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UNIVERSITÀ DEGLI STUDI DI MILANO

ACORDO DE COOPERAÇÃO INTERNACIONAL

Acordo de cooperação acadêmica, científica e técnica entre a Universidade Federal de São Carlos (Brasil) e a Universidade de Milão (Itália)

A Universidade Federal de São Carlos, com sede no *campus* São Carlos, na Rodovia Washington Luís, km 235, em São Carlos (SP), Brasil, representada neste ato por sua reitora, Prof.ª Dr.ª Wanda Aparecida Machado Hoffmann; e a Universidade de Milão, sediada na Via Festa del Perdono, n.º 7, em Milão, Itália, representada neste ato por seu reitor, Prof. Elio Franzini; interessadas em promover formalmente a cooperação acadêmica, científica e técnica entre elas, e cientes de que tal colaboração pode resultar em seu fortalecimento e avanço contínuos, celebram este acordo, que se rege pelos termos e condições a seguir:

CLÁUSULA PRIMEIRA – PROPÓSITO

A Universidade Federal de São Carlos e a Universidade de Milão concordam em promover cooperação acadêmica, científica e técnica entre elas, em áreas do conhecimento e/ou sobre temas do interesse de ambas, o que pode incluir:

a) Mobilidade de professores e pesquisadores;
b) Desenvolvimento conjunto de projetos de pesquisa, nomeadamente o projeto "Aquecimento estocástico cooperativo e ligação óptica com átomos frios" (Anexos A e B);
c) Coorganização de eventos acadêmicos, científicos e culturais, tais como: congressos, simpósios, seminários e colóquios;
d) Cessão e troca de informações e publicações científicas e técnicas;
e) Outras atividades acadêmicas, científicas e técnicas do interesse de ambas as Partes e que correspondam aos objetivos institucionais de cada uma delas.

CLÁUSULA SEGUNDA – IMPLEMENTAÇÃO

A realização de qualquer das atividades previstas na cláusula anterior, a ser implementada no âmbito deste Acordo, deve observar as normas das duas Partes, está sujeita a programas ou projetos formais que tenham sido aprovados previamente pelas autoridades ou órgãos competentes das instituições, deve apresentar-se no formato disponível no Anexo A, e depende da disponibilidade dos recursos financeiros necessários.

CLÁUSULA TERCEIRA – FINANCIAMENTO

As Partes envidarão esforços para obter fundos oriundos de fontes internas e/ou externas de fomento, a fim de tornar possível a realização de atividades acadêmicas, científicas e técnicas no âmbito deste Acordo. As Partes não estão obrigadas a fornecer garantia de disponibilidade de fundos.

CLÁUSULA QUARTA – EXIGÊNCIAS

Professores, pesquisadores e funcionários técnicos e administrativos que participarem de atividades no âmbito deste Acordo deverão cumprir os requisitos de imigração do país da instituição anfitriã e contratar seguro internacional de cobertura médico-hospitalar, contra acidentes pessoais, de responsabilidade civil e de repatriação sanitária e funerária para toda a sua respectiva estadia no exterior.

CLÁUSULA QUINTA – DIREITOS DE PROPRIEDADE INTELECTUAL

Cada Parte possuirá a propriedade intelectual (PI) que for gerada por seus respectivos professores, pesquisadores, alunos e funcionários no desenvolvimento de projetos e atividades no âmbito deste Acordo. Considerando que o presente instrumento é relevante para o avanço da ciência e para a produção de conhecimento e tecnologia, as Partes concordam em fornecer uma à outra licenças mútuas não exclusivas e não onerosas para a utilização da PI para fins não comerciais em atividades acadêmicas de cada uma delas.

Na hipótese de ambas as Partes serem responsáveis pela geração conjunta de PI, a propriedade dessa PI será compartilhada em conformidade com a contribuição de cada uma delas na invenção, observadas as respectivas legislações nacionais aplicáveis, as convenções internacionais em vigor sobre a matéria e, quando for o caso, também a política para PI da(s) instituição(ões) responsável(is) pelo financiamento das equipes de pesquisa. Se essa PI for passível de exploração comercial, nenhuma das Partes poderá explorá-la sem o consentimento da outra e deverá fazê-lo segundo termos e condições a serem estipulados por escrito em um acordo específico.

CLÁUSULA SEXTA – PUBLICAÇÃO DE RESULTADOS

As Partes deverão publicar em conjunto os resultados decorrentes da cooperação objeto deste Acordo, respeitadas a prática acadêmica usual e suas respectivas políticas. No caso de publicação a ser feita por uma das Partes, esta solicitará o consentimento por escrito da outra Parte com antecedência mínima de 30 (trinta) dias. Caso tal consentimento não seja dado dentro desse prazo, considerar-se-á autorizada a publicação.

As Partes terão a liberdade de utilizar quaisquer informações científicas e técnicas criadas ou transferidas no decorrer do desenvolvimento das atividades previstas na Cláusula Primeira, para os objetivos de seus projetos de pesquisa e desenvolvimento. Não obstante, a utilização, por qualquer das Partes, com objetivo de pesquisa e desenvolvimento, de informações resultantes das atividades e experiências da outra Parte estará sujeita a um acordo específico separado.

CLÁUSULA SÉTIMA – CONFIDENCIALIDADE DE INFORMAÇÕES

Este Acordo e todos os documentos e informações disponibilizados por uma Parte à outra, no âmbito de ou em conexão com o presente instrumento ou qualquer compromisso contratual subsequente, serão tratados com confidencialidade ("Informação Confidencial"), nos termos das políticas de cada Parte e das respectivas legislações nacionais. A Informação Confidencial não poderá ser utilizada a não ser para os objetivos aos quais ela foi disponibilizada e não poderá ser revelada, por qualquer das Partes, para nenhuma outra parte sem o consentimento prévio, por escrito, da outra Parte.

Não obstante, nenhuma das Partes descumprirá a obrigação de manter a confidencialidade da Informação Confidencial ou de não a divulgá-la a terceiros caso:

i. a Informação Confidencial seja conhecida, antes de seu recebimento, pela Parte que a divulgar e caso não esteja sujeita a nenhuma obrigação de confidencialidade pela outra Parte; ou
ii. a Informação Confidencial seja ou torne-se conhecida publicamente sem a violação deste Acordo ou de qualquer outro compromisso de confidencialidade; ou
iii. a Informação Confidencial tenha sido obtida de terceiros pela Parte que a divulgar sob circunstâncias em que esta não possuía motivos para crer que tivesse havido violação de dever de confidencialidade; ou

iv. a Informação Confidencial tenha sido desenvolvida de modo independente pela Parte que a divulgar; ou
v. a Informação Confidencial seja divulgada em conformidade com lei, regulamento ou ordem de qualquer órgão judicial de jurisdição competente, e se a Parte que houver sido obrigada a fazer a divulgação tenha informado a Parte à qual pertencia a informação, dentro de prazo razoável após o recebimento da ordem de divulgação, de que fora obrigada a fazer a divulgação e de qual informação tivera de divulgar; ou
vi. a Informação Confidencial seja aprovada para divulgação por escrito por um representante autorizado da Parte à qual ela pertença.

CLÁUSULA OITAVA – VIGÊNCIA

Este Acordo entra em vigor na data da última assinatura pelas Partes e permanecerá vigente pelo prazo de 5 (cinco) anos.

CLÁUSULA NONA – TERMOS ADITIVOS

Qualquer alteração nas disposições deste Acordo, incluindo a prorrogação de seu prazo de vigência, fixado na cláusula anterior, deve ser efetuada mediante termo aditivo devidamente firmado pelas Partes.

CLÁUSULA DEZ – COORDENAÇÃO

Como coordenadores deste Acordo, são designadas as seguintes pessoas: pela Universidade Federal de São Carlos, Prof. Dr. Romain Pierre Marcel Bachelard, do Departamento de Física; e, pela Universidade de Milão, Prof. Dr. Nicola Umberto Cesare Piovella, do Departamento de Física "Aldo Pontremoli".

CLÁUSULA ONZE – RESCISÃO

Este Acordo pode ser rescindido a qualquer momento por qualquer das Partes, por meio de notificação fundamentada por escrito à outra Parte, apresentada com antecedência mínima de 3 (três) meses e aviso de recebimento. As atividades eventualmente em curso na ocasião da rescisão serão concluídas adequadamente.

CLÁUSULA DOZE – RESOLUÇÃO DE CONTROVÉRSIAS

Questões e controvérsias oriundas da interpretação ou da execução deste Acordo serão solucionadas mediante entendimento direto e amigável entre as Partes. Quando tal solução não for possível, elas indicarão consensualmente um terceiro, pessoa física, para atuar como árbitro ou mediador.

As Partes firmam o presente instrumento em quatro vias idênticas e para um só efeito, sendo duas em português e duas em inglês.

São Carlos, São Paulo (Brasil), 9/12/2019 Milão (Itália), - 9 GEN. 2020

Prof.ª Dr.ª Wanda Aparecida Machado Hoffmann
Reitora
Universidade Federal de São Carlos

UNIVERSIDADE FEDERAL DE SÃO CARLOS

Prof. Elio Franzini
Reitor
Universidade de Milão

UNIVERSITAS STUDIORUM MEDIOLANENSIS

ANEXO A – Formato de apresentação da atividade acadêmica, científica e/ou técnica específica a ser implementada

Natureza/Título da atividade	Projeto de pesquisa conjunto "Aquecimento estocástico cooperativo e ligação óptica com átomos frios", selecionado pela Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) no âmbito do programa SPRINT – *São Paulo Researchers in International Collaboration* em outubro de 2019, sob a chamada para propostas Edição 2/2019
Fonte de Financiamento	Processo FAPESP n.º 2019/12842-2, referente ao programa SPRINT
Responsável direto – Universidade Federal de São Carlos	Prof. Dr. Romain Pierre Marcel Bachelard (Departamento de Física)
Responsável direto – Universidade de Milão	Prof. Nicola Umberto Cesare Piovella (Departamento de Física "Aldo Pontremoli")
Wanda [assinatura] **Assinatura – representante da Universidade Federal de São Carlos**	Nome: Prof.ª Dr.ª Wanda Aparecida Machado Hoffmann Função: reitora Data: 9/12/2019
[assinatura] **Assinatura – representante da Universidade de Milão**	Nome: Prof. Elio Franzini Função: reitor Data: - 9 GEN. 2020

ANEXO B – Projeto de pesquisa a ser desenvolvido em conjunto

Ver projeto anexo.

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.