30th of November 2021

N_{15}

Normale Physics Review

NPR

École normale supérieure

— *Fights Bohr-dom* —

Édito N_{15} : the NPR at the origins of physicists

It is fantastic to be constantly exposed to new fascinating phenomena and ideas. It is great to discover the different ways of thinking and tackling scientific problems. The Normale Physics Review plays an important role in conveying all these different exciting facets of physics. In this issue: deconfinement phase transition, ants and optics, Quantum Ideas Factory, and much more. I wish I had such review to read when I was a student! As written in this issue, this is a time at which M2 students begin to look for a PhD. Within all the information provided to help and guide them, there is one missing piece: personal histories. How did the career of well-known physicists unravel from the very beginning? How did they choose their PhDs? The Normale Physics Review makes a very good job in describing students life. Interviewing "grown-up" physicists about the beginning of their career and their life as students would be a very instructive and interesting addition. It would show the multitude of career paths that one can follow, and provide some guidance on how to choose and construct your own path.

– *Giulio Biroli*[1]

Announcements

Mystère de la nature

Heisenberg écrivait : "Nous vivons dans un monde si complètement transformé par l'homme que nous rencontrons partout les structures dont il est l'auteur... emploi des instruments de la vie quotidienne, transformation du paysage par l'homme, de sorte que l'homme ne rencontre plus que lui-même."

Dans cette première réunion (le 2 décembre), nous interrogerons notre rapport à la nature par un itinéraire à travers la philosophie, la poésie, la littérature, et le témoignage de la civilisation sioux. La réunion se déroulera à travers des lectures, échanges, projections... Pas de physique directement en vue pour le moment (une suite est prévue le 27 janvier qui abordera davantage l'approche scientifique et artistique de la nature) mais physiciennes et physiciens y sont bien sûr chaleureusement conviés !

– Lionel Djadaojee

1. Professor of Theoretical Physics - École Normale Supérieure, 24 Rue Lhomond, Paris, France

PhysicienNES

Une nouvelle association est en train de voir le jour au département de physique. Chacun aura sûrement remarqué la faible proportion de femmes en physique, que ce soit parmi les étudiants, les profs ou les chargés de TDs. Que peut-on faire pour que cela change ? Les étudiantes du département sont déjà conquises par la physique, alors nous avons pensé qu'il fallait agir en amont : il faut récupérer les jeunes filles avant qu'elles ne décident (inconsciemment) que les sciences dures ne sont pas faites pour elles !

PhysicienNES aimerait donc intervenir dans des collèges et des lycées, pour sensibiliser les jeunes - filles comme garçons - à la question, et leur faire prendre conscience de leurs stéréotypes. On peut même espérer susciter de l'enthousiasme pour la physique auprès des filles !

Vous pouvez évidemment nous rejoindre pour participer à cette action de sensibilisation ! L'association est encore à ses débuts et toute aide supplémentaire est la bienvenue. Pour nous rejoindre ou en savoir plus il vous suffit de contacter Oriane Devigne, Victor Lequin ou Juliette Savoye (`oriane.devigne@ens.psl.eu`, `victor.lequin@ens.psl.eu`, `juliette.savoye@ens.psl.eu`) !

Class life

Research seminars week for master 2 students

Last week (November 15th to 19th) was scheduled the research seminars week. That is a presentation of the research units of the different universities involved in ICFP master : the ENS-PSL, Université de Paris, Sorbonne Université (figure 1) and Université Paris-Sud. Along the days, general presentations of the main research axis, poster presentations of internship proposal were given to students. Poster presentations were an opportunity to discuss directly with the researchers of their subjects and their research. In addition, students got the great opportunity to visit labs during *open house* afternoons, and could then see the different set-ups (for those who judiciously decided to visit experiments, others might see only computers and blackboards) and discuss in an informal way with researchers and PhD students and post-docs. A time to feel the lab atmosphere!

Figure 1 – Tipi *of Sorbonne Université, where the meeting of Thursday took place*

Thursday was a particular day for us, the *corporate day* that took place at the ENS (see figure 2). During this day, companies presented us their activities and upcoming challenges, and introduced to us internships, thesis or job opportunities.

I think I forgot to mention the crucial part of this week : the lunch break, during which meals were provided by the organizing university. A smart idea to catch the interest of (hungry) physicist students! If I need to emphasize only one thing of this week, it would be the buffet of Tuesday noon at Sorbonne!

– Ludovic Brivady

Figure 2 – *Opening of the corporate day by Giulio Biroli*

Quantum Ideas Factory

Thursday October 29th, 15 :00 h, after an intense week of courses, we headed from Gare de l'Est to the beautiful city of Heidelberg. Four students from our master were to take part of the Quantum Ideas Factory (Qif), to take place during the weekend October 30th to November the 1st, in the Institute for Physics of the University of Heidelberg. The event was kind of kick start for a pan-European initiative, the Efeqt program (Empowering the Future Experts in Quantum Science and Technology for Europe). The program's aim is to provide master students in quantum science and technologies, and related fields with a complementary training in close contact with research in world class institutions, preparing them for a future career in the field.

The event started with a wonderful city tour organized by physics student from the host institute, who showed us the most emblematic places of the city, making particular emphasis in small details related to the scientific history of the city and the student life, which is an important part of the spirit of a city, whose population is 25% university students! Right after, we got into business, and all teams were introduced by experts to the challenges in which they were going to work : quantum machine learning, quantum simulator design, quantum fluids of light, quantum digital simulations, and real-world control and calibration of high-fidelity operations on superconducting qubits. All topics were exciting and every one got hands on work in what was to be an intense two days of brain-storming and creativity. Under the supervision of the experts, yet with a total freedom to propose and define our own strategies and questions we worked continuously during three days, alternating with some splendid food, and with a good time for networking, visiting labs and of course having some fun!

The outcome of the weekend was impressive, and I have to admit, surprising for most of the attendants. The collaborative environment and collective thinking led to very exciting results. A deep understanding of each of the topic, with some innovative questions, and interesting implementations characterized the ensemble of the presentations. The quality of the works was reflected in the long wait for the results. The event was, for those who are at the beginning of the EFEQT program, a perfect starting point, for those that just took part of this individual event, an enriching experience from which we got a lot of knowledge and some good friends and connections. The program is going to have a second big event, a summer school in the University of Strasbourg, which date is yet to be announced, which again should be open for applicants not attending the EFEQT program, so, keep an eye on it!

– Carlos Lopetegui

PHYSICIST'S LIFE

M1 Internship : spectral indices of dust grains

Maybe some of you remember Anaëlle MAURY from the speech she gave to the φ20 promotion last Spring, regarding the formation of Class 0 protostars within molecular clouds. Last year, I did my M1 research internship alongside her, and the main focus of those four months and a half in her team was the study of spectral indices. More specifically the observed spectral indices α of the dust grains in circumstellar envelopes.

Why should we care about dust grains, and the spectral indices of their emission ?

The term *dust grain* defines molecular aggregates with diameters ranging from a few nanometers to a few tens of micrometers (so, way tinier than the dust on your shelves). Now, in order to build a bit of a scenery here, let's rewind to *how* a Solar-type star is born. In some regions of the galaxy, interstellar matter tends to accumulate over time, leading to the formation of molecular clouds, where the dust represents 1% of the matter, the remaining 99% being gas. Even though it only represents 1% of the total mass, the dust contribution is far from negligible as the grains interact tremendously with light by scattering, absorbing or diffracting it. These molecular clouds are the birthplace of stars. They collapse and fragment to produce dense protostellar cores, which are then likely to contract, undergoing the pull of their own gravity, to create Class 0 [2] protostars. Later on, the protostar will evolve through the following stages (up to Class III) by accreting the material from the surrounding envelope, and may form a circumstellar disk where future planets would then form from the collisions and accretion of dust grains. Or at least, it was the theory. However, there are suspicions about a faster dust grain growth than expected, meaning that the process of planetary formation may already occur in the earliest stages of the protostellar evolution. These conclusions were drawn from studies on spectral index α, because it is a good indicator of the grains' size. Long story short : at the observed wavelengths, the lower α is, the bigger are the emitting grains. The fact is : surprisingly low α values were observed.

So, what did my internship consist in ?

The aim of my internship was to study the α values of the light coming from the dusty circumstellar envelope during the earliest stage of the stellar formation. During the Class 0 stage, the future star is still embedded in dense and opaque coats of dust and gas, which implies a very cold environment [3] (of the order of 30 K). When looking at these objects in the visible part of the spectrum, we might only witness a dark region, from which no light seems to be shined. It is actually due to the interstellar extinction, or interstellar *reddening* : the light we observe from (or *through*) these objects is shifted to the longer wavelengths (medium to far infrared) as these cold dust grains re-emit the absorbed radiation of shorter wavelengths. This is why telescopes like Alma [4] are used for these studies. But my work was on simulations rather than observations. Using the code Ramses which simulates the birth of a star, and the post-processing algorithm Polaris, I investigated the influence of various parameters on α, such as the luminosity of the protostar or different population of dust grains sizes. Basically, I spent most of my time writing and running python scripts to extract the data from the output files, and to analyse this data. So I computed α from the emission maps [5], and studied its evolution with respect to the distance to the protostar, or to the temperature for instance. From all the explored parameters, the only one that happened to allow me to recover the observed low values of α was a significant growth in the grain population (from tens of micrometers up to 1 millimeter!). A more thorough study would also investigate the influence of the grains' composition, or of the presence of an ice mantle on them to confirm this early grain evolution hypothesis. Alas, I didn't have time to explore these trails, but hopefully one day I will!

– Romane Cologni

2. Class 0 : the youngest stage of stellar evolution in the protostellar phase.

3. In comparison, the temperature of the less dense interstellar medium is about 100K.

4. Atacama Large Millimeter/submillimeter Array, located in Chile, 5000 meters altitude.

5. $\alpha(\nu) = \frac{\partial \log S_\nu(\nu)}{\partial \log \nu}$, S_ν being the radiative flux density. So α is the slope of the Spectral Energy Distribution (in log-log scale).

Bachelor's thesis : Superconductivity

Superconductivity is arguably pretty interesting (for physicists) and potentially very useful (for many people, but also physicists). For example, it can be used to create very strong magnetic fields which are needed in medical devices or particle accelerators. However, superconductors only work at very low temperatures, which is not very practical... *High*-temperature superconductors are those that work above 77K, the temperature at which nitrogen boils ! Therefore, the quest to find and understand high-temperature superconductors is ongoing.

Cuprates, special materials containing layers of copper oxide are promising candidates, being superconductive well beyond 100K at intermediate doping levels. But since their discovery in 1986, the superconducting mechanism in cuprates has not yet been completely explained.

One strategy to find more about this is to look at just a single charge carrier in the copper oxide layers : better understanding what a single charge carrier does might help (a little bit) in understanding what billions, billions and billions of them do ! This is what I worked on last year in the quantum many-body physics group headed by Fabian Grusdt at the Ludwig-Maximilians-Universität in Munich, Germany. It all started out as a Bachelor's thesis, but things got much more exciting very quickly and I ended up continuing the project as a research assistant for nearly a year in total.

The copper oxide layers in the cuprates can be approximated by a 2D Ising antiferromagnet, i.e., at low enough temperatures, you have long-range antiferromagnetic order, with spins alternating between up and down, ordered like the colors on a chess board. You insert a charge carrier by removing one of the spins (doping a hole into the system). A spin next to the hole can then "hop" to the hole to fill it. But then the site where that spin came from is empty : the hole has just moved to a neighboring site. However, the spin that hopped now is in a different place and has new neighbors : maybe they don't like each other because they point in the same direction ! Since we have antiferromagnetic interactions, aligned spins next to each other increase the system's energy. Thus, when the hole moves, it rearranges the spins on the 2D lattice by moving all the spins along its way, leaving a trail in the lattice. This resulting configuration will generally have a higher energy than before (see figures).

With a bit more work, one can argue that the doped hole in our antiferromagnet decomposes into two quasiparticles, a spinon and a chargon. A spinon is a quasiparticle carrying no charge but a spin, and a chargon is... well, I'll let you guess. It turns out that the calculations are much easier when using this quasiparticle picture. The results show that at $T = 0$, the spinon and chargon can both move around but together they form a bound state and will not separate very far. The spinon moves quite slowly and the chargon moves fast around it, kind of like a hyperactive dog on a leash that runs around its master who is out for a walk.

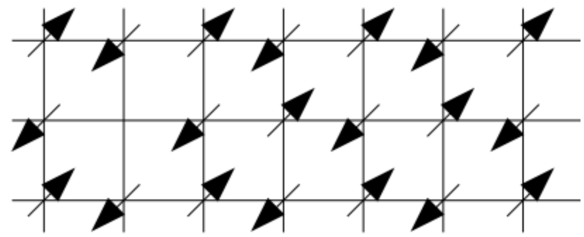

Figure 3 – *At T=0, the ISING antiferromagnet is in its groundstate, with spins pointing in alternating directions. One of the spins is removed to create a charge carrier, i.e. a hole is doped into the material.*

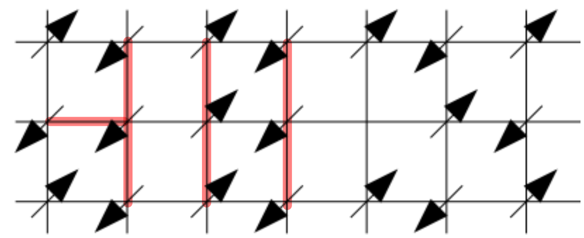

Figure 4 – *The doped hole can hop from site to site. In this image, the hole has hopped three steps to the right from its starting point in the first image. By doing so, it has shuffled the spins along its path : Now some of the spins are next to spins pointing in the same direction, which costs energy (shown in red). Thus, when the hole hops, it increases the system's energy.*

But of course in reality the temperature is not zero ! My project was to calculate this behavior at nonzero temperatures, which is challenging since one has to take into account the thermal excitations of the lattice which will not necessarily be in its groundstate, the checkerboard-like pattern, anymore. Another problem is that the Hilbert space of the system grows exponentially with system size (a typical problem in quantum many-body physics). The first problem can be solved using Monte Carlo sampling which gives you some "typical" lattice configurations at a given temperature. Then you do the calculations for each of these configurations and take the average. The second one was a bit more tricky, but we managed to solve it using the finite-temperature Lanczos algorithm which can be used to estimate expectation values of observables without knowing the entire density matrix of the system.

With these calculations, both in and out of equilibrium, we discovered a phase transition from the spinon-chargon bound state at low temperatures to a phase where spinon and chargon can move independently of one another. This phase transition is connected to the order-disorder phase transition of the Ising antiferromagnet, but it is not the same : it occurs at a slightly different temperature since it is determined by the short-range spin correlations and not the long-range spin correlations like the order-disorder transition. This phase transition is called a deconfinement phase transition since the spinon and holon are no longer confined in a bound state – it has nothing to do with Covid, I promise!

There were some interesting analytical calculations to be done on this topic, but mostly I spent my time 1) coding in Python, 2) waiting for my jobs to start on the computing cluster, 3) trying to find out why my jobs on the computing cluster crashed, and then 4) more coding. Of course sometimes that's a bit tedious, but once you get the hang of how the cluster works, it's much better. This research project was a lot of fun and I can encourage you all to check out some of the fascinating stuff being done in quantum many-body physics! If you want to read some more about this :

— Lauritz Hahn, Annabelle Bohrdt, and Fabian Grusdt, "*Dynamical signatures of thermal spin-charge deconfinement in the doped Ising model*", arxiv :2109.09732.
— Fabian Grusdt, Marton Kanasz-Nagy, Annabelle Bohrdt, Christie S. Chiu, Geoffrey Ji, Markus Greiner, Daniel Greif, and Eugene Demler. 3/21/2018. "*Parton Theory of Magnetic Polarons : Mesonic Resonances and Signatures in Dynamics.*" Physical Review X, 8, 011046, Pp. 1-39.
— Fabian Grusdt, Annabelle Bohrdt and Eugene Demler. 06/17/2019. "*Microscopic spinon-chargon theory of magnetic polarons in the t-J model.*" Physical Review B, 99, 224422, Pp. 1-14.

– Lauritz Hahn

Physics PhD : Superradiant Quantum Phase Transition with Landau Polaritons

I am a PhD student working in theoretical condensed matter physics, and I will tell you about my (very interesting) subject. I am doing my PhD under the direction of Pierre Nataf, Thierry Champel and Denis Basko at Laboratoire de Physique et Modélisation des milieux condensés (Lpmmc) at Grenoble. We are working on the possibility to observe the Superradiant Quantum Phase Transition (Sqpt), which has not yet been observed at thermodynamic equilibrium.

So my PhD deals with cavity quantum electrodynamics (Cqed), which studies the light-matter coupling at the quantum level. In fact, coupling two-level systems to quantum harmonic oscillators is the key idea of Cqed [1], where the quantum harmonic oscillator here corresponds to a cavity photon mode, and thus requires to treat the electromagnetic field as quantized. In the 1950s, Purcell showed that the spontaneous emission rate could be strongly influenced by modifying the boundary conditions of the electromagnetic field with the help of mirrors or cavities [2]. These boundary conditions modify the amplitude of the field (more precisely the amplitude of its vacuum fluctuations), and the use of a cavity can thus serve to control the coupling of the field to the atomic excitations.

Among the paradigmatic models of Cqed, the Dicke model describes the interaction of N identical two-level systems (which have a transition frequency ω_{eg}) coupled to the same cavity photon mode with frequency ω_{cav}, and which is given by the following Hamiltonian :

$$\hat{H} = \frac{\omega_{\mathrm{eg}}}{2}\sum_{j=1}^{N}\sigma_{\mathrm{z}}^{(j)} + \omega_{\mathrm{cav}}\hat{a}^{\dagger}\hat{a} + \frac{\Omega_0}{\sqrt{N}}\left(\hat{a}+\hat{a}^{\dagger}\right)\sum_{j=1}^{N}\left(\sigma_{+}^{(j)}+\sigma_{-}^{(j)}\right);$$

where $\hat{a}$ and $\hat{a}^{\dagger}$ are respectively the annihilation and creation bosonic operator for the photon field and where the Pauli matrices $\sigma_{\mathrm{a}}^{(j)}$ (a = x, y, z) encode the degrees of freedom of the j^{th} two-level system ($\sigma_{\pm}^{(j)} = \frac{1}{2}(\sigma_{\mathrm{x}}^{(j)} \pm \mathrm{i}\sigma_{\mathrm{y}}^{(j)})$).

The interaction between the atomic transition and the cavity field is measured by the vacuum Rabi frequency Ω_0. The regime with Ω_0 comparable to the two-level transition frequency is called the ultrastrong coupling regime [3]. In such a regime, and for a large number of atoms coupled to the same cavity mode, a superradiant quantum phase transitions (Sqpt) has been predicted [4]. In fact, this model has a well defined thermodynamic limit. It has been shown that in this limit and for the ground state ,the *polaritonic modes* (which correspond to the eigenmodes of the strongly-coupled system constituted by the matter and the photonic part) *exhibit a gapless critical point which separates two phases : the normal phase from the superradiant phase*, so it corresponds to a quantum phase transition.

Above the quantum critical point located at $\Omega_0^{\mathrm{cr}} = \frac{1}{2}\sqrt{\omega_{\mathrm{eg}}\omega_{\mathrm{cav}}}$ and which can be obtained by tuning Ω_0, the ground state is characterized by a finite static average of the photon field which corresponds to the order parameter of the quantum phase transition. Furthermore, at resonance, i.e. $\omega_{\mathrm{eg}} = \omega_{\mathrm{cav}}$, we can see that the critical Rabi frequency is half of the electronic frequency, so that the system is located in the ultrastrong coupling regime.

But despite fundamental and potentially technological interest [5,6], the Sqpt has never been observed at equilibrium, *why*?

In fact, in real (physical) systems, the Hamiltonian contains additional terms that cannot be neglected in the ultrastrong coupling regime. For instance there is an extra A^2 term that we should add to the previous Dicke Hamiltonian. The amplitude of this term is responsible of the disappearance of the quantum phase transition due to gauge invariance, for uniform photonic field, and which is sometimes called "No-go theorem".

So my thesis supervisors found a way to circumvent this No-go theorem that I will detail later. But first, before coming to the details, we know that *we need a device which allows us to obtain a huge value for the RABI frequency*. This necessary large value of Ω_0 has been reached in the last five years in some systems, such as superconducting circuits and *LANDAU polaritons* [6,7].

So you can surely guess thanks to the article's title that I am going to talk about the last ones. So LANDAU polaritons are a mixed system made of a two-dimensional electron gas (2DEG) (which is confined in a semi-conductor quantum well (Qw)) under a perpendicular magnetic field and the photons of a resonating cavity, things than can be summed up in the sketch in figure 5.

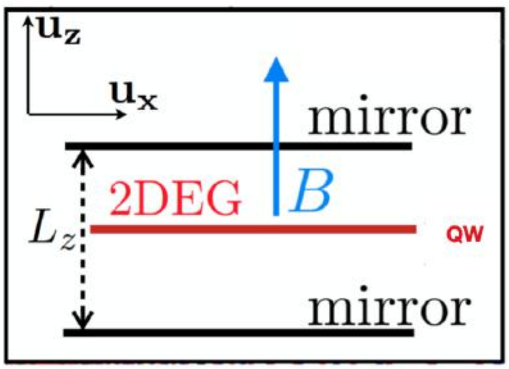

Figure 5 – *Sketch of the device to obtain LANDAU polaritons*

If we apply a perpendicular magnetic field B to a two-dimensional electron gas, the electron energy spectrum is given by a set of discrete levels, called LANDAU levels, which have quantized values for the energy $\epsilon_n = \hbar\omega_c\left(n + \frac{1}{2}\right)$, where n is an integer, $\omega_c = \frac{eB}{m^* c}$ the cyclotron pulsation, and where m^* is the effective electron mass in the 2DEG. Then, at zero temperature, all LANDAU levels are fully occupied below the FERMI energy (figure 6).

In such a device, the ultrastrong coupling regime has been reached. However, an ingredient is missing to obtain the SQPT : the RASHBA spin-orbit coupling.

In fact, my Phd's supervisors have discovered that the RASHBA spin-orbit coupling in the 2DEG could allow the LANDAU polaritons to undergo the superradiant transition [9]. In fact, we need crossings of eigenvalues of the decoupled 2DEG, and the RASHBA spin-orbit is at the origin of some crossings of LANDAU levels at certain values of B, corresponding to dipole-allowed excitations with zero energy.

Furthermore, there is also the need of the non-vanishing

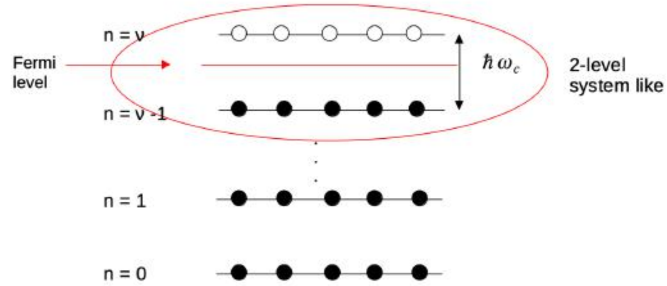

Figure 6 – *Sketch of LANDAU Levels behind the FERMI energy. The transitions between the last filled level and the first empty one are coupled to the electromagnetic field of a resonator*

dipole matrix elements. Let us call q_x the wavevector of the field (in an 1-dimensional resonator). One can show that for some values of $q_x \neq 0$, the dipole matrix elements don't vanish, producing the divergence of a key quantity, leading to a system instability. We thus obtain a *polaritonic mode softening*, which is very similar to the one obtained in the DICKE model.

Unfortunately, they have also found that *the instability regions are very narrow.*

So the aim of my work is to study better conditions for the occurence of the superradiant phase in LANDAU polaritons by studying theoretically some possible additional physical ingredients, like for instance the ZEEMAN coupling. We have been able to find a generalization of the results with RASHBA, by adding ZEEMAN coupling. In particular, the ZEEMAN coupling allows increasing the size of the instability region. This size depends linearly on the inverse of the width of the quantum wells (for sufficiently narrow ones) and when the 2DEG is placed in the middle of the cavity.

Furthermore, we have also been able to show that with only ZEEMAN coupling, the SQPT can in principle occur for $q_x = 0$. In this case, the width of the quantum wells required is not experimentally achievable. By adding the RASHBA spin-orbit coupling, one allows crossings of LANDAU levels, so the SQPT can be obtained for realistic quantum well thicknesses. In addition, in the case where the 2DEG is placed on one of the mirrors, the most favorable situation for the instability to occur is the case when $q_x = 0$!

So to sum up :

- SQPT can be reached in cavity QED system with RASHBA spin-orbit coupling and non-uniform cavity fields (singularity of spin-flip transitions).
- We have obtained a generalization of the results with RASHBA, by adding ZEEMAN coupling : it allows increasing the size of the instability region for narrow quantum wells.
- In principle, the SQPT can occur for $q_x = 0$ when there is only ZEEMAN coupling. The effect can be enhanced with

Landau levels crossings.

If you are interested or have any questions, don't hesitate to contact me, it would be a pleasure to tell you more about our work (`manzanaresguillaume1993@gmail.com`).

[1] Haroche, S. and Raimond, J.-M. *Exploring the Quantum : Atoms, Cavities, and Photons* (Oxford University Press, USA, 2006).

[2] Purcell, E. *Spontaneous emission probabilities at radio frequencies*. Physical Review **69**, 681 (1946).

[3] C. Ciuti, G. Bastard, and I.Carusotto, Phys. Rev. B 72, 115303 (2005).

[4] C. Emary and T. Brandes, Pre, **67**, 066203 (2003).

[5] P. Nataf and C. Ciuti, Prl **104**, 023601.

[6] P. Nataf and C. Ciuti, Prl **107**, 190402 .

[7] D. Hagenmüller, S. De Liberato, and C. Ciuti, Prb, **81**, 235303 (2010).

[8] G. Scalari et al., Science, **335**, 1323 (2012).

[9] P. Nataf, T. Champel, G. Blatter, and D. M. Basko, Phys. Rev. Lett. **123**, 207402 (2019)

– Guillaume Manzanares

Good question

Over the last century, through the discovery of qantum mechanics, qpecial relativity, and general relativity, physicists gained a tremendous understanding of both very small and very large scales. This understanding rests on two pillars. The first one is the standard model, which utilizes the framework of Quantum Field Theory (QFT) to describe three of four known fundamental forces : electromagnetic, strong, and weak interactions. To explain the last interaction, gravity, we need the help of general relativity which uses the language of differential geometry. Together, these two theories have been able to pass with flying colors any experiment that has been thrown at them, so far. [6]

Despite the success of these two theories, theoretical physicists are far from satisfied. Indeed, attempts at merging the two pillars have been unsuccessful so far, and until the fusion into the "theory of everything" is made, we know that we do not have the full story. Unfortunately, the search is severely hindered by the fact that, with our current technology, there are no experiments that can provide any clues. Indeed, gravity is so weak that it is virtually nonexistent at the scales where quantum mechanical effects are strong. Thankfully, the lack of experiments never stopped theorists, as they have a trick up their sleeve : instead of performing the experiment, they can just imagine it.

6. Although this might change soon c.f. "Muon g-2" experiment.

So since our imagination is the only barrier, what system should we consider that has a good chance to expose the tension between our two pillars ? One answer is black holes. Their huge mass obviously generates a more than non-negligible gravitational field, but their extreme density packs matter so tightly that quantum effects are bound to appear. Indeed, the singularity in their middle clearly signals that there is a breakdown of general relativity.

Now that we have the object of study, let us observe it. There is one small caveat : since this black hole lives in our minds, we should tell it how to behave. But how could we know that, since we do not have the proper theory to describe it ? That is an excellent point, but we still might get away with it using approximations, only considering setups where our theories are still applicable. In this case, we consider a big black hole so that curvatures at the horizon are not too extreme (where general relativity breaks down), and we assume that the matter (quantum fields) around the black hole has low enough energy that it won't affect the geometry of the spacetime. This is the so-called "semi-classical" approximation : we let our quantum fields evolve on the curved spacetime, and we assume that they won't influence back the geometry in any meaningful manner.

Using this trick, Hawking completed our experiment and discovered that black holes must evaporate. More precisely, a black hole of mass M will emit radiation that is described by the density matrix $\rho = e^{-\beta H}$ where $1/(k_B\beta) = T = \frac{\hbar c^3}{8\pi \mathcal{G} k_B M}$ is the temperature of the black hole. This is the result of our thought experiment. Now, we should analyze it and search whether it gives interesting insights or inconsistencies. We will argue that this evaporation is non-unitary, violating one of the axioms of quantum mechanics.

Let us start with a spherical shell of matter described by a pure state, denoted by $|\psi\rangle$. We let this shell collapse into a black hole. If we assume that quantum mechanics is fundamentally correct, the black hole state should be described by $\hat{U}|\psi\rangle$, where $\hat{U}$ is a unitary operator. According to Hawking, this black hole will evaporate through the emission of Hawking radiation. We wait until the black hole evaporates away [7], and we collect the produced radiation which will be described as a thermal density matrix [8] $\rho = e^{-\beta H}$. Such a density matrix describes a mixed state, in other words there is no $|\phi\rangle$ such that $\rho = |\phi\rangle\langle\phi|$. This is in contradiction with the assumed unitary evolution. Indeed, if the black hole evaporation were unitary, the final radiation state should be described by $\rho = \hat{U}'|\psi\rangle\langle\psi|\hat{U}'^{\dagger}$.

7. The attentive reader might notice that this goes against our assumption of a "large" black hole. However, the experiment can also be set up without waiting up to the end of the evaporation, but the explanation becomes more technical.

8. This expression is actually incorrect since the black hole decreases in mass as it evaporates, and so its temperature changes. The real density matrix will be some kind of integral of thermal density matrices over temperatures.

Through this thought experiment, we thus managed to show that black holes ”destroy information” in the sense that their evolution is non-unitary. This apparent incompatibility of unitarity and general relativity has been dubbed ”the black hole information paradox”. There are several reasons why it is very interesting and promising to study this particular problem. First of all, it seems that it forces us to choose between two extremely well-established principles : unitarity and the equivalence principle. We would much rather not have to choose, so the best-case scenario would be to understand why the thought experiment is wrong. Here we can either abandon some other axioms that were used (e.g., locality) or find that some assumptions were incorrect (e.g., the horizon is ”fuzzy” c.f. fuzzballs).

Whatever the resolution turns out to be eventually, the search for it will certainly bring us at least one step closer to quantum gravity.

– Vassilis Papadopoulos

Normale Book Review

Il est temps d'une autre recommandation de lecture de la Npr ! Ce coup-ci il s'agit des *Tenseurs en mécanique et en élasticité* de Léon Brillouin. Datant de 1938, on pourrait presque le lire uniquement par charme ou intérêt historique mais il garde une pédagogie que je trouve précieuse et n'est pas aussi daté qu'on pourrait le penser.

La première moitié du livre est consacrée à la présentation des tenseurs mais c'est un peu réducteur - il arrive en effet jusqu'aux notions de courbure dans les variétés riemaniennes. Mais n'ayez pas peur ! Le début attaque tout en douceur et de manière très pédestre : c'est là l'avantage, on peut le lire qu'on veuille compléter son cours de mécanique des milieux continus ou anticiper celui de relativité générale. Le tout est très bien ficelé et assez limpide.

Pourtant, que ceux qui veulent un livre de physique ne soient pas déçus ! Arrivés à la moitié des 360 pages (que vous ayez suivi les 150 premières ou non), le chapitre de mécanique analytique vous prendra de court par sa beauté : la force de la géométrie différentielle (dont vous n'avez pas besoin de comprendre le détail pour apprécier ce chapitre) combinée aux sublimes idées de mécanique rationnelle raviront n'importe quel passionné de physique théorique. On y voit Hamilton-Jacobi comme une onde de choc, et personnellement comme un coup de foudre, avant de toucher du doigt la relativité sans qu'il soit possible d'en ignorer la pertinence vu l'exposition naturelle et convaincante qu'il en est faite.

S'ensuit une magnifique balade en physique quantique avant d'attaquer le gros de la deuxième moitié de l'ouvrage : la mécanique des milieux continus. Une plongée en profondeur dans les déformations élastiques, ondes dans les solides (dont quelques effets non linéaires de la propagation) et autres joyeusetés laisse la place pour les 50 dernières pages à la spécialité de Brillouin, la physique du solide, exposée à grand renfort de schémas et de visualisations graphiques.

En bref *Les Tenseurs*, sous son titre austère, double son offre d'une exposition claire du formalisme mathématique tensoriel par une fantastique promenade à travers la physique théorique dont on ne peut que tomber amoureux. Le brio de Brillouin éblouira tout L3 en manque mécanique analytique ou n'importe quel physicien nostalgique de sa première lecture du Landau !

– Victor Lequin

Sir, I have a question

New problems

If you enjoy scratching your head on deep questions about the nature of the universe or simply having a thought about small, everyday problems, this section is for you !

Here is a selection of 10 questions that may inspire you...

I : If some hair goes in the washing machine with your clothes, you might find it afterwards all tangled up in a bunch of bundles. The same happens if you wash a number of aprons at the same time : their strips will come out all tangled together. Can you explain this ?

II : Still on the topic of hair, when one hair is floating on water one can observe spots of light along the hair. Why is that ?

III : Why do ships have a keel ?

IV : What is that "clock" that we are used to attach to an observer in relativity ?

V : What is the frequency of emission of bubbles in a glass of champagne ?

VI : How much time does it take to saturate a room in CO_2 ? Is there a strategy to ventilate a room efficiently in these cold days ? (see `https://projetco2.fr/`)

VII : Is there a scale under which the description of viscosity in Navier-Stokes equations is not valid anymore ?

VIII : What are the cardiac pulses ? Could quantify them with an order of magnitude ?

IX : Why does milk ascend during ebullition ? We can also observe the same phenomena with chickpeas.

X : Astronauts' bodies go through many surprising changes during a trip to space. Notably, could you get an order of magnitude of how much they grow after 6 months spent in space ?

Answers to previous questions

Question **IX** of N_{13} :

We'd like to estimate the number of self-service bikes "Vélib" in circulation.

By observation, one can assess that the implantation of stations is restricted to the near suburbs of Paris (la "Petite couronne"), namely an area of 675 km^2 (We took this area to be a disk of radius 15 km). And we assume the spreading to be homogeneous in space with an average distance between stations of 400 m. To justify this we argue that journeys smaller than 400 m are achieved faster for a pedestrian than a cyclist. Above this distance, cycling is faster. Then to be comfortable, the implantation need to limit the distance of the walker to 400 m.

Thus, a station covers an area of 0.48 km^2. This gives a total number of station of 1400 to cover the all area.

Taking that there is in average 15 bikes per station, one gets that there is around 21000 "Vélib" in circulation in Paris. Which is of the same order of magnitude as the official count : `https://www.velib-metropole.fr/service`.

– Ludovic Brivady

Question **VI** of N_{14} :

You might know that the number of neurons in brains is huge : around 10^{11} in the human brain, 10^7 for rodents. Then, it is often more convenient to work with smaller networks, notably for simulation. But, can we ensure that statistical properties of the networks are preserved when we scale them ? It is a similar issue one can face in hydrodynamics experiments, when we should pay attention to the value of non-dimensional parameters such as the Reynolds number.

Consider the following case : a network of N cells, receiving in average K inputs (inputs are collected by *synapses*, in the following we will thus use the expression *synaptic input*). Each input is pondered by the connection strength J. The activity of a cell averaged over the population is denoted by m. Then, we can compute the synaptic input by :

$$\mu = \sum_{\text{connections}} \begin{pmatrix}\text{connection}\\ \text{strength}\end{pmatrix} \times \begin{pmatrix}\text{activity of}\\ \text{pre-synaptic cell}\end{pmatrix}.$$

For our scaling, we want to keep the statistical properties of the network unchanged over a modification of the network size N. In particular, the variance of the synaptic input should be independent of the number of connections for a given value of m.

An useful approximation for computation is to consider a sparse but numerous network. That is assuming $1 \ll K \ll N$, the neurons are identical and have their parameters equal to the mean values (mean-field approximation). A pre-synaptic neuron is expected to connect with a probability $K/N \ll 1$. Then the *mean* synaptic input is :

$$\mu = \sum_{\text{cells}} K/N \times J \times m = KJm.$$

We can also compute the variance σ^2 of the synaptic input by summing tha variance associated with each synapse :

$$\sigma^2 \approx N \times \left(K/N \times (Jm)^2 - (K/N \times Jm)^2 \right) \approx K(Jm)^2;$$

at the zeroth order in K/N.

Finally, for the variance to be independent of of K, we should ensure the following scaling : $J \propto 1/\sqrt{K}$.

References :

- Van Vreeswijk, C. & Sompolinsky, H. Chaotic balanced state in a model of cortical circuits. Neural Comput. 10, 1321–1371 (1998).
- Barral, J., D Reyes, A. Synaptic scaling rule preserves excitatory–inhibitory balance and salient neuronal network dynamics. Nat Neurosci 19, 1690–1696 (2016). https ://doi.org/10.1038/nn.4415

– Ludovic Brivady

MYSTERY PHOTO

Solution of N_{14}

Dans la N_8, M. Chevy exprimait, au sujet des analogies en physique, « tout est dans tout, et réciproquement ». En voici une nouvelle illustration ! Les fourmis, elles aussi, obéissent au principe de Fermat (et toute la nature regorge d'exemples d'optimisation). Sur la photographie mystère de la N_{14} (issue de l'article de recherche `https://doi.org/10.1371/journal.pone.0059739`), des fourmis se déplacent d'une fourmilière à leur source de nourriture. Au cours de leur trajet, il y a changement de milieu : la surface verte est plus rugueuse que la surface blanche, il est donc plus difficile de s'y déplacer. Or on observe qu'après un certain temps d'exploration, les fourmis choisissent le chemin le plus court : il y a « réfraction » du faisceau de fourmis à l'interface entre les deux milieux [9]

D'où cela vient-il ?

Lors de leur déplacement, les fourmis déposent des phéromones sur le sol : celles qui trouvent le chemin le plus rapide pourront plus fréquemment faire des allers-retours entre la fourmilière et la source de nourriture, et y déposer ainsi plus de phéromones. En se guidant vers les endroits où la concentration en phéromones est la plus importante, les fourmis

9. Petit exercice sympathique au passage : si leur vitesse initiale est de 8 cm/s, quelle est alors leur vitesse dans le milieu vert au vu de cette photographie ?

choisiront à coup sûr le meilleur chemin. Ingénieux ! Si bien que cela a inspiré l'application GPS Waze, qui fonctionne sur un principe analogue, à l'aide de traceurs (un bel exemple de bio-inspiration !).

Aussi, des chercheurs se sont amusés à pousser l'analogie avec les lois de l'optique géométrique, avec la réalisation de lentilles à fourmis (convergentes et divergentes, voir l'article `https://doi.org/10.1016/j.crhy.2005.07.001`). Prochaine étape : interférence de fourmis par des fentes d'Young ? À vous de jouer !

– Lionel Djadaojee

Photo of N_{15}

The mystery photo of our current edition is shown on figure 7. Any guess to what it might me ? Huge thanks to Mathieu LIZEE (PhD student at LPENS - Micromégas group) for his picture !

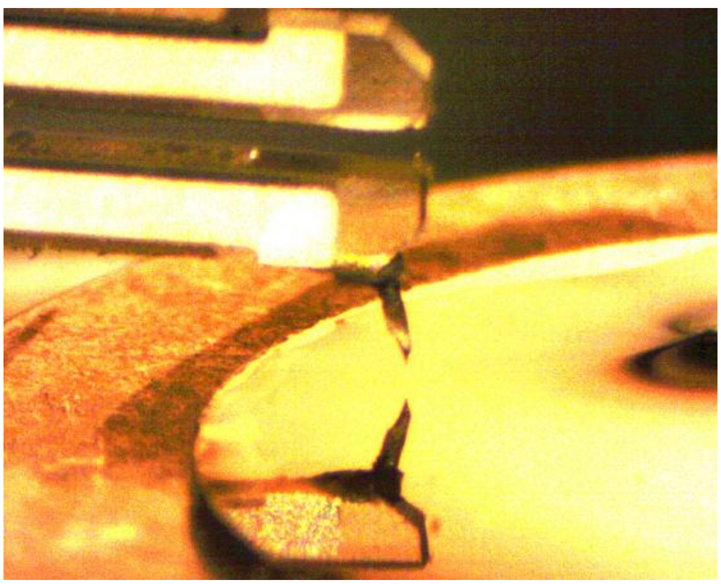

Figure 7

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We thank our contributors for their marvelous articles and questions. We also thank everyone who sent us their feedback and encouragements. And thank you, dear reader !

We need you !

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