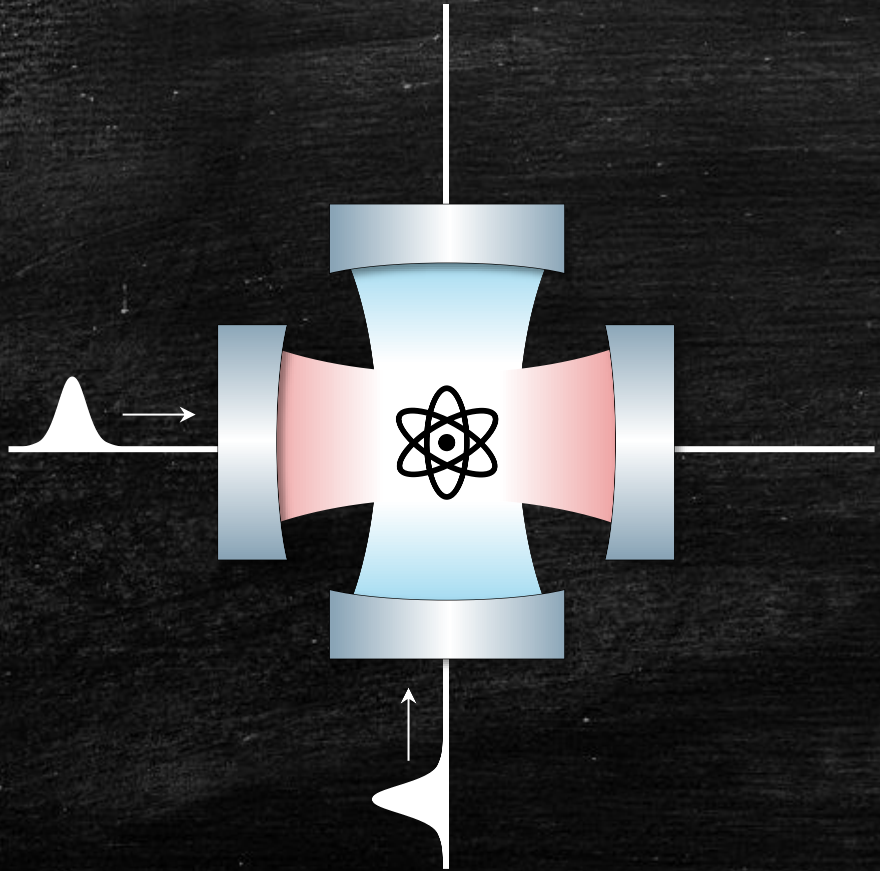
LIGHT BEAM IS SPLIT INTO ITS TWO-MODE BRIGHT AND DARK COMPONENTS

T: DARK COMPONENT

R: BRIGHT COMPONENT

BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

CROSS-CAVITY SYSTEM



HAMILTONIAN:

$$H = \sum_{\ell=r,t} \int d\omega\, \omega \left[A_\ell^\dagger(\omega) A_\ell(\omega) + B_\ell^\dagger(\omega) B_\ell(\omega)\right]$$

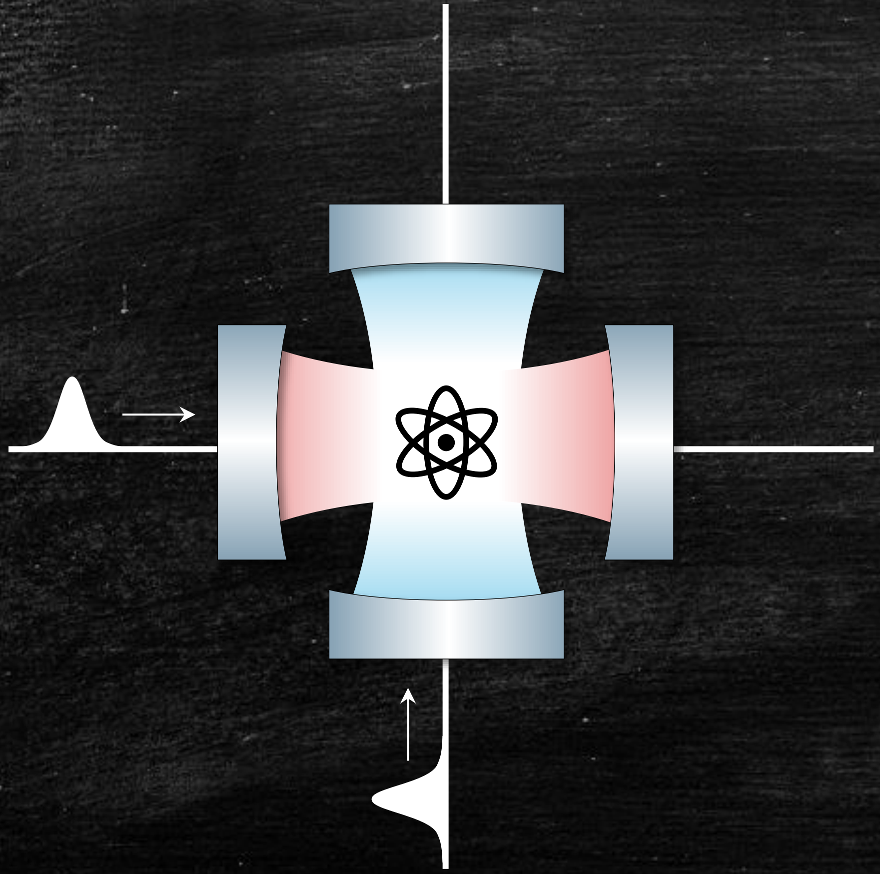
$$+i\sqrt{\frac{\kappa}{2\pi}} \sum_{\ell=r,t} \int d\omega \left[a^\dagger A_\ell(\omega) - a A_\ell^\dagger(\omega)\right]$$

$$+i\sqrt{\frac{\kappa}{2\pi}} \sum_{\ell=r,t} \int d\omega \left[b^\dagger B_\ell(\omega) - b B_\ell^\dagger(\omega)\right]$$

$$+g(a+b)\sigma_+ + g\left(a^\dagger + b^\dagger\right)\sigma_- - i\Gamma\sigma_+\sigma_-$$

BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

CROSS-CAVITY SYSTEM



HEISENBERG-LANGEVIN ($\sigma_z \approx -1$):

$$\dot{a}(t) = -ig\sigma_- - \kappa a(t) + \sqrt{\kappa} a_{\text{in}}^r(t),$$

$$\dot{b}(t) = -ig\sigma_- - \kappa b(t) + \sqrt{\kappa} b_{\text{in}}^r(t),$$

$$\dot{\sigma}_-(t) = -ig[a(t) + b(t)] - \Gamma \sigma_-(t).$$

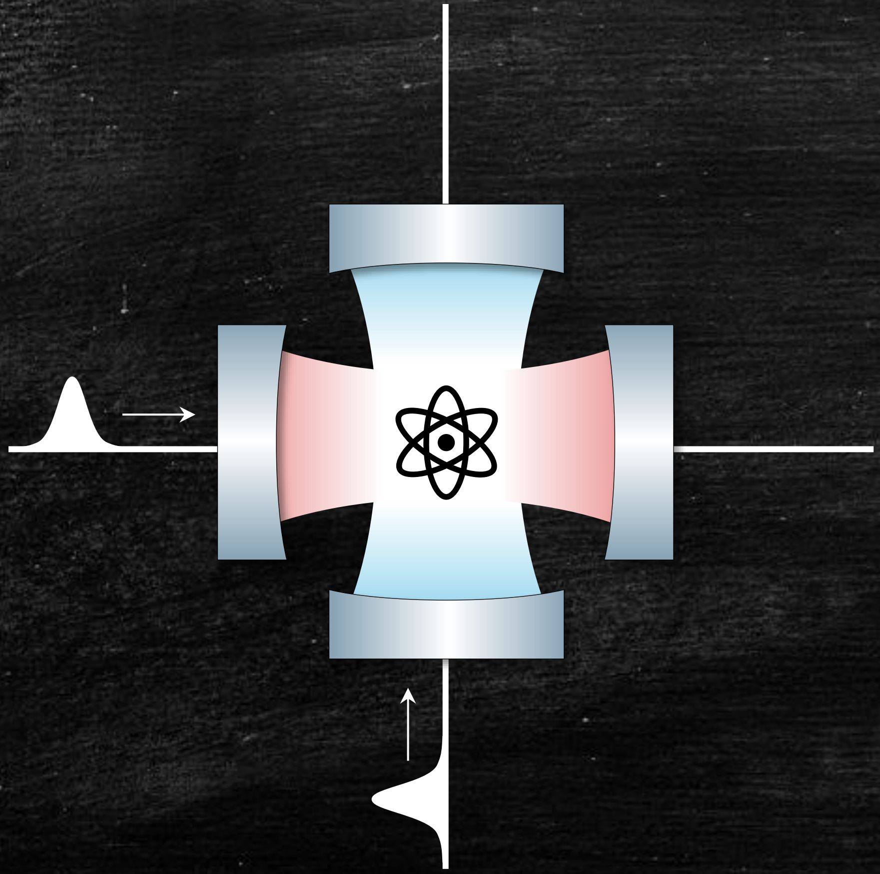
INPUT-OUTPUT RELATIONS:

$$a_{\text{out}}^r(t) = \sqrt{\kappa} a(t) - a_{\text{in}}^r(t), \qquad a_{\text{out}}^t(t) = \sqrt{\kappa} a(t),$$

$$b_{\text{out}}^r(t) = \sqrt{\kappa} b(t) - b_{\text{in}}^r(t), \qquad b_{\text{out}}^t(t) = \sqrt{\kappa} b(t).$$

BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

CROSS-CAVITY SYSTEM



COLLECTIVE-MODE OPERATORS:

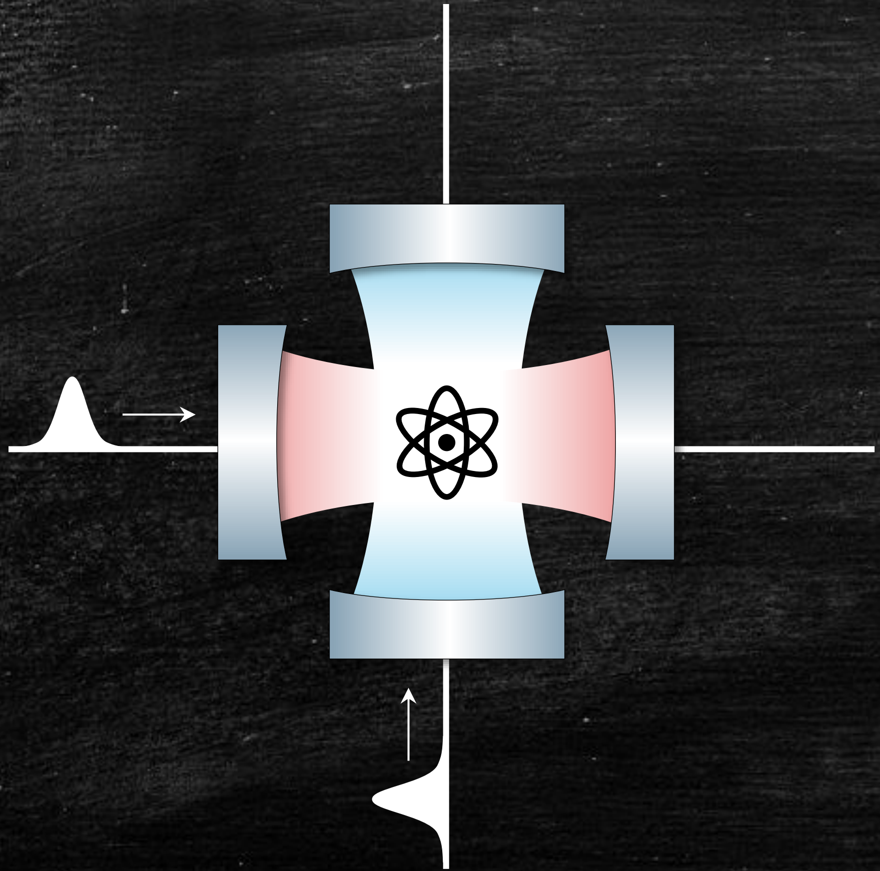
$X_{\text{in}}^{\pm} = \frac{1}{\sqrt{2}}(a_{\text{in}}^{r} \pm b_{\text{in}}^{r}) \rightarrow$ INCOMING FIELD

$X_{\text{out}}^{\pm} = \frac{1}{\sqrt{2}}(a_{\text{out}}^{r} \pm b_{\text{out}}^{r}) \rightarrow$ REFLECTED FIELD

$Y_{\text{out}}^{\pm} = \frac{1}{\sqrt{2}}(a_{\text{out}}^{t} \pm b_{\text{out}}^{t}) \rightarrow$ TRANSMITTED FIELD

BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

CROSS-CAVITY SYSTEM



SYSTEM RESPONSE (RESONANT INCOMING FIELD):

$$X^{+}_{\text{out}} = -\left(\frac{C}{1+C}\right) X^{+}_{\text{in}},$$

$$X^{-}_{\text{out}} = 0,$$

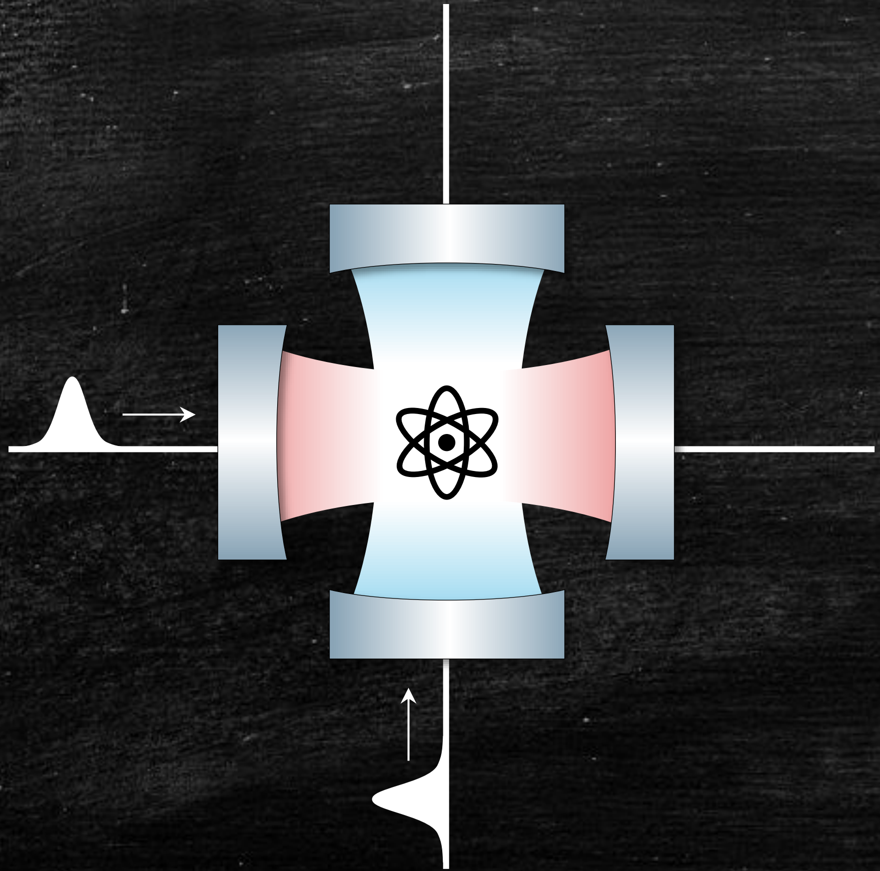
$$Y^{+}_{\text{out}} = \left(\frac{1}{1+C}\right) X^{+}_{\text{in}},$$

$$Y^{-}_{\text{out}} = X^{-}_{\text{in}}.$$

$$C = \frac{g^2}{\kappa\Gamma}$$

Beam splitter for dark and bright states of light

Cross-cavity system



System response (resonant incoming field):

$X^{+}_{\mathrm{out}} = -\left(\frac{C}{1+C}\right) X^{+}_{\mathrm{in}},$

$X^{-}_{\mathrm{out}} = 0,$

$Y^{+}_{\mathrm{out}} = \left(\frac{1}{1+C}\right) X^{+}_{\mathrm{in}},$

$Y^{-}_{\mathrm{out}} = X^{-}_{\mathrm{in}}.$

Dark states:

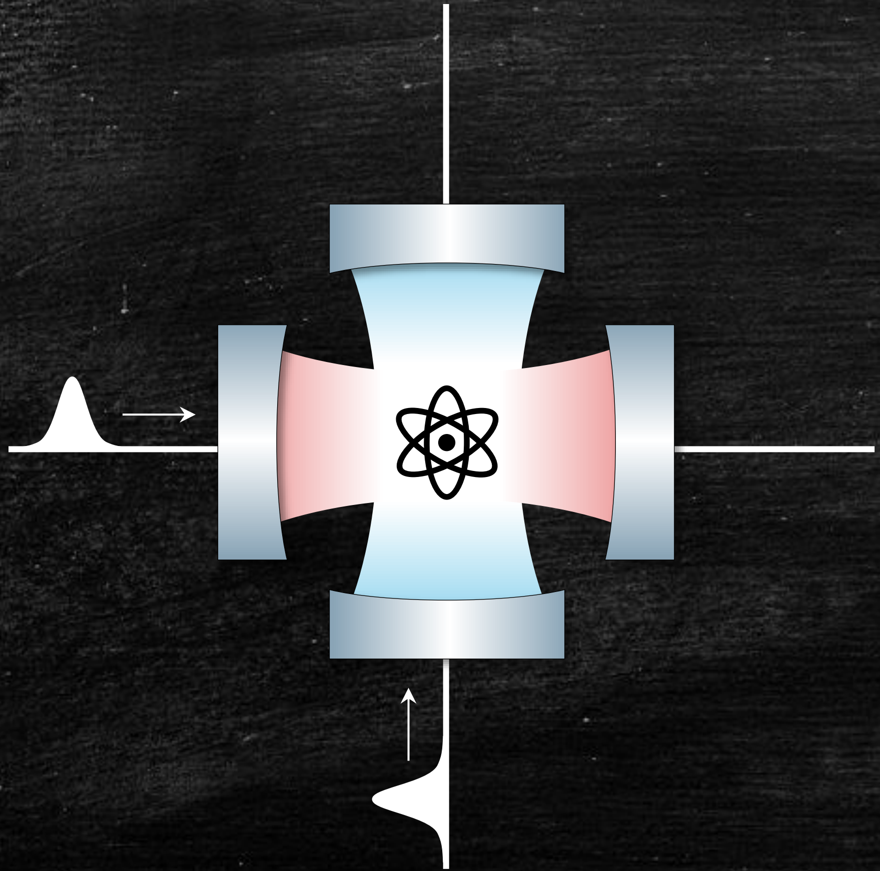
$$|\Psi_D^N\rangle_{\mathrm{in}} = \frac{(X_{\mathrm{in}}^{-})^{\dagger N}}{\sqrt{N!}} |0\rangle|0\rangle$$

Bright states:

$$|\Psi_B^N\rangle_{\mathrm{in}} = \frac{(X_{\mathrm{in}}^{+})^{\dagger N}}{\sqrt{N!}} |0\rangle|0\rangle$$

BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

CROSS-CAVITY SYSTEM



HIGH-COOPERATIVITY REGIME ($C \to \infty$)

$X^+_{\mathrm{out}} = -X^+_{\mathrm{in}},$

$Y^-_{\mathrm{out}} = X^-_{\mathrm{in}}.$

DARK STATES:

$$|\Psi^N_D\rangle_{\mathrm{in}} = \frac{(X^-_{\mathrm{in}})^{\dagger N}}{\sqrt{N!}} |0\rangle|0\rangle$$

BRIGHT STATES:

$$|\Psi^N_B\rangle_{\mathrm{in}} = \frac{(X^+_{\mathrm{in}})^{\dagger N}}{\sqrt{N!}} |0\rangle|0\rangle$$

BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

EXAMPLE:

$$|\psi\rangle_{\text{in}} = \left(\mu_a|1_{\text{in}}\rangle_\alpha^r|0\rangle_\beta^r + \mu_b|0\rangle_\alpha^r|1_{\text{in}}\rangle_\beta^r\right)|0\rangle_\alpha^t|0\rangle_\beta^t$$

$$= \left(\mu_+\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{in}} + \mu_-\left|\Psi_{\mathcal{D}}^1\right\rangle_r^{\text{in}}\right)|0\rangle_\alpha^t|0\rangle_\beta^t$$

$$|\psi\rangle_{\text{out}} = -\mu_+\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{out}}|0\rangle_\alpha^t|0\rangle_\beta^t + \mu_-|0\rangle_\alpha^r|0\rangle_\beta^r\left|\Psi_{\mathcal{D}}^1\right\rangle_t^{\text{out}}$$

$$\mu_\pm = \frac{1}{\sqrt{2}}(\mu_a \pm \mu_b)$$

$$\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{in}} = \frac{1}{\sqrt{2}}\left(|1_{\text{in}}\rangle_\alpha^r|0\rangle_\beta^r + |0\rangle_\alpha^r|1_{\text{in}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{D}}^1\right\rangle_r^{\text{in}} = \frac{1}{\sqrt{2}}\left(|1_{\text{in}}\rangle_\alpha^r|0\rangle_\beta^r - |0\rangle_\alpha^r|1_{\text{in}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{out}} = \frac{1}{\sqrt{2}}\left(|1_{\text{out}}\rangle_\alpha^r|0\rangle_\beta^r + |0\rangle_\alpha^r|1_{\text{out}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{D}}^1\right\rangle_t^{\text{out}} = \frac{1}{\sqrt{2}}\left(|1_{\text{out}}\rangle_\alpha^t|0\rangle_\beta^t - |0\rangle_\alpha^t|1_{\text{out}}\rangle_\beta^t\right)$$

Beam splitter for dark and bright states of light

Example: $\mu_a = 1, \mu_b = 0$

$$|\psi\rangle_{\text{in}} = |1_{\text{in}}\rangle_\alpha^r |0\rangle_\beta^r |0\rangle_\alpha^t |0\rangle_\beta^t$$

$$= \frac{1}{\sqrt{2}}\left(\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{in}} + \left|\Psi_{\mathcal{D}}^1\right\rangle_r^{\text{in}}\right)|0\rangle_\alpha^t |0\rangle_\beta^t$$

$$|\psi\rangle_{\text{out}} = -\frac{1}{\sqrt{2}}\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{out}} |0\rangle_\alpha^t |0\rangle_\beta^t + \frac{1}{\sqrt{2}}|0\rangle_\alpha^r |0\rangle_\beta^r \left|\Psi_{\mathcal{D}}^1\right\rangle_t^{\text{out}}$$

$$\mu_\pm = \frac{1}{\sqrt{2}}(\mu_a \pm \mu_b)$$

$$\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{in}} = \frac{1}{\sqrt{2}}\left(|1_{\text{in}}\rangle_\alpha^r |0\rangle_\beta^r + |0\rangle_\alpha^r |1_{\text{in}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{D}}^1\right\rangle_r^{\text{in}} = \frac{1}{\sqrt{2}}\left(|1_{\text{in}}\rangle_\alpha^r |0\rangle_\beta^r - |0\rangle_\alpha^r |1_{\text{in}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{out}} = \frac{1}{\sqrt{2}}\left(|1_{\text{out}}\rangle_\alpha^r |0\rangle_\beta^r + |0\rangle_\alpha^r |1_{\text{out}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{D}}^1\right\rangle_t^{\text{out}} = \frac{1}{\sqrt{2}}\left(|1_{\text{out}}\rangle_\alpha^t |0\rangle_\beta^t - |0\rangle_\alpha^t |1_{\text{out}}\rangle_\beta^t\right)$$

Beam splitter for dark and bright states of light

Example: $\mu_a = \frac{1}{\sqrt{2}},\ \mu_b = \frac{1}{\sqrt{2}}$

$$|\psi\rangle_{\text{in}} = \frac{1}{\sqrt{2}}\left(|1_{\text{in}}\rangle_\alpha^r|0\rangle_\beta^r + |0\rangle_\alpha^r|1_{\text{in}}\rangle_\beta^r\right)|0\rangle_\alpha^t|0\rangle_\beta^t$$

$$= \left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{in}}|0\rangle_\alpha^t|0\rangle_\beta^t$$

$$|\psi\rangle_{\text{out}} = -\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{out}}|0\rangle_\alpha^t|0\rangle_\beta^t$$

$$\mu_\pm = \frac{1}{\sqrt{2}}(\mu_a \pm \mu_b)$$

$$\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{in}} = \frac{1}{\sqrt{2}}\left(|1_{\text{in}}\rangle_\alpha^r|0\rangle_\beta^r + |0\rangle_\alpha^r|1_{\text{in}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{D}}^1\right\rangle_r^{\text{in}} = \frac{1}{\sqrt{2}}\left(|1_{\text{in}}\rangle_\alpha^r|0\rangle_\beta^r - |0\rangle_\alpha^r|1_{\text{in}}\rangle_\beta^r\right)$$

$$\left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{out}} = \frac{1}{\sqrt{2}}\left(|1_{\text{out}}\rangle_\alpha^r|0\rangle_\beta^r + |0\rangle_\alpha^r|1_{\text{out}}\rangle_\beta^r\right)$$

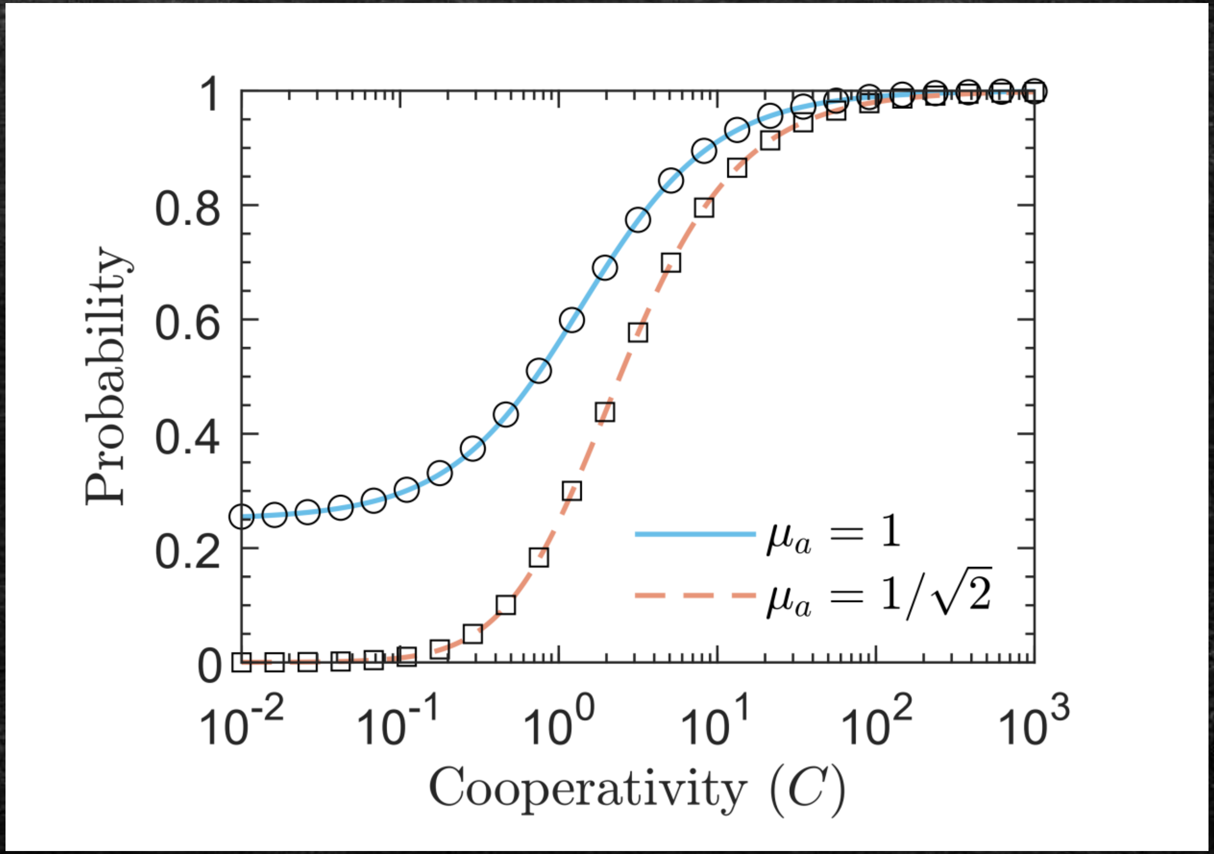
$$\left|\Psi_{\mathcal{D}}^1\right\rangle_t^{\text{out}} = \frac{1}{\sqrt{2}}\left(|1_{\text{out}}\rangle_\alpha^t|0\rangle_\beta^t - |0\rangle_\alpha^t|1_{\text{out}}\rangle_\beta^t\right)$$

EXAMPLE:

$$|\psi\rangle_{\text{in}} = \left(\mu_a |1_{\text{in}}\rangle_\alpha^r |0\rangle_\beta^r + \mu_b |0\rangle_\alpha^r |1_{\text{in}}\rangle_\beta^r\right) |0\rangle_\alpha^t |0\rangle_\beta^t$$

$$|\psi\rangle_{\text{out}} = -\mu_+ \left|\Psi_{\mathcal{B}}^1\right\rangle_r^{\text{out}} |0\rangle_\alpha^t |0\rangle_\beta^t$$

$$+\mu_- |0\rangle_\alpha^r |0\rangle_\beta^r \left|\Psi_{\mathcal{D}}^1\right\rangle_t^{\text{out}}$$



BEAM SPLITTER FOR DARK AND BRIGHT STATES OF LIGHT

THE INCIDENT LIGHT MAY ALSO BE CLASSICAL!

FOR INSTANCE:

IN-PHASE COHERENT STATES: $|\alpha, \alpha\rangle = e^{-|\alpha|^2} \sum_{N=0}^{\infty} \frac{\alpha^N}{\sqrt{N!}} \left|\Psi_{\mathcal{B}}^N\right\rangle$

OUT-OF-PHASE COHERENT STATES: $|\alpha, -\alpha\rangle = e^{-|\alpha|^2} \sum_{N=0}^{\infty} \frac{\alpha^N}{\sqrt{N!}} \left|\Psi_{\mathcal{D}}^N\right\rangle$

CONCLUSIONS

BEAM SPLLITERS ARE INDISPENSABLE ELEMENTS IN OPTICAL AND PHOTONICS SYSTEMS, AND ARE THEREFORE EMPLOYED IN BOTH CLASSICAL AND QUANTUM TECHNOLOGIES.

THEY CAN DIVIDE INCIDENT LIGHT ACCORDING TO ITS POWER, POLARIZATION, OR WAVELENGHT.

IN OUR WORK, WE HAVE INTRODUCED A BEAM SPLITTER CAPABLE OS SEPARATING A LIGHT BEAM IN ITS TWO-MODE BRIGHT AND DARK COMPONENTS.

CONCLUSIONS

OUR RESULTS PAVE THE WAY FOR NEW APPLICATIONS OF BEAM SPLITTERS THAT LEVERAGE THE COLLECTIVE PROPERTIES OF LIGHT.

CONTRIBUTING TO THE ADVANCEMENT OF QUANTUM OPTICS AND QUANTUM TECHNOLOGIES!

THANK YOU!

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