Quantum scattering of light by a nanostructure: preservation and destruction of the quantum purity

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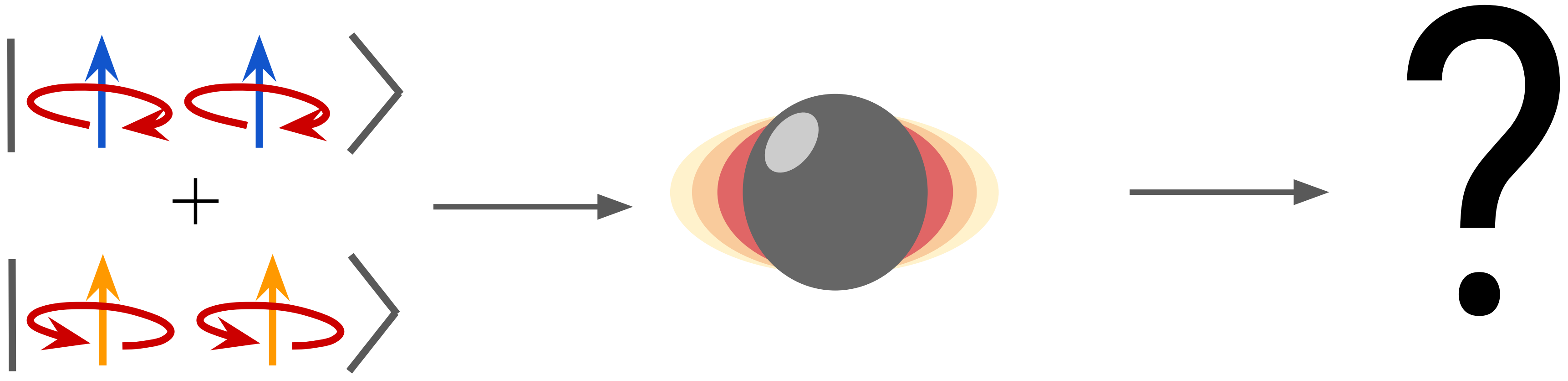
Donostia-San Sebastián

Nanolight 2022, 6-12 March 2022, Benasque

Entangled states

Nanostructure



(angular momentum)

A. Büse, *et al.* , “Symmetry Protection of Photonic Entanglement in the Interaction with a Single Nanoaperture”, **Phys. Rev. Lett. 121, 173901 (2018)**

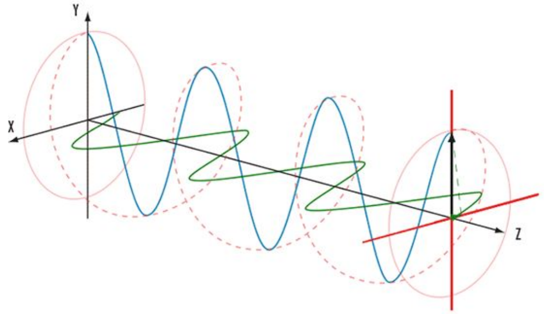
Spin, Helicity, Orbital angular momentum

Circular left polarized light (Plane Wave)

$$\vec{E} = E_0(\vec{r}) \begin{pmatrix} 1_x \\ i_y \\ 0_z \end{pmatrix} e^{i(kz-\omega t)}$$

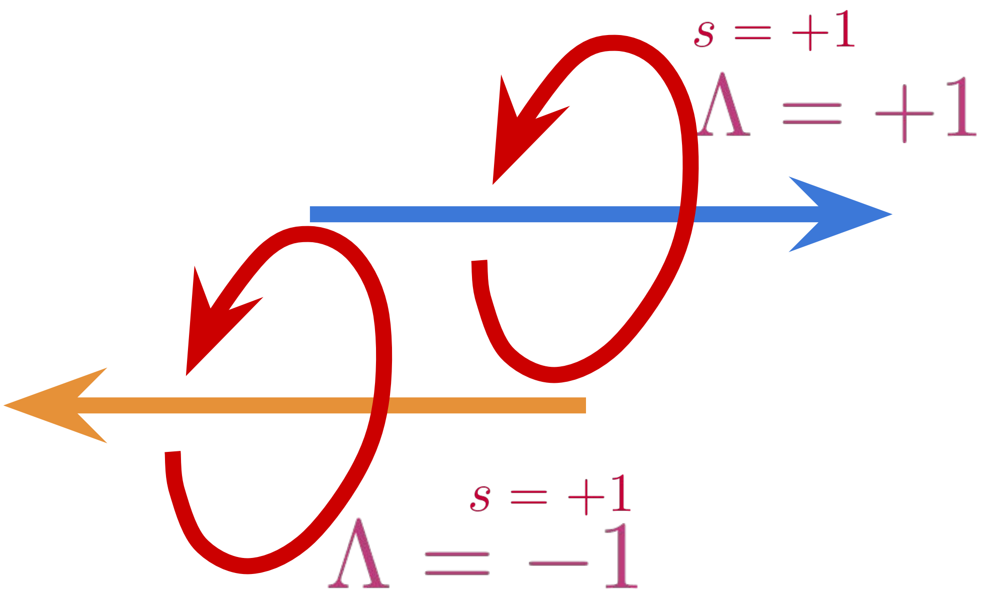
Spin & Helicity

$s = +1$ $\quad s = -1$



[Credits: Edmund Optics]

- **Spin (s)**
- **Helicity (Λ)** *Spin projected in the direction of propagation*



Spin, Helicity, Orbital angular momentum

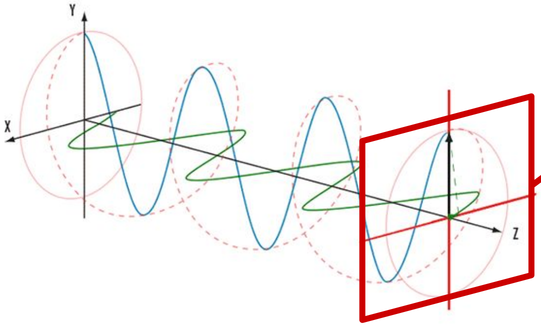
Circular left polarized light (Plane Wave)

$$\vec{E} = E_0(\vec{r}) \begin{pmatrix} 1_x \\ i_y \\ 0_z \end{pmatrix} e^{i(kz-\omega t)}$$

Orbital angular momentum (l)

Spin & Helicity

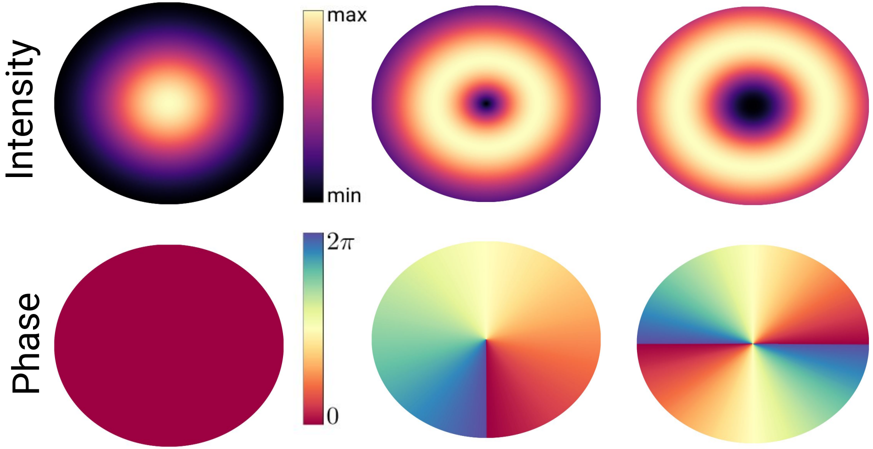
$s = +1$ $s = -1$



$E_0(\vec{r})$

[Credits: Edmund Optics]

- **Spin (s)**
- **Helicity (Λ)**
- **Orbital angular momentum (l)**



$l = 0$ $l = +1$ $l = +2$

Gaussian beam *Laguerre-Gauss beam*

Spin, Helicity, Orbital angular momentum

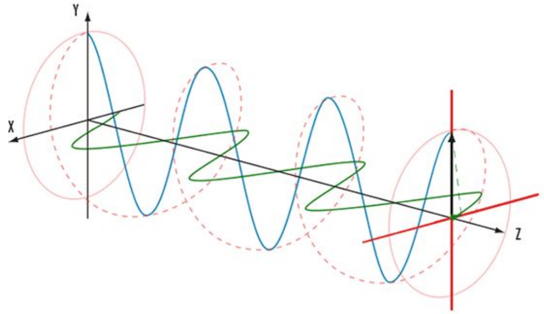
Circular left polarized light (Plane Wave)

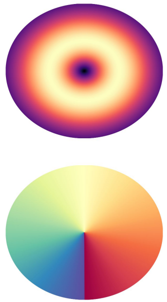
$$\vec{E} = E_0(\vec{r}) \begin{pmatrix} 1_x \\ i_y \\ 0_z \end{pmatrix} e^{i(kz-\omega t)}$$

Orbital angular momentum (l)

Spin & Helicity

$s = +1$ $s = -1$





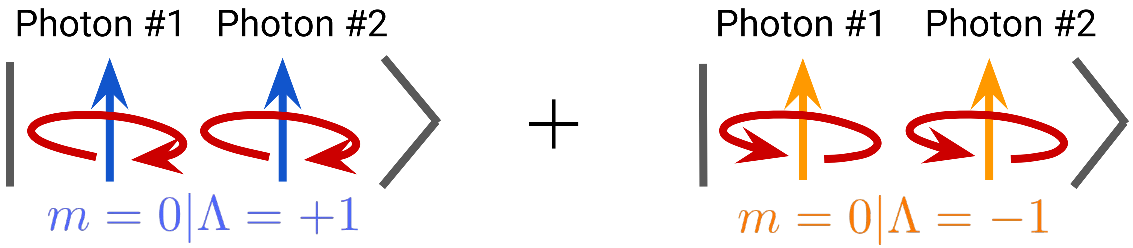
$l = +1$

[Credits: Edmund Optics]

- **Spin (s)**
- **Helicity (Λ)**
- **Orbital angular momentum (l)**
- **Total angular momentum (m)**

$$m = l + s$$

Entangled states



$$|\psi_+\rangle = \frac{1}{\sqrt{2}}\left[|++\rangle + |--\rangle\right]$$

Entangled states: Basis

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}\left[|++\rangle + |--\rangle\right]$$

$$|\psi_-\rangle = \frac{1}{\sqrt{2}}\left[|++\rangle - |--\rangle\right]$$

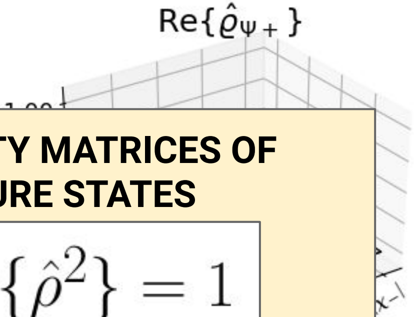
$$|\chi_+\rangle = \frac{1}{\sqrt{2}}\left[|+-\rangle + |-+\rangle\right]$$

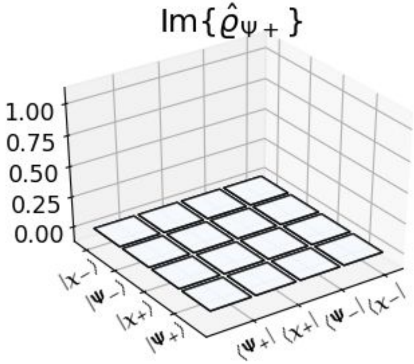
$$|\chi_-\rangle = \frac{1}{\sqrt{2}}\left[|+-\rangle - |-+\rangle\right]$$

Density matrix

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}\left[|{+}{+}\rangle + |{-}{-}\rangle\right]$$

$$\hat{\rho}_{\psi+} = |\psi_+\rangle\langle\psi_+|$$





DENSITY MATRICES OF PURE STATES

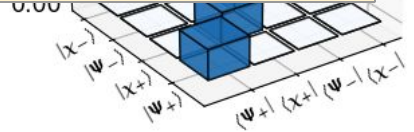
$$\mathrm{Tr}\{\hat{\rho}^2\} = 1$$

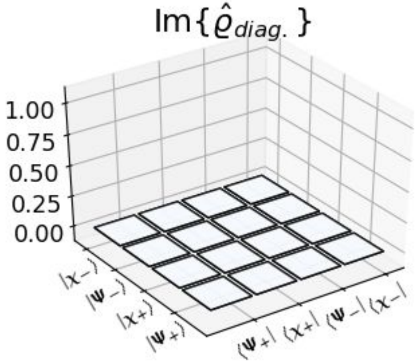
$$\hat{\rho}_{diag.} = |\psi_+\rangle\langle\psi_+| + |\psi_-\rangle\langle$$

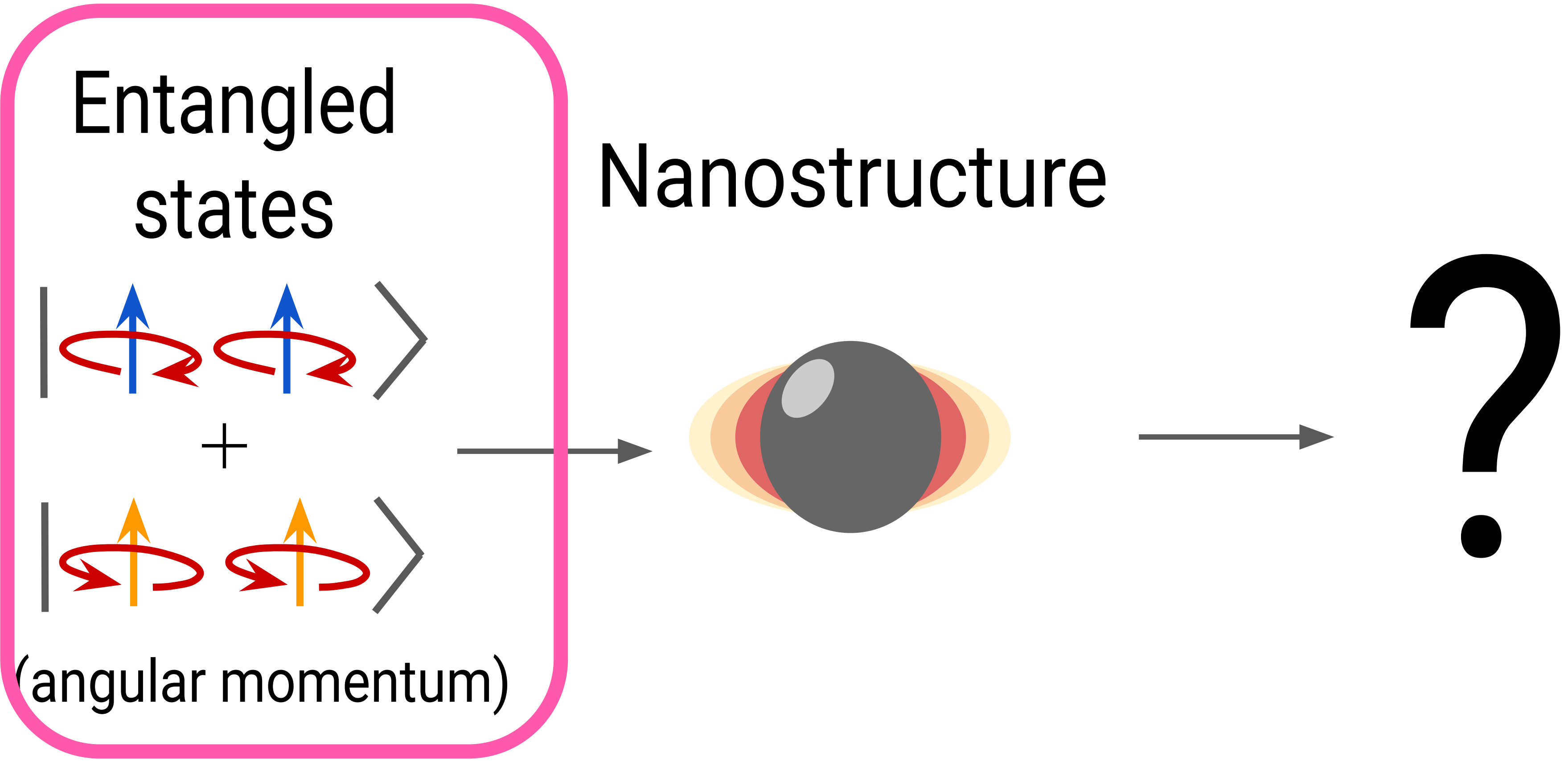
$$|\chi_+\rangle\langle\chi_+| + |\chi_-\rangle\langle\chi_-$$

DENSITY MATRICES OF NON-PURE STATES

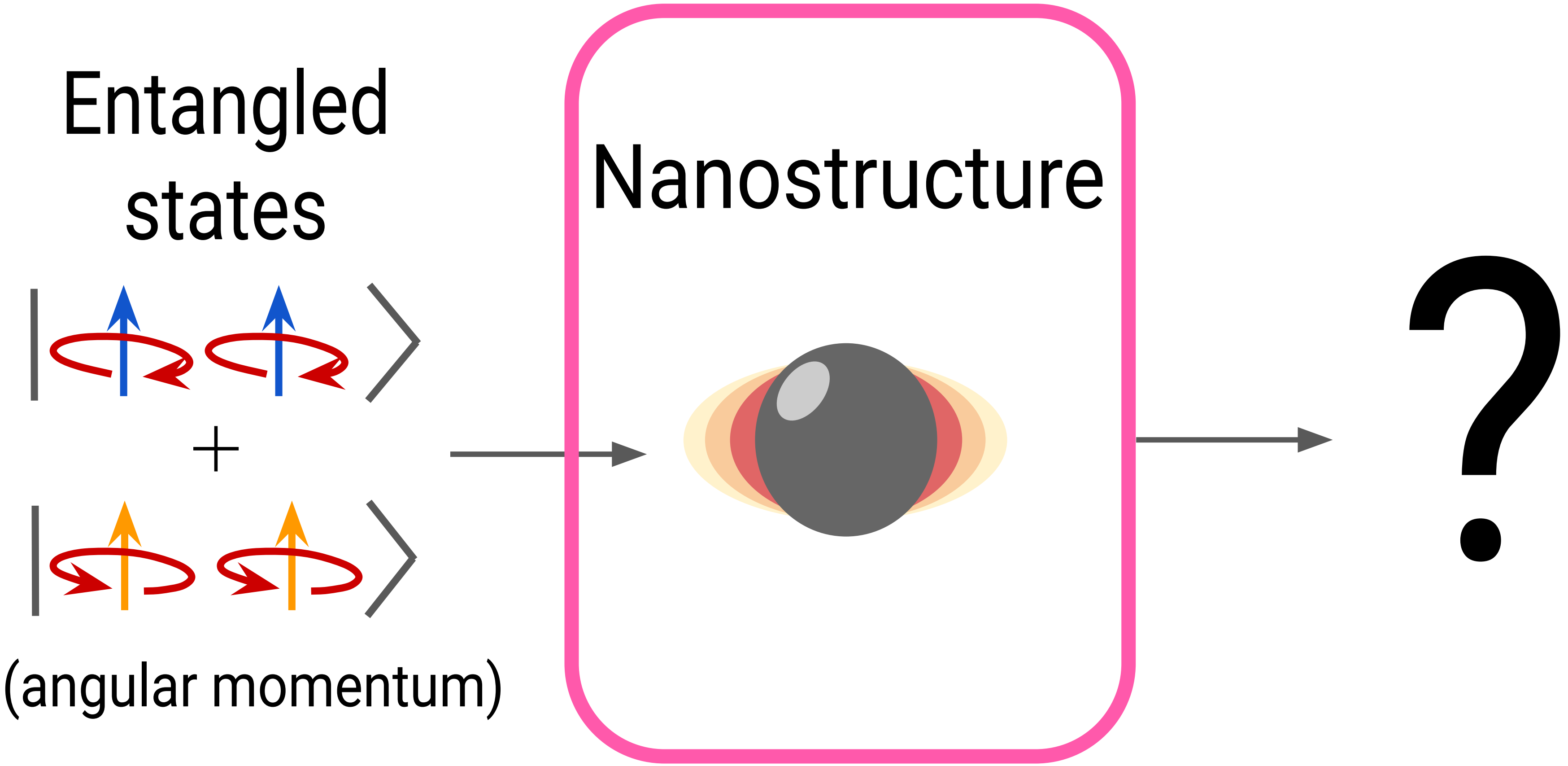
$$\mathrm{Tr}\{\hat{\rho}^2\} < 1$$







A. Büse, *et al.* , “Symmetry Protection of Photonic Entanglement in the Interaction with a Single Nanoaperture”, **Phys. Rev. Lett. 121, 173901 (2018)**



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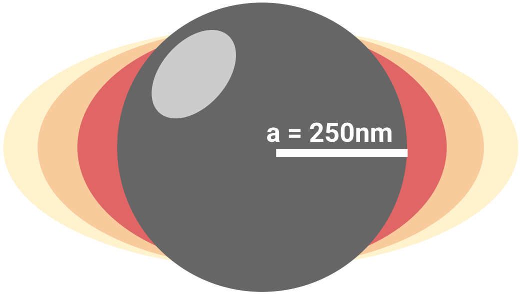
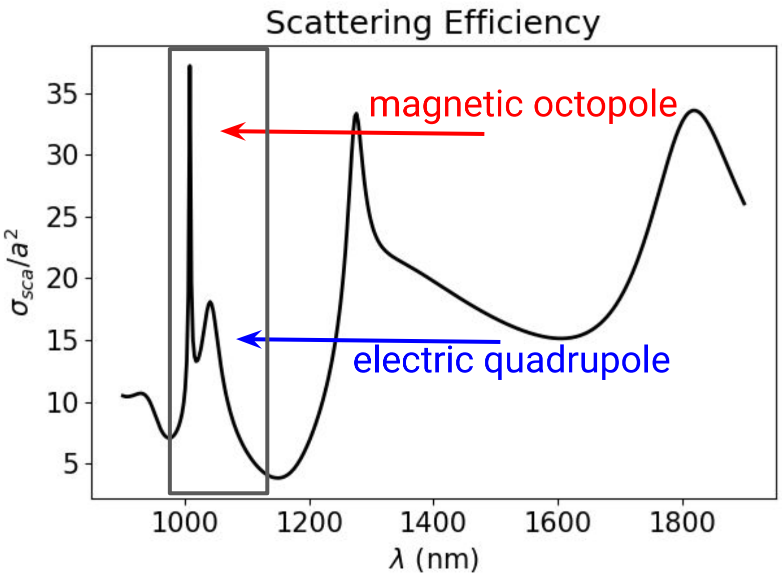
Dielectric spherical nanoparticle





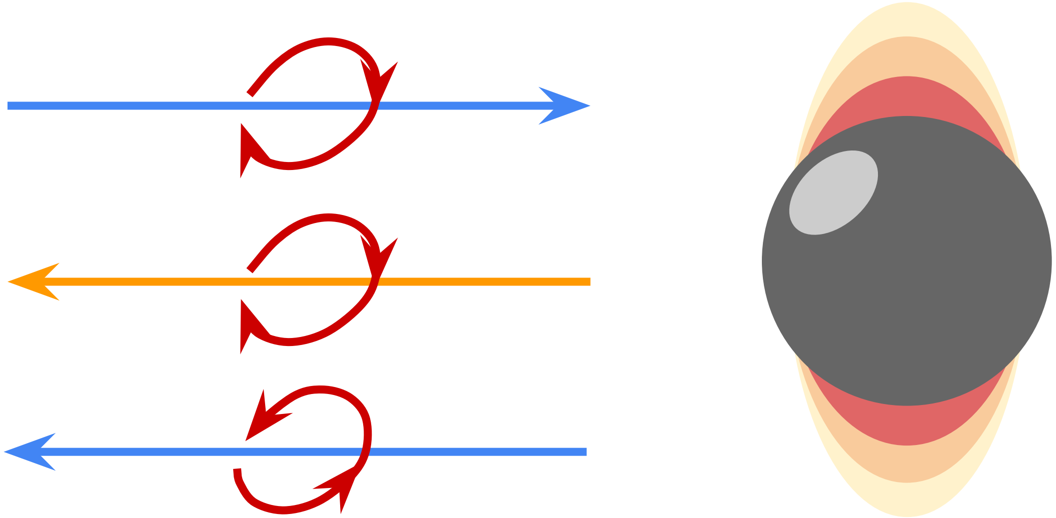
Resonances in dielectrics:
Strong localization of electric and magnetic fields

Spherical nanoparticles

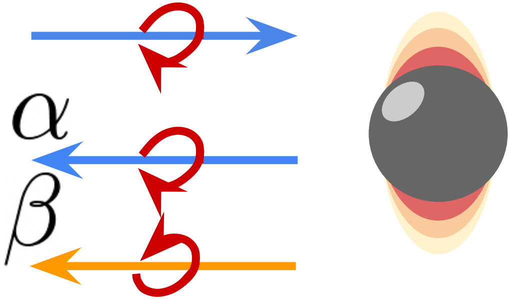
Conserve total angular momentum!

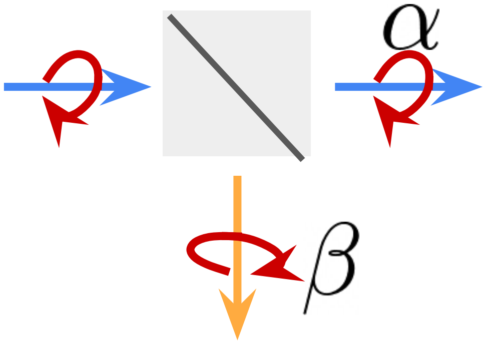
… but not helicity sign

	m	Λ
IN	0	$+1$
OUT	0	-1
	0	$+1$



Lossy beam splitter transformation



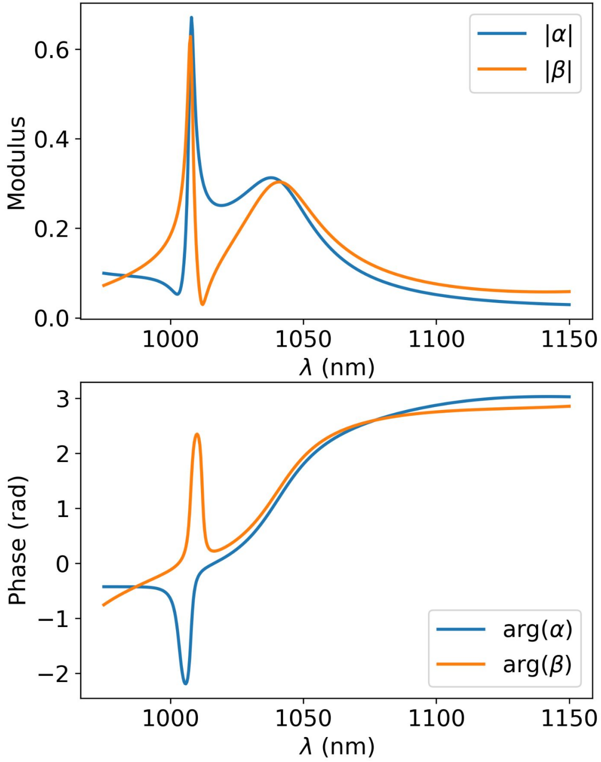


$$\hat{a}_-^{out\dagger}(\omega) = \alpha(\omega)\hat{a}_-^{in\dagger}(\omega) + \beta(\omega)\hat{a}_+^{in\dagger}(\omega) + \hat{F}_-^{\dagger}(\omega)$$
$$\hat{a}_+^{out\dagger}(\omega) = \alpha(\omega)\hat{a}_+^{in\dagger}(\omega) + \beta(\omega)\hat{a}_-^{in\dagger}(\omega) + \hat{F}_+^{\dagger}(\omega)$$

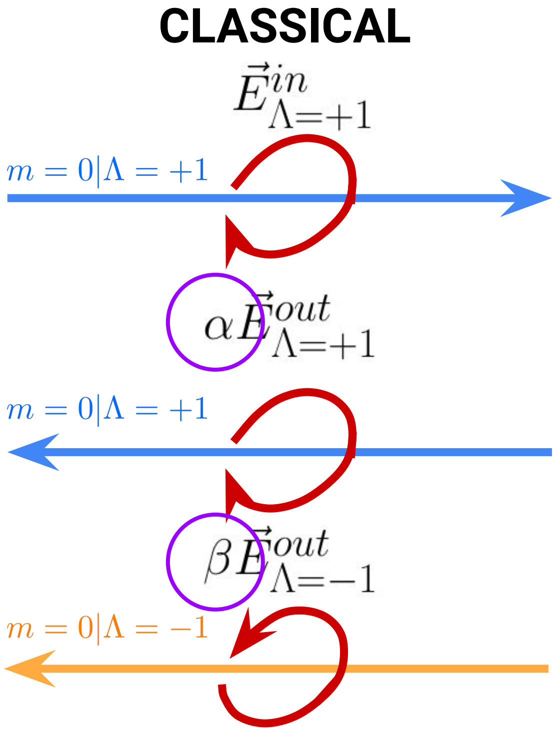
$\hat{a}_\pm^{in}$	Input helicity operators	α β	Scattering coefficients
$\hat{a}_\pm^{out}$	Output helicity operators	$\hat{F}_\pm$	Losses operators

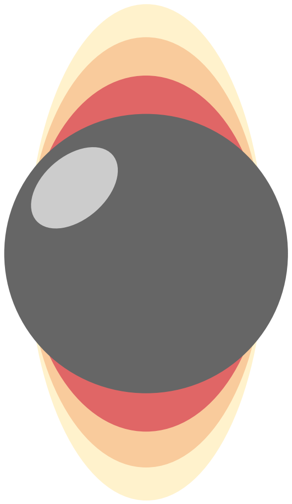
S. M. Barnett, J. Jeffers, A. Gatti, and R. Loudon, **"**Quantum optics of lossy beam splitters**", Phys. Rev. A 57, 2134 (1998)**

Classical response: Scattering coefficients

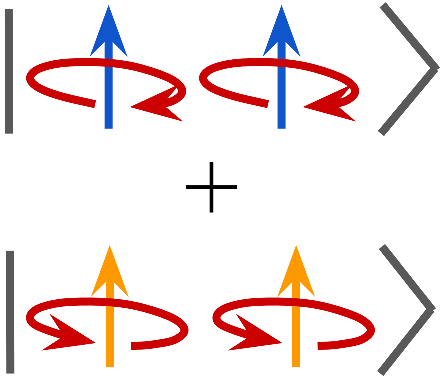


Calculated with Mie's theory



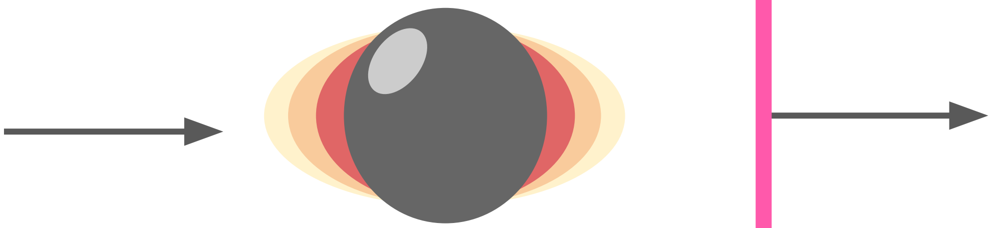


Entangled states



(angular momentum)

Nanostructure



Main results: Loss of purity

?

A. Büse, *et al.* , “Symmetry Protection of Photonic Entanglement in the Interaction with a Single Nanoaperture”, **Phys. Rev. Lett. 121, 173901 (2018)**

Entangled states: Basis

IN

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}\left[|{+}{+}\rangle + |{-}{-}\rangle\right]$$

$$|\psi_-\rangle = \frac{1}{\sqrt{2}}\left[|{+}{+}\rangle - |{-}{-}\rangle\right]$$

$$|\chi_+\rangle = \frac{1}{\sqrt{2}}\left[|{+}{-}\rangle + |{-}{+}\rangle\right]$$

$$|\chi_-\rangle = \frac{1}{\sqrt{2}}\left[|{+}{-}\rangle - |{-}{+}\rangle\right]$$

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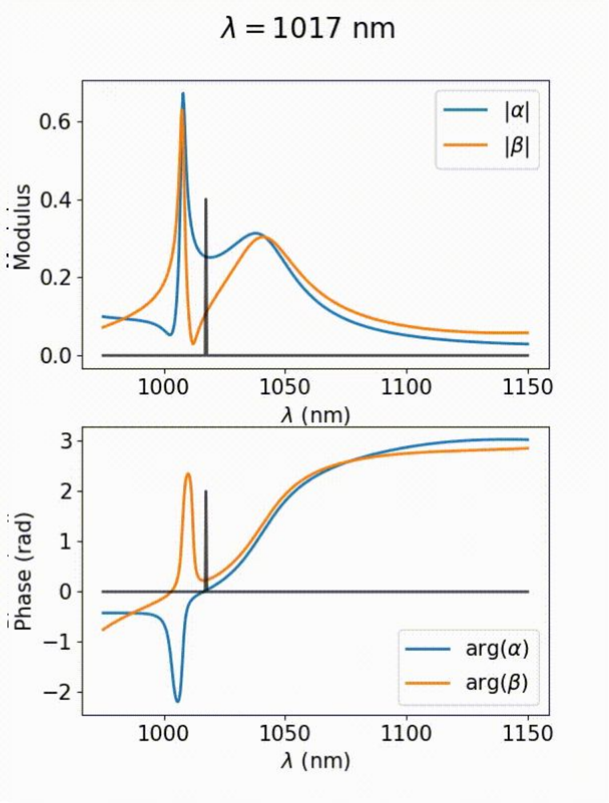
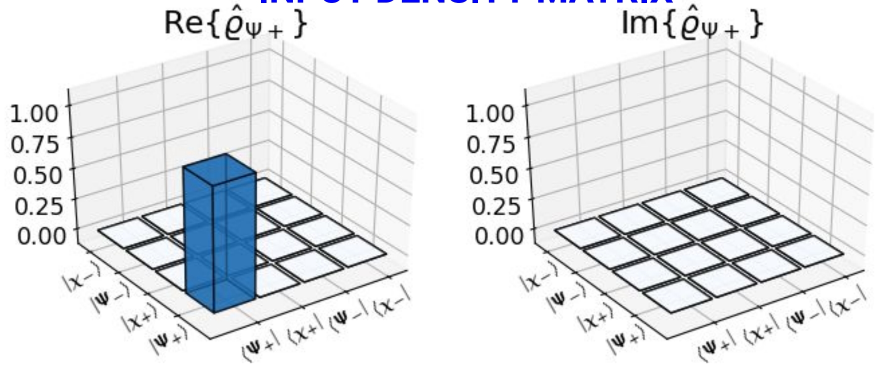
Monochromatic input: Conservation of purity



INPUT DENSITY MATRIX



Entangled states: Basis

IN **OUT**

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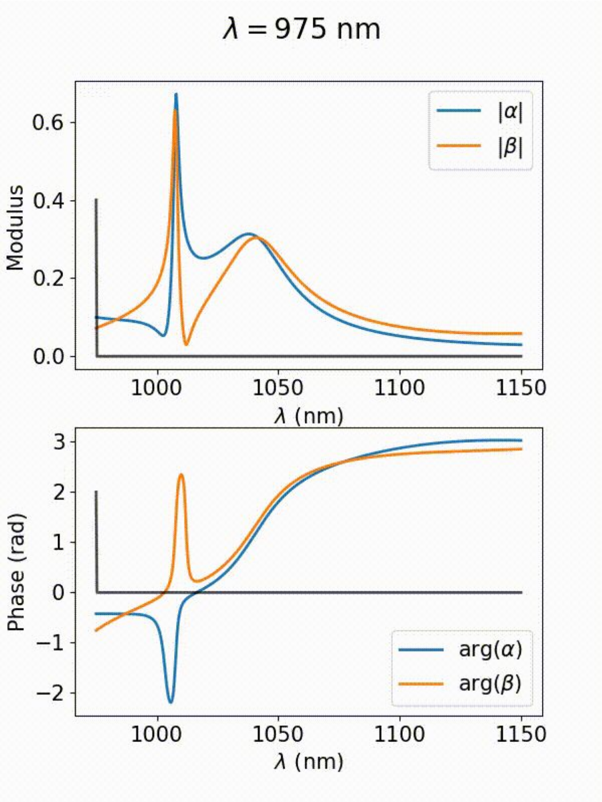

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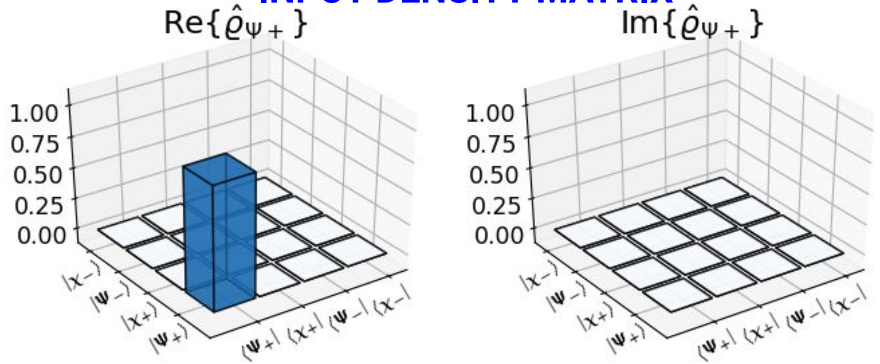
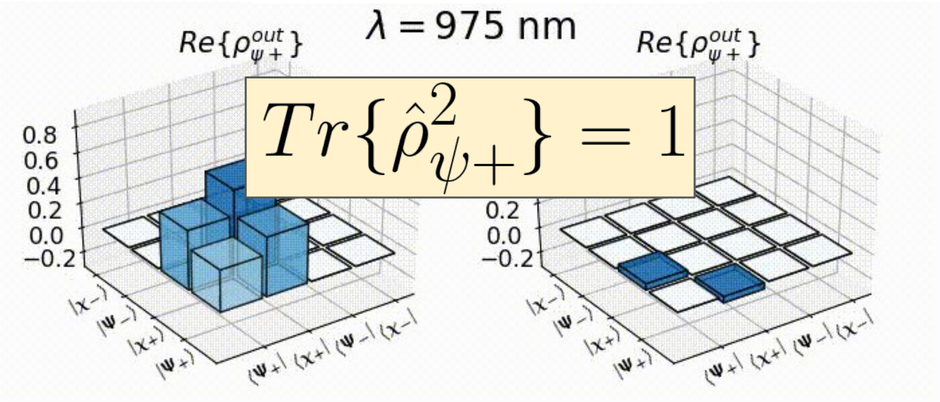
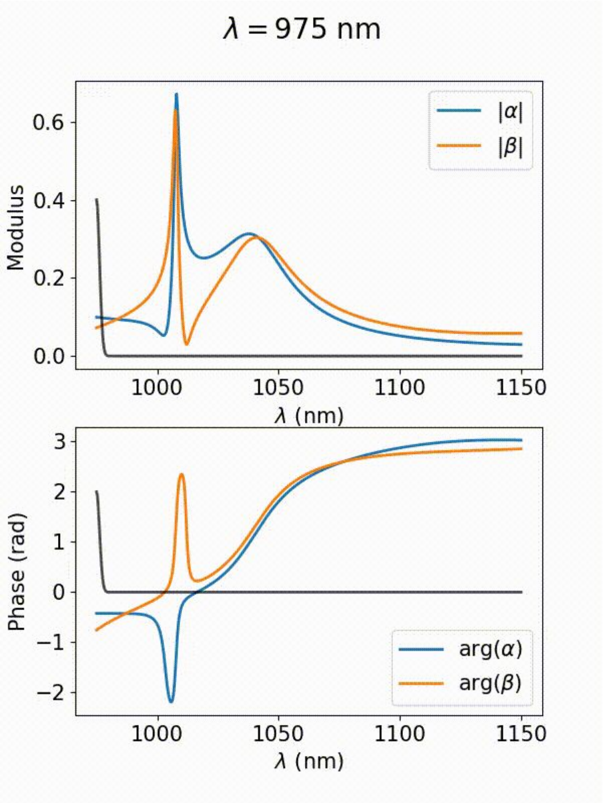


OUTPUT DENSITY MATRIX

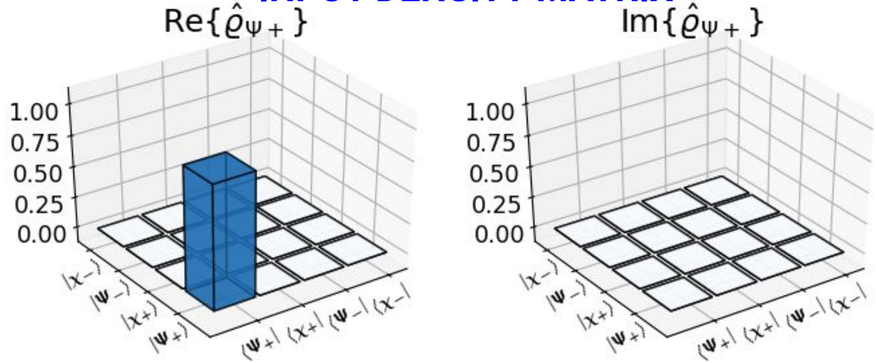


$$Tr\{\hat{\rho}^2_{\psi+}\} = 1$$

Pulse input: Loss of purity



INPUT DENSITY MATRIX



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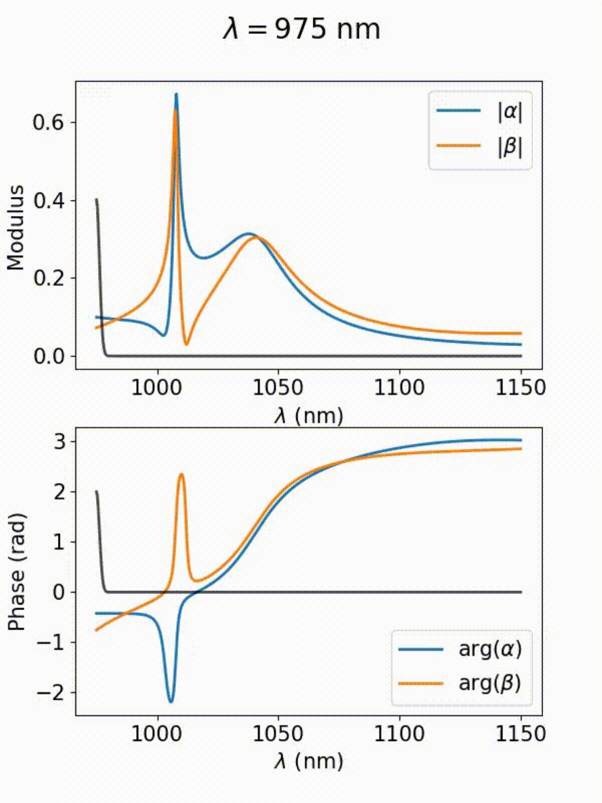
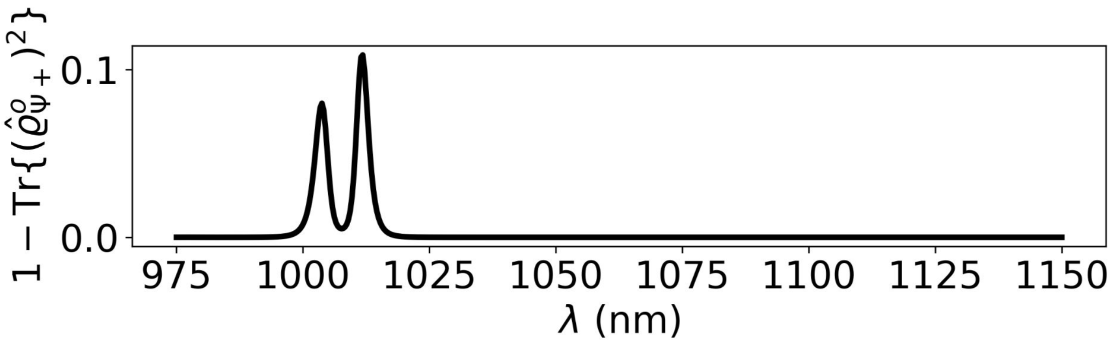
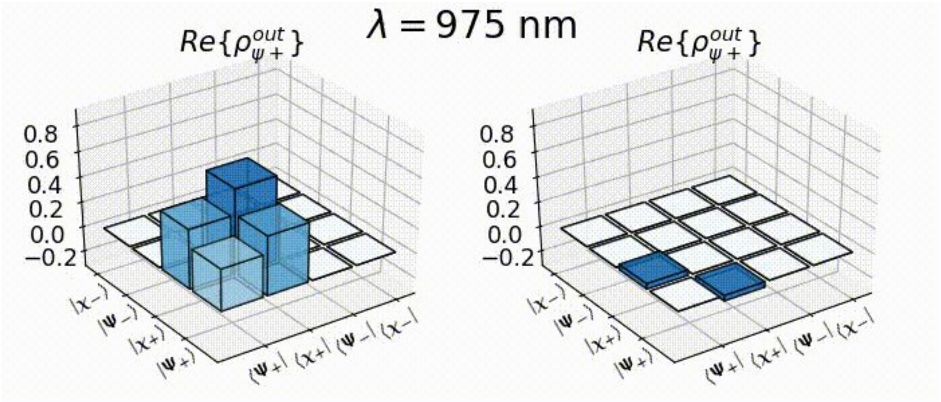
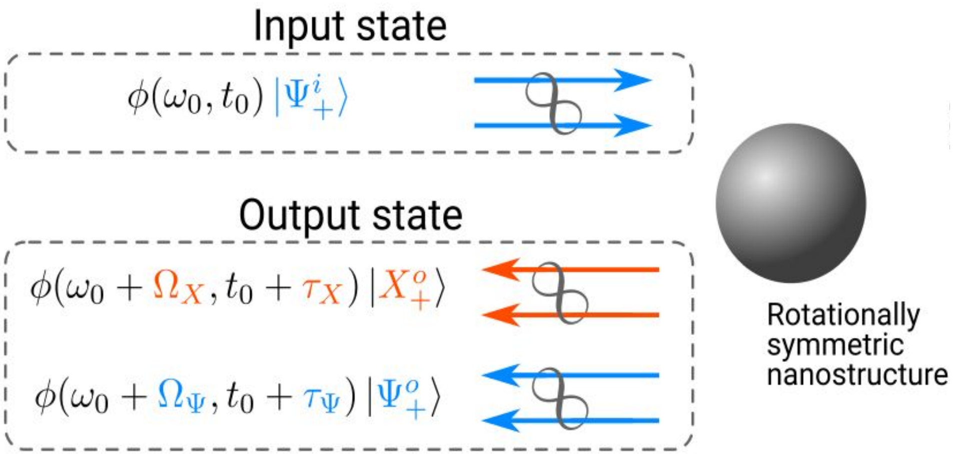


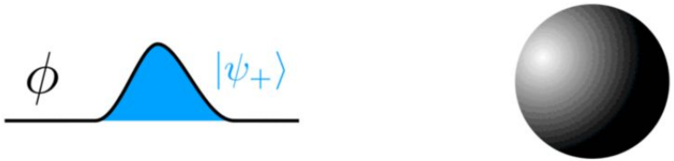
LOSS OF PURITY





Origin of the loss of purity





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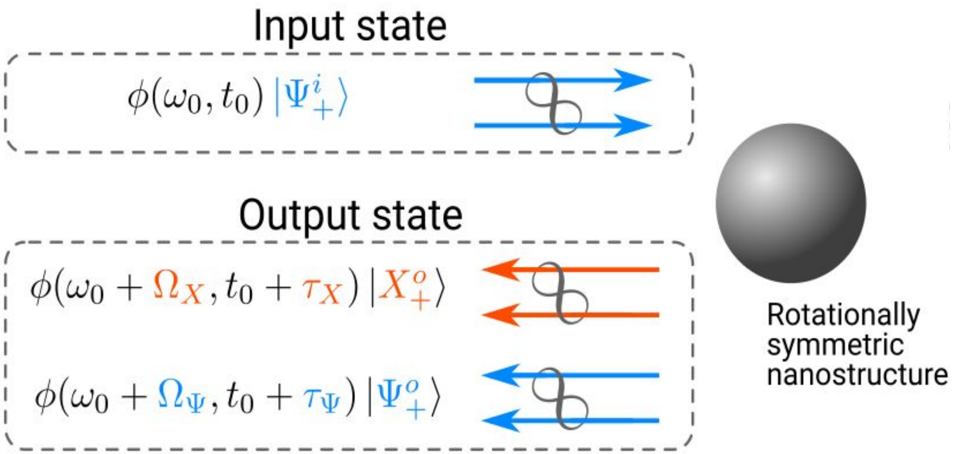
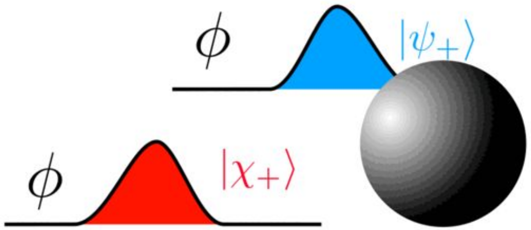
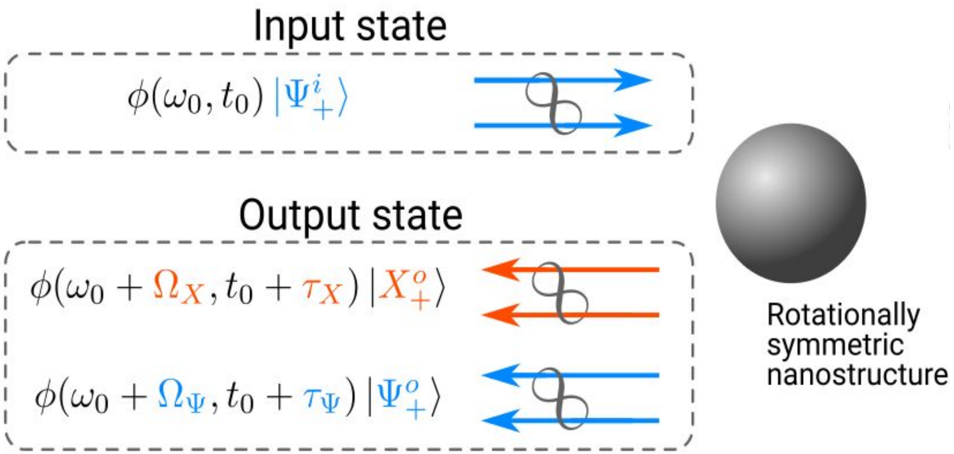
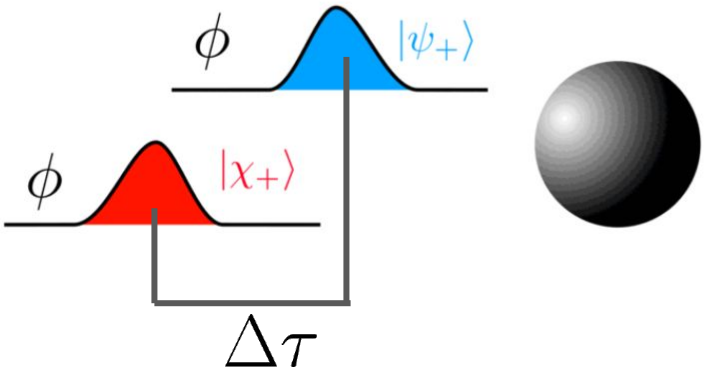




R. Rangarajan, M.Goggin, and P. Kwiat, “Optimizing type-I polarization-entangled photons,” **Opt. Express 17, 18920-18933 (2009)**

Origin of the loss of purity





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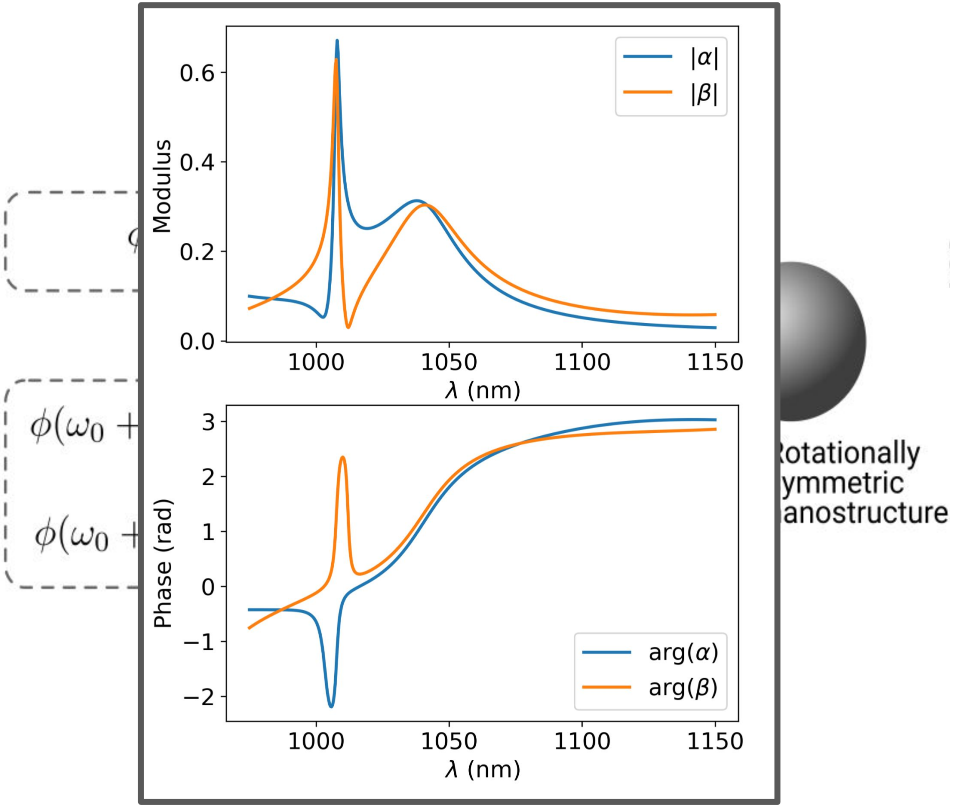
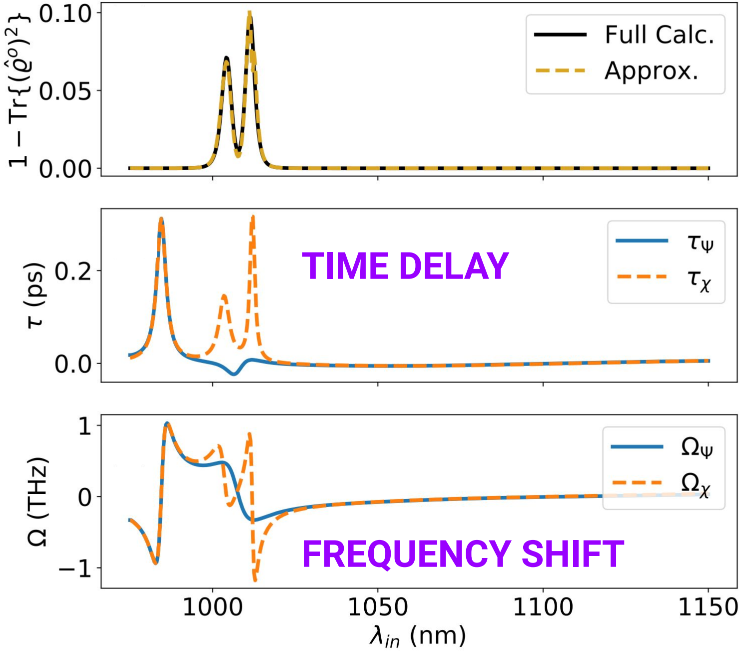




Conclusions

- Framework to treat the **scattering of quantum states** of light by a nanostructure.

- **Loss of quantum purity** in the scattering process: **interaction with optical resonances.**

- **Origin** of the loss of quantum purity: **time-delay** and **frequency-shift.**

Funding:

- Proyect Ref. No. PID2019-107432GB-I00 founded by MCIN/AEI/10.13039/501100011033
- Eusko Jaurlaritza project KK-2019/00101
- Project IT1164-19 for consolidated groups of the Basque University, through the Department of Education, Research and Universities of the Basque Government

MINISTERIO DE CIENCIA E INNOVACIÓN

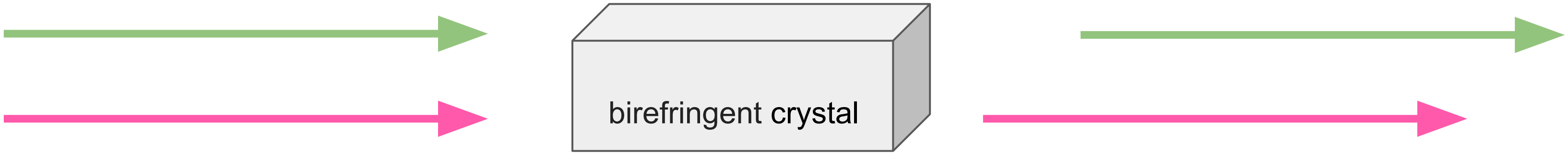
AGENCIA ESTATAL DE INVESTIGACIÓN

EUSKO JAURLARITZA GOBIERNO VASCO

Analogous situation in birefringent crystals

IN **OUT**

$$\phi(\omega_0, t_0)\,|HH\rangle + \phi(\omega_0, t_0 + \Delta t)\,|VV\rangle$$



$$\phi(\omega_0, t_0)\,|HH\rangle + \phi(\omega_0, t_0)\,|VV\rangle$$

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