Istituto Nazionale di Fisica Nucleare

Dipartimento Interateneo di Fisica "M. Merlin"

Doctoral Course XXXIII cycle - Research Activity Report II year

From Correlation Imaging to Quantum Correlations

Giovanni Scala

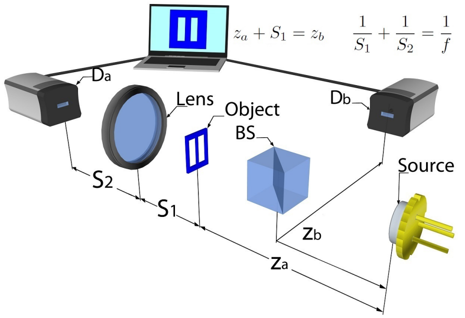
Supervisor: Prof. Saverio Pascazio

Outline

- Spatial correlations of light for imaging and sensing
  - double slit experiment at the second-order
  - how to restore the interference pattern (turbolence-free concept comes up)
- Quantum Electrodynamics in the media
  - Spontaneuos emission and Lamb shift in asymmetric systems
  - proposed experiment
- Measuring Quantum Correlations
  - criteria of separability
  - my criterion of separability

Second order Imaging

The scheme exploits second-order correlations of light propagating through disjoint paths.



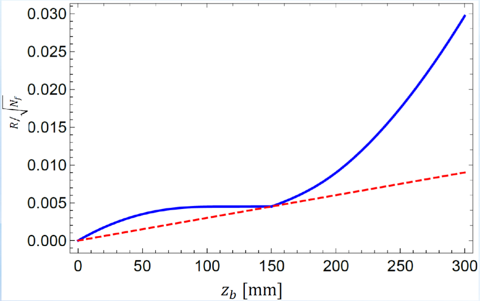
Correlation function

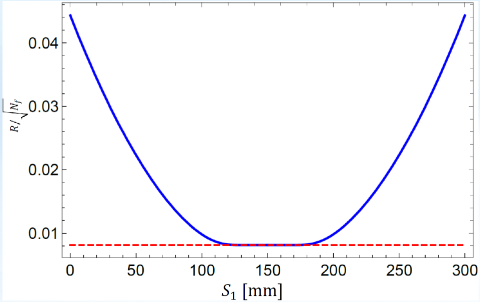
$$\Gamma(x_C, x_T) = \langle \Delta I_C(x_C) \Delta I_T(x_T) \rangle$$

$$= \left| \int \mathcal{S}(x_s) g_T(x_T, x_s) g_C^*(x_C, x_s) dx_s \right|^2$$

SNR in a correlation plenoptic microscope

SNR for the refocused image (solid blue line), and for a ghost image (red dashed line) for SETUP1 (left) and SETUP2 (right) taken at $z_a = z_b$ (for S1) and at $S_2^f = (1/f - 1/S_1)^{-1}$ (for S2) as a function respectively of z_b and S_1.



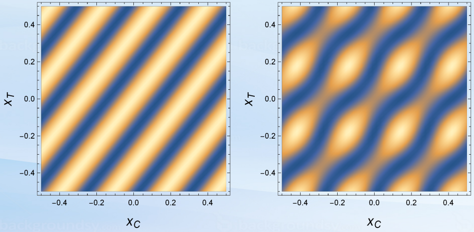


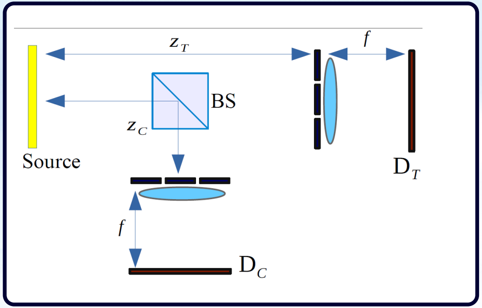
SETUP1 **results more advantageous than** SETUP2**:** e.g. at $z_b = S_1 = 80\,\mathrm{mm}$, one tenth of the frames is needed in SETUP2 to reach the same SNR as in

Intensity correlations for distance detection

G. Scala, M. D'Angelo, A. Garuccio, S. Pascazio, and F. V. Pepe, Phys. Rev. A 99,(2019)

After that, we are exploiting the Young experiment at the second order





QED in assisted-media in microcavity

Modelling the atom as a dipole of charge Q, with a heavy positive charge in the fixed position $\boldsymbol{R} = 0$ and a moving negative charge of mass m and coordinate $-\mathbf{r}$, one finds the dipole Hamiltonian

$$H_{\mathrm{int}}^{\mathrm{dip}} = \frac{Q}{\epsilon_0}\mathbf{r} \cdot \int_0^1 \boldsymbol{\Pi}(-s\mathbf{r})\,\mathrm{d}s,$$

- **Regularization of ultraviolet divergence** for the decay rate Γ [?]

$$\Gamma = \frac{2\pi}{\hbar^2} \sum_{b \neq a} \theta(\omega_{ab}) \int \left| \langle a | H_{\mathrm{int}}^{\mathrm{dip}} | b; (\boldsymbol{q}, \omega) \rangle \right|^2 \mathrm{d}^3\boldsymbol{q},$$

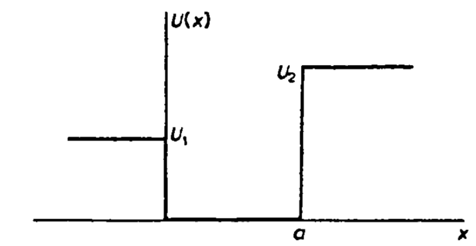
- The theory works for a continuos medium!

Applications: Quantum Well

A semiconductor quantum well surrounded by two layers of material with wider band gap, for the confinement of a quasi-electron by an appropriate potential

This is my *artificial atom* surrounded by a continuos medium.
I study

- environment coupling (enhancement of intrinsic dipole moment effects)
- new transition lines due to the asymmetry
- we are considering other testbeds



Quantum Correlations

Is a given state entangled and does it contain quantum correlations, or is it separable, and does not contain any quantum correlations?

A state of a bipartite system living in $\mathcal{H}_A \otimes \mathcal{H}_B$ represented by a density matrix ρ is separable if (Werner,1989)

$$\rho = \sum_k p_k \rho_k^A \otimes \rho_k^B,$$

where p_k is a probability distribution and ρ_k^A (ρ_k^B) are density operators of subsytem A (B).

Let a system in $\mathcal{H}_A \otimes \mathcal{H}_B$ with dimensions d_A and d_B. Let G^A_α and G^B_β denote arbitrary orthonormal basis in $\mathcal{B}(\mathcal{H}_A)$ and $\mathcal{B}(\mathcal{H}_B)$, such that $\mathrm{Tr}(G^{A\dagger}_\mu G^A_\nu) = \delta_{\mu\nu}$, and the same for G^B_β. $D^T_t = \mathrm{diag}\{t, 1, \ldots, 1\}, t = a, b \in \mathbb{R}$.
Now, given a bipartite state ρ one defines the following correlation matrix

$$C_{\alpha\beta} = \langle G^A_\alpha \otimes G^B_\beta \rangle = \mathrm{Tr}(\rho G^A_\alpha \otimes G^B_\beta).$$

If ρ is separable, by CCNR criterion $\|C\|_{\mathrm{tr}} \leqslant 1$. Instead my criterion is

$$\|D^A_a C D^B_b\|_{\mathrm{tr}} \leqslant \sqrt{\frac{d_A - 1 + a^2}{d_A}} \sqrt{\frac{d_B - 1 + b^2}{d_B}}.$$

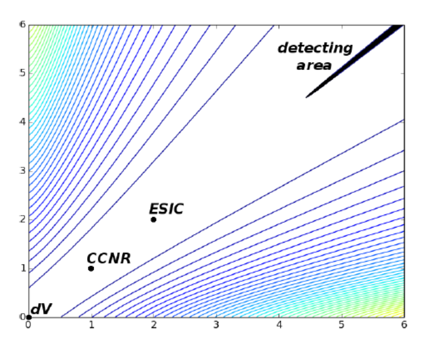


Figura: Three characteristic points on the *ab*-plane: $(0,0)$ – dV; $(1,1)$ – CCNR, and $(2,2)$ – ESIC. The state is detected by my criterion for (a,b) belonging to the "detecting area".

- **This criterion is very strong and it could a prominent presciption for quantumness**

Activities

I did all my exams and also attended the following schools and conferences:

- *51st Symposium on Mathematical Physics*, Toruń (Poland), 16–18 June 2019, with presentation of the talk "The Friedrichs-Lee model and its singular coupling limit";
- *Summer School: Topics in Quantum Probability*, Genoa, 1–3 July 2019;
- *Introductory Course on UltracoldQuantum Gases*, Innsbruck (Austria), 8–10 July 2019;
- *Italian Quantum Information Science conference*, Milan, 9–12 September 2019, with presentation of the poster "Bound states in the continuum for an array of quantum emitters".
- *YQIS 2019: 5th International Conference for Young Quantum Information Scientists*, University of Gdansk, Sopot, Poland, September 25-27, 2019.

Collaborations and Publications

During this year I have worked with *prof. D. Chruściński, prof.ssa K. Słowik and prof. G. Sarbicki*

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

- G. Scala, M. D'Angelo, A. Garuccio, S. Pascazio, and F. V. Pepe, *"Signal-to-noise properties of correlation plenoptic imaging with chaotic light"*, Phys. Rev. A 99, 053808 (2019)
- G. Sarbicki, G. Scala, and D. Chruściński, *"A family of multipartite separability criteria based on correlation tensor"* (submitted to PRL)
- P. Facchi, S. Pascazio, F. V. Pepe, G. Scala, K. Słowik, *"QED for asymmetric systems in a medium"* (will be submitted in November)

Thank you for the attention!