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UNIVERSITÀ DEGLI STUDI DI MILANO

INTERNATIONAL COORPERATION AGREEMENT

Academic, scientific and technical cooperation agreement by and between the Federal University of São Carlos (Brazil) and *Università degli Studi di Milano* (Italy)

The Federal University of São Carlos, based on São Carlos campus, at *Rodovia* Washington Luís, km 235, in São Carlos, in the state of São Paulo, Brazil, in this act represented by its Rector, Prof. Wanda Aparecida Machado Hoffmann, Ph.D., and *Università degli Studi di Milano*, based at 7 *Via Festa del Perdono*, in Milan, Italy represented in this act by its Rector, Prof. Elio Franzini, aiming to formally promote academic, scientific and technical cooperation between them, and acknowledging that such collaboration may result in their continuous strengthening and advancement, enter into this Agreement, which shall be governed by the following terms and conditions:

SECTION 1 – PURPOSE

The Federal University of São Carlos and *Università degli Studi di Milano* agree to promote academic, scientific and technical cooperation between them, in knowledge areas and/or regarding scientific topics of their mutual interest, which may comprise:

a) Exchange of faculty and researchers.
b) Joint development of research projects, such as the project "Cooperative stochastic heating and optical binding with cold atoms" (see Annexes A and B).
c) Co-organization of academic, scientific and cultural events, *e.g.*, conferences, symposia, seminars and colloquia.
d) Assignment and exchange of scientific and technical information and publications.
e) Other academic, scientific and cultural programs, projects and activities that the Parties may mutually wish to develop, in accord with their respective institutional purposes.

SECTION 2 – IMPLEMENTATION

The development of any activity listed in the previous clause, which will be implemented under this Agreement, shall respect the rules in force at both Parties, will be subject to formal programs or projects that have been prior approved by their respective authorities or authorized bodies, must be displayed following the format provided in Annex A hereto and will depend upon the availability of appropriate funds.

SECTION 3 – FUNDING

Both Parties shall strive to procure funding from internal and/or external sources, in order to propitiate the development of academic, scientific and technical activities under this Agreement. The Parties are not compelled to give any guarantee regarding the availability of funds.

SECTION 4 – REQUIREMENTS

Faculty, researchers and technical and administrative staff taking part in activities under this Agreement shall comply with the immigration requirements of the country where the host institution is situated and must purchase insurance of international medical and hospital services, personal accident, civil liability, and medical and mortal remains repatriation, covering their respective whole stay abroad.

SECTION 5 – INTELLECTUAL PROPERTY RIGHTS

Each Party shall own all Intellectual Property (IP) rights which are generated by its faculty, researchers, students and agents within the development of projects and activities hereunder. Considering that this Agreement is important to the progress of science and the production of knowledge and technology, both Parties agree to provide each other with non-exclusive, cost free, mutual licenses to make use of such IP for the sole purpose of internal non-commercial academic activities.

In the event that both Parties are responsible for the joint generation of IP, such IP shall be jointly owned in accordance with the inventive contribution made by each Party and in compliance with the national legislation of their respective countries, the valid international conventions on the subject and, where the case, also with the policies for IP defined by the institution(s) which is(are) responsible for funding the research staff. Should such IP be capable of commercial exploitation, neither Party shall exploit it without the prior consent from the other, following terms to be agreed in writing by means of a specific agreement or contract.

SECTION 6 – PUBLICATION OF RESULTS

Both Parties shall jointly publish results arising from the cooperation set forth herein, in accordance with the usual academic practice and their respective policies. In the event of publication by one Party, the other Party shall be asked to give thirty (30)-day prior written consent. If such consent is not given within the stipulated period, the publication will be considered to have been authorized.

Both Parties shall be free to use any scientific and technical information created or transferred in the course of the collaborative academic activities described in Section 1 hereof for their own research and development purposes. However, any use by either Party of the other Party's background information for research and development purposes shall be the subject of a separate specific agreement.

SECTION 7 – CONFIDENTIALITY OF INFORMATION

This Agreement and all documents and information provided by one Party to the other party under or in connection herewith or any subsequent contractual duties shall be treated as confidential ("the Confidential Information"), pursuant the policies of each Party and the national legislation of both countries. The Confidential Information shall not be used except for the purposes for which it was made available, and the Confidential Information shall not be disclosed to any other person without the prior written consent of the disclosing party.

Neither Party will be in breach of any obligation to keep any Confidential Information confidential or not to disclose it to any other party to the extent that it:

i. is known to the party making the disclosure before its receipt and not subject to any obligation of confidentiality to another party; or
ii. is or becomes publicly known without any breach of this Agreement or any other undertaking to keep it confidential; or
iii. has been obtained by the party making the disclosure from a third party in circumstances where the party making the disclosure has no reason to believe that there has been a breach of an obligation of confidentiality; or
iv. has been independently developed by the party making the disclosure; or
v. is disclosed pursuant to the requirement of any law or regulation or the order of any Court of competent jurisdiction, and the party required to make that disclosure has

informed the other party whose information it is, within a reasonable time after being required to make the disclosure, of the requirement to make the disclosure and the information required to be disclosed; or

vi. is approved for release in writing by an authorized representative of the party whose information it is.

SECTION 8 – EFFECTIVE TERM

This Agreement is valid as from the date of the last signature by both Parties and will remain in force for five (5) years.

SECTION 9 – AMENDMENTS

Any changes to the terms and conditions of this Agreement, including the extension of the duration hereof, shall only become effective by means of a written amendment or addendum signed by both Parties.

SECTION 10 – COORDINATION

As coordinators for this Agreement the following are appointed: on behalf of the Federal University of São Carlos, Dr. Romain Pierre Marcel Bachelard, professor of the Department of Physics; and on behalf of *Università degli Studi di Milano*, Dr. Nicola Umberto Cesare Piovella, professor of *Dipartimento di Fisica* "Aldo Pontremoli".

SECTION 11 – TERMINATION

This Agreement may be terminated at any time by either Party by giving at least three (3) months' advance written well-founded termination notice to the other Party, along with return receipt. Eventually ongoing activities by the time of the termination will be duly concluded.

SECTION 12 – SETTLEMENT OF DISPUTES

Questions and controversies arising from the interpretation or execution of this Agreement will be friendly solved by the Parties. In case a friendly solution is not possible or achieved, they shall jointly appoint a third party, natural person, to act as arbitrator or mediator.

Both Parties sign this agreement in four identical copies, two in Portuguese and two in English, to the same effect.

São Carlos, São Paulo (Brazil), 9 DEC. 2019 Milan (Italy), - 9 GEN. 2020

Wanda Hoff

Prof. Wanda Aparecida Machado Hoffmann, Ph.D.
Rector
Federal University of São Carlos

UNIVERSIDADE FEDERAL DE SÃO CARLOS UFSCar

Prof. Elio Franzini
Rector
Università degli Studi di Milano

UNIVERSITAS STUDIORUM MEDIOLANENSIS

ANNEX A – Display format of the specific academic, scientific and/or technical activity to be jointly implemented

Activity nature/title	Joint research project "Cooperative stochastic heating and optical binding with cold atoms", selected by São Paulo Research Foundation (FAPESP) on the framework of program SPRINT – São Paulo Researchers in International Collaboration in October 2019, under the call for proposals 2nd Edition/2019
Funding source	FAPESP Grant Number 2019/12842-2 in connection with SPRINT program
Direct responsible – Federal University of São Carlos	Prof. Romain Pierre Marcel Bachelard, Ph.D. (Department of Physics)
Direct responsible – *Università degli Studi di Milano*	Prof. Nicola Umberto Cesare Piovella, Ph.D. (*Dipartimento di Fisica* "Aldo Pontremoli")
Wanda Hoff **Signature for and on behalf of the Federal University of São Carlos**	Name: Prof. Wanda Aparecida Machado Hoffmann, Ph.D. Title: rector Date: 9 DEC. 2019
Signature for and on behalf of *Università degli Studi di Milano*	Name: Prof. Elio Franzini Title: Rector Date: - 9 GEN. 2020

ANNEX B – Research project to be jointly developed

See enclosed project.

Cooperative Stochastic Heating and Optical Binding with Cold Atoms

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Coordinator in Brazil: **Romain Pierre Marcel Bachelard**

Coordinator in Italy: **Nicola Umberto Cesare Piovella**

1st of July 2019

Keywords:

Light scattering

Cold Atoms

Cooperative scattering

Optical binding

Summary – Large ensembles of cold atoms present strong cooperative properties as they scatter light, which results in a modified spontaneous emission. While cooperative scattering has been extensively studied up to date, its consequences on stochastic effects and on optical forces are still to be investigated, and it is the two objectives of the present project. The first goal will be to elucidate whether random emission events resulting from modes of cooperative scattering enhance or rather reduce the heating. The second goal addresses the optical binding regime, when mutual optical forces lead to a self-organization of the cloud. The two PIs have recently shown that optical binding of $N = 2$ cold atoms is possible, although stochastic effects (spontaneous emission) challenge the stability of these pair states. In this project, we will take advantage of superradiance to show that the cooling mechanism that make these states possible can be amplified to the point where it can counter stochastic effects: Our study will focus both on 1D chains and 2D lattices, as the dimensionality affects in a critical way the cooperation strength.

Introduction – Light–matter interaction has always been both a central subject of scientific investigation and a pioneer of technological innovation. Exploring and exploiting the optomechanical coupling between light and matter has initiated the exciting and lively research field of optomechanics, especially during the last decade where quantum optomechanical effects finally became measurable[1,2]. In particular, optical forces can be at the origin of novel nonlinearities leading to self-organized matter structures[3]. The resulting ordered structures are beautiful examples of novel quantum states of matter, appearing as a consequence of non-equilibrium, nonlinear quantum dynamics. From the perspective of applications, they lend themselves to innovative quantum simulations of many-body systems with types of tailored interactions not achievable by externally imposed optical lattices.

While optical cavities and other systems with an environment-modified density of states allow one to strongly enhance the light-matter coupling, this project rather focuses on the many-particle ("cooperative") enhancement that can be found in light scattering by cold atoms. The hallmark of the dipole-dipole coupling is superradiance[4], where the radiation of in-phase emitters allows to accelerate the emission process. Although initially discussed in the context of a fully-inverted system of quantum emitters, it was later identified closed to the ground state, in the linear-optics regime. More generally, the light-induced coupling through the exchange of real and virtual photons results in a long-range interaction that produces a macroscopic scattering mode, even for dilute systems[5].

Self-organization processes with cold atoms generally include mirrors to allow for a feedback of the light[6], yet self-organization in the 3D free space scattering case remains to be demonstrated. Indeed, while multiple scattering processes by the atoms themselves can in principle provide such feedback, spontaneous emission seem to be a strong adversary. Our strategy is to focus on atoms confined in a 2D plane, within a stationary wave, although their scattering properties are fundamentally 3D. This setup has been shown by the PIs to be appropriate for optical binding of pairs of atoms[7,8]. Optical binding has been widely investigated in the context of steady-state regime for dielectric sphere arrays trapped through dissipative forces. In the cold atom case, stochastic effects, due to the fact that the 2D trapping of the atoms (which also serves as a pump for the optical binding), results in a significant heating: for $N = 2$ atoms, the cooling effect achieved by the dipole-dipole interaction is insufficient to guarantee the bound state stability.

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Scientific program

This project aims at determining the impact of stochastic effects from cooperative modes, and at achieving optical binding in large atomic samples, considering the long-range dipole-dipole interactions. A direct manifestation of these interactions is the well-known phenomenon of superradiance, where the in-phase atomic dipoles emit in an accelerated way. We will investigate the impact of cooperativity on the optical binding of $N \gg 1$ atoms, considering that the acceleration of the emission has the potential to enhance the cooling effect that is present in the binding of $N = 2$ particles (for an appropriate choice of detuning). The study of 1D and 2D configurations will allow to tune the cooperativity and the fluctuations, as they depend critically on the system dimensionality. Indeed, the large systems we aim to study will be subjected to significant fluctuations in the dipolar force, i.e., stochastic heating effects that originate in cooperative scattering modes: Such effects remain to be investigated systematically, and it is an important objective of this project, as it may determine the statibility of dense atomic samples.

1. Optical binding of 1D chains of cold atoms – Instead of trapping the atoms in a single stationary wave, two crossed stationary waves can be created to confine the atoms in 1D, a technique standard in optical lattices. Yet, if no trapping is imposed in the last direction, each atom becomes subjected to the optical forces generated by its colleagues, and a 1D self-organization process may be triggered. A particularly interesting point is that the atoms are expected, under the effect of the exchanged photons, to organize at a distance of multiples of λ, the light wavelength, up to cooperative corrections. Then, imagining a line of atoms separated by λ, each atom will feel the dipolar force created by all other atoms, which shall add up coherently. The resulting optical potential may thus be much deeper than for a pair of atoms, and optical binding become stable. Indeed, stochastic effects are mainly due to the pump (the stationary wave), rather than the radiation from the other atoms: this first contribution will remain unchanged by the addition of many atoms.

The steps foreseen to study the 1D configuration are the following:

- Study of the optical potential self-generated by a 1D chain of atoms, considering that cooperative corrections bring a correction (that increases with the system size) to the naive separation of λ.
- Characterization of the cooperative cooling rate for the chain of atoms.
- Study of the global stability of the 1D chain, considering both cooling and stochastic effects (the detuning and the number of atoms are crucial parameters).

2. Optical binding of a 2D lattice of cold atoms – In two dimensions, the atoms may organize in different configurations. Yet, since the pair physics suggests an optimal spacing of λ, one may expect a series of equilateral triangles, so each atom will be at the center of a hexagon, thus possessing six nearest neighbors. The optical potential created by these neighbors is already expected to be six times deeper than the one of the pair case, which supports the idea of an increased stability for the system.

A notable difference compared to the 1D case is that, beyond these nearest neighbors, each atom receives the field from atoms that are not at a multiple of the wavelength, i.e., whose contribution may contribute destructively to the binding. In this case, the determination of the optical potential, of the cooling rate and of the overall stability of the system is thus much more challenging.

This objective will be approached through the following steps:

- Determination of the optical potential for a 2D lattice of cold atoms, studying the most stable configuration (i.e., with deepest potential). More than in the 1D case where most atoms are expected to contribute constructively to the binding, boundary effects may be critical in 2D.

- Study of the cooling rate, and its competition with stochastic heating, for different lattice configurations.

3. Fluctuations in the optical forces: cooperative stochastic effects – Optical binding relies on a coherent contribution from the optical forces. Regarding its fluctuations, for a pair of atoms at a distance of the order of the optical wavelength most of the light scattered (that is, ~97%) comes directly from the incident wave itself, rather than from mutually exchanged photons, and so do stochastic effects associated to spontaneous emission: the atomic recoil can essentially be understood from the single-atom case. Nevertheless, with the rise of collective effects as the number of atoms increase, optical forces generated by the other atoms will represent a stronger and stronger contribution, and significant stochastic effects coming from these will emerge. A crucial difference with the pump field is that these correspond to collective scattering modes, i.e., their properties cannot be stated simply in terms of (isotropic) single-atom physics. Although these effects are known to be present, their cooperative nature has not been evidenced up to now, although the equations that describe them were written down. Indeed, in disordered systems, evaluating them may be a particularly challenging task.

We will thus characterize these in our 'simplified' frame of self-ordered lattices, where semi-analytical calculations may be much more tractable. In particular, we aim to study both the 1D and 2D configurations to understand if the role of these fluctuations is, in essence, very similar to the single-atom ones, or if the presence of strongly cooperative modes, with highly anisotropic properties, can change the deal.

At first, we will concentrate on the 1D case, as it presents a much simpler framework, where only the projection of the atomic recoil on the chain axis need to be studied. One important point will be to determine how inhomogeneous these fluctuations are, since atoms at the system boundaries may undergo stochastic effects quite different from the atoms at the center of the chain.

Then, the 2D case will be studied, where different lattice configurations will result in new anisotropies for the collective modes, so the cooperative stochastic effects may be qualitatively different. We note that while this study is an important step to assess the experimental feasibility of optical binding with cold atoms, it is also an investigation of fundamental importance, as cooperative stochastic effects may lead to stability properties or phase transitions that are unexpected from the naive single-atom picture.

Impact on the main project

Cooperative spontaneous emission is expected to be particularly strong in the dense regime, that is, the regime reached to probe Anderson localization of light. It is thus crucial to understand their impact on the cloud, as it may lead to unexpected heating and forces. The study of these effects in different dimensions is particularly important for the main project, which also addresses the dense regime in different dimensions.

Expected results

Scientifically, we aim at characterizing the stochastic effects resulting from the fluctuations in the dipolar force, and at showing that cooperative effects allow for the formation of many-atom optically bound states. Practically, we expect to publish several joint papers (at least 4) that would result from the project, in high level journals (Phys. Rev. Lett., Phys. Rev. A). We will naturally divulgate our results in scientific conferences. We also expect this project to have a positive impact on the students in each group, as they will have the opportunity to interact with the visiting researchers.

On the long-term, this mobility project is important to guarantee an active participation of the Brazilian group to the European network activities, and continue to submit joint projects (such as the present European one, which was preceded by another European RISE project from FP7, from which the Brazilian researchers could directly benefit).

Past results

The collaboration between Profs. Bachelard and Piovella over the past year has been extremely fruitful. Several projects took place, resulting in a number of **19 jointly published papers** since 2010: see https://romain.df.ufscar.br/publications.html for details.

The present project will guarantee the continuity of the collaboration between the two professors, by providing financial support to the Brazilian researcher: the two professors presently benefits of a funding from a European project dedicated to self-organization processes (Marie Skodowska-Curie action, grant agreement 72146), which allows the Italian group to travel to São Carlos.

Yet due to the rules of the Horizon 2020 framework, Brazilian researchers do not benefit directly from this funding (apart from receiving European researchers), and the present SPRINT mobility will represent the support necessary for the Brazilian researchers to visit the Italian group.

Teams

The Brazilian coordinator has a strong expertise in long-range interactions and their applications to light-matter interactions, on which he has been working for many years. He is working in close collaboration with Prof. Philippe Courteille, a cold atom experimentalist in São Carlos, which experiment is also dedicated to light-matter instabilities (FAPESP Thematic 2013/04162-5): the feedback from the experimental group will thus be particularly useful to discuss the feasibility of the proposed scheme. The Brazilian team for this mobility project is composed of:

- Prof. Romain P M Bachelard (coordinator)
- Dr. Carlos Eduardo Maximo, a post-doctoral researcher who has experience in the field
- one post-doctoral researchers that has to be hired within the frame of the JP2 main project (2 post-doc scholarships were granted to that end).

Prof. Piovella is a recognized theorist in light-matter interactions, who dedicated many years to the study of Free Electron Laser dynamics, as well as its "cold-atom counterpart", the Collective Atomic Recoil Laser. While Prof. Bachelard brings the long-range expertise, important to understand the large-size scaling of the problem, as well as numerical skills, Prof. Piovella has more than two decades of experience in self-organization processes, and will bring strong analytical insights.

At the moment, the Italian team that will dedicate to this project is composed of

- Prof. Nicola C U Piovella
- Angel T Gisbert, PhD student from the European project.

Missions

Period	Brazil -> Italy		Italy -> Brazil	
	Researcher	**Duration**	**Researcher**	**Duration**
Year 1	Romain Bachelard	12 days	Nicola Piovella	10 days
	Study of heating/cooling in 1D chains		Study of heating/cooling in 1D chains	
Year 1	Carlos E Maximo	10 days	Angel Gisbert	12 days
	Study of heating/cooling in 2D chains		Study of heating/cooling in 2D chains	
Year 2	Romain Bachelard	10 days	Nicola Piovella	10 days
	Study of fluctuations/heating in 1D		Study of fluctuations/heating in 1D	
Year 2	Post-doctoral researcher	12 days	Angel Gisbert	12 days
	Study of fluctuations/heating in 2D		Study of fluctuations/heating in 2D	

To realize this project, we have planned 2 missions per year and per side. These missions will aim at synchronizing our efforts, gather results and analyses, and develop the theory in a more unified way.

The chronogram for the missions is the following:

The price of the São Paulo-Milan ticket, way and return, is estimated to 900 US$. Using a basis of per-diem of 250 US$ in Milano, the above missions amount to US$8800 euros per year.