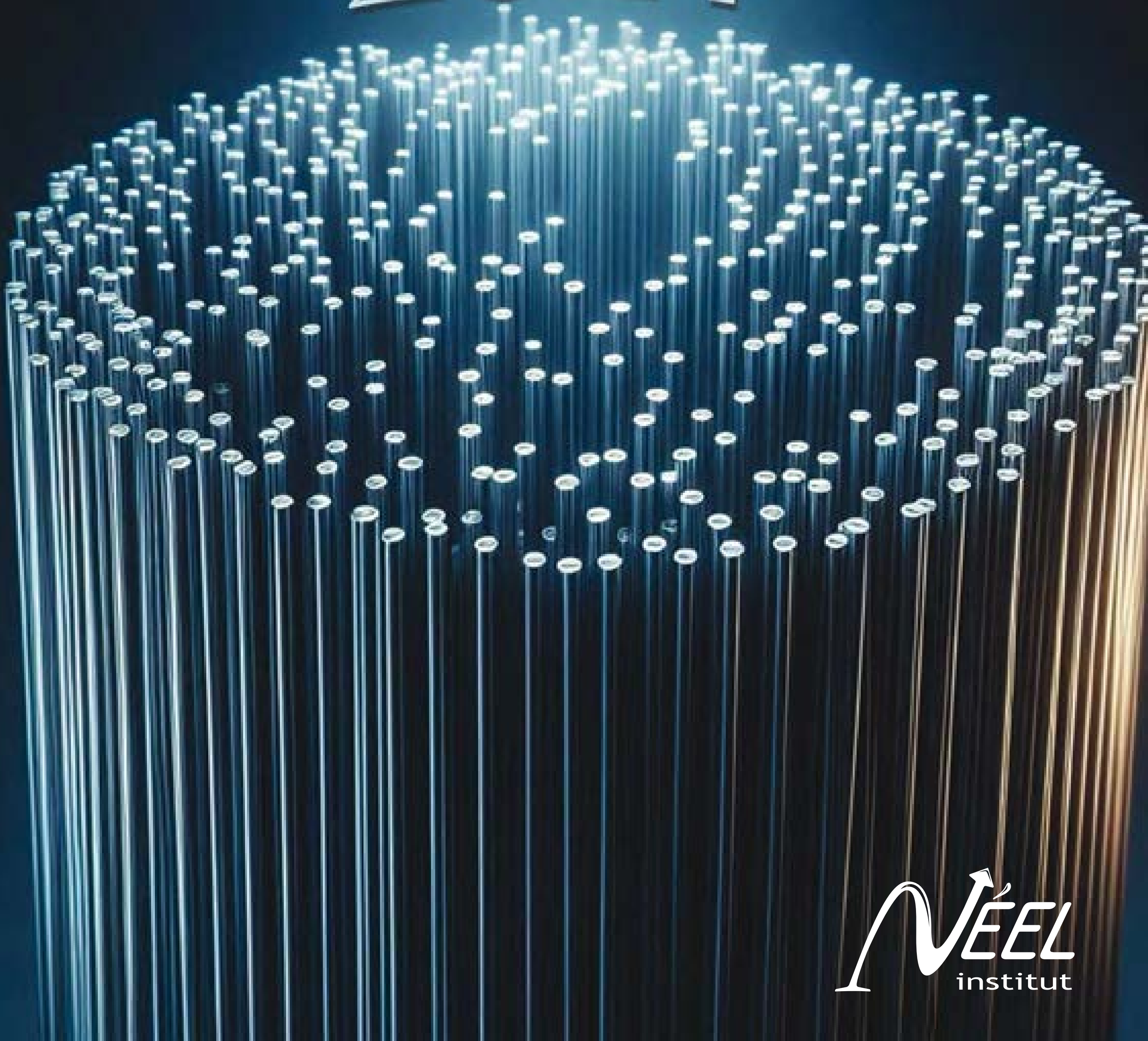
HIGHLIGHTS 2024

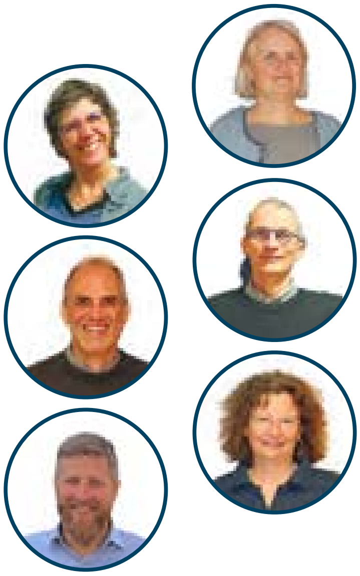


NÉEL institut

EDITO

Highlights 2024
Institut Néel

Grenoble, France



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Welcome to this new issue of Institut Néel Highlights. Going through the different items will provide you an overview of our main achievements for 2024. Of course giving an exhaustive overview of NEEL activities in a few pages is not possible and you can get more information browsing our website https://neel.cnrs.fr.

Institut Néel is a CNRS laboratory (Unité Propre de Recherche) with strong links with Université Grenoble Alpes. Our main stream research focusses on fundamental science in condensed matter physics and chemistry. Since physics and chemistry are the basis of many societal issues, the laboratory also develops top level scientific and engineering activities at different interfaces. The whole benefits from the historically strong technological skills of the laboratory which we are committed to further develop.

The articles you're about to discover illustrate the dynamism of our laboratory. They also highlight the diversity of our research themes, from theory to experiments, from the synthesis of materials to the study of their properties, but also very low temperatures, search for dark matter, unconventionnal superconductivity, quantum optics or glasses properties…

Eventually, I would like to thank all the authors and C.Lacroix who edited these pages and wish you a pleasant reading !

Laurence Magaud
Director of Institut NÉEL
Grenoble, France

Because scientific research is at the heart of our concerns, we support Stand Up for Science.

Photo de couverture Andrew Fefferman
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Artist's impression of the aluminum wire refrigerant.

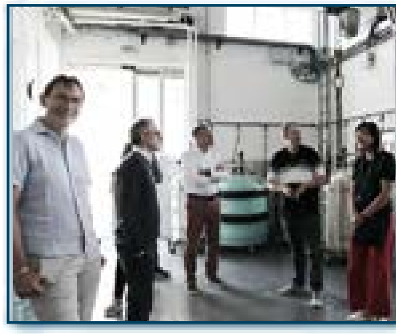
Contents

Events

The laboratory received a visit from Liliana Buda-Prejbeanu, Deputy Scientific Director of Grenoble INP – UGA.

Pierre Agostini, Nobel Prize in Physics 2023, at Institut Néel.

Taïwan Quantum Delegation.



Institut Néel was delighted to welcome the management of IPCMS, the Strasbourg Institute of Physics and Chemistry of Materials.

Kick-off France 2030 CryoNext program.
This large-scale program is part of an action plan requested by the Ministry in 2022 to secure French supply and develop high-performance cryogenics systems for quantum technologies. It comprises 7 R&D projects. Institut Néel is involved in most of the projects.

Institut Néel-SIMaP meeting day.

Visit from Claire Villevieille, Director of Labex MateriAlps.

14 years of LabEx LANEF: Achievements and Prospects

Lab

Renovation of the supra train: a new lease of life thanks to the financial support of the Alpes Delegation.

Trainee teachers visit Institut Néel.

Exploring Very Low Temperatures with C'est Toujours Pas Sorcier.

Institut Néel hosted the RobustSuperQ Days 2024 – another sparkling action organized within the framework of the French Quantum Plan, funded by the ANR.

Another Néel dilution cryostat directed to Atacama

The TIFUUN instrument is in construction by an international collaboration led by Delft and involving partners from The Netherlands, Japan and France. TIFUUN is a revolutionary on-chip spectro-imager to be installed on the ASTE 10-meters telescope, operated by Japan and located in Chile at 4,860 meters altitude. ASTE is only 6 km from the location of our previous instrument, CONCERTO on APEX. Drawing on our expertise (see Highlights Néel 2021), the initial Institut Néel contribution to the project has been the design and construction of a special dilution cryostat and a compact, remotely controlled Gas Handling System (GHS).

One of the Institut Néel's predecessors, the CRTBT (Centre de Recherches sur les Très Basses Températures), began developing innovative instrumentation for observing the Universe at millimeter wavelengths in the 1980s. This work, originally driven by the exceptional skills and energy of Alain Benoit, continues to thrive and has earned our Institute international recognition. This recognition is particularly due to the instruments we have invented, designed, and deployed, such as NIKA2 (Néel IRAM KID Arrays 2), which operates on the 30-meter Pico Veleta telescope in Spain, and CONCERTO on the 12-meter APEX in Chile.

Since mid-2022, Alessandro Monfardini from the HELFA team and Emilio Barria, Grégory Garde and Martino Calvo from the Cryogenics group of Institut Néel have been participating in an international collaboration led by Delft University of Technology, involving partners from Japan, SRON, and our group. This project, named TIFUUN (Terahertz Integral Field Unit with Universal Nanotechnology), aims to develop an imaging spectrometer system with multiple Integral Field Units (IFUs), each containing up to 100 spectral pixels (spaxels). Each IFU will be tailored to a specific astronomical science goal, primarily focusing on remote regions of the Universe, such as galaxy clusters, the epoch of reionization, and the first galaxies. The project is funded by a European ERC grant (Akira Endo, Delft) from September 2022.

As with our previous instruments, the key to success lies in operating highly sensitive detectors and optical systems at temperatures below 100 mK. This is made possible by our expertise in custom sub-Kelvin cryogenics. Our initial contribution to the project, coinciding with intense experimental activity, has been the design, fabrication, and testing of a highly compact dilution refrigerator capable of supporting a large focal plane operating near the absolute zero. Additionally, we have constructed a suitable Gas Handling System designed for installation at an altitude of 5,000 meters in a hostile environment.

A critical step in this project was our visit to the ASTE telescope in Chile in April 2023 (Martino Calvo, Grégory Garde, Alessandro Monfardini). During the visit, we collaborated with our Japanese colleagues to inspect the receiver cabin where our cryostat will be installed and to evaluate potential locations for the GHS. The visit was greatly facilitated by the proximity of the ASTE site to our CONCERTO-APEX location, which is only about 15 minutes away via a 4WD road from the telescope where we worked from 2020 to 2023.

In April 2024, after extensive laboratory characterization in Grenoble, we delivered the dilution cryostat, the heart of the TIFUUN instrument, along with its Gas Handling System, to Delft to commence the integration of the optics and detectors. Thanks to the brand-new CNRS truck, we were able to transport the equipment safely and efficiently to Delft in a single trip. The installation was completed in less than a day, and on our return journey to Grenoble, we successfully performed the first remote cooldown, achieving a base temperature of 45 mK.

The integration of the optics and detectors is being overseen by our colleagues in the Netherlands, under the coordination of Prof. Akira Endo. The detectors will be Kinetic Inductance Detectors (KID), similar to those we are also developing in-house (PTA, IRAM, and Nanofab). Once this integration is complete, we will assist in the deployment of TIFUUN on the incredible Atacama plateau.

Figure 1

Caption

Figure 1: **The TIFUUN cryostat (right) and Gas Handling System (left)** *| The TIFUUN system, which is entirely cryogen-free, has been installed and operational in Delft since April 2024, awaiting the installation of optics and detectors before deployment to the telescope. The base temperature achieved in Delft is approximately 45 mK, with the cool-down process completed remotely.*

Contacts

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More information...

https://neel.cnrs.fr/equipes-poles-et-services/helium-du-fondamental-aux-applications-helfa

https://neel.cnrs.fr/equipes-poles-et-services/cryogenie

Easy cooling of condensed matter below 1 mK

A substance in thermal equilibrium with the pervasive cosmic microwave background would reach a temperature of 2.73 kelvin. However, scientists can far surpass this base temperature of the universe. Starting in the 19th century, liquefaction of "permanent" gases was demonstrated, culminating with the liquefaction of helium under atmospheric pressure at 4.2 kelvin in 1908. Once it was produced in sufficient quantities, the temperature of liquid helium could be further reduced by pumping its vapor as it boiled, yielding temperatures of order 1 kelvin. The reduction of thermal agitation at such low temperatures yielded the discovery of startling new phenomena including the flow of electrons without resistance (superconductivity) and the flow of liquid helium without viscosity (superfluidity).

Since the vapor pressure of liquid helium decreases precipitously as its temperature is decreased below 1 kelvin, pumping becomes an impractical cooling technique and different methods are required to achieve temperatures in the millikelvin range and below. Access to temperatures near 10 mK was greatly simplified with the appearance of cryogen-free ("dry") dilution refrigerators, which do not use a liquid helium bath and provide much more experimental space. They have facilitated rapid advances in fields such as superconducting quantum technology, astrophysics and materials science, and have led to the growth of the cryogenics industry around the world.

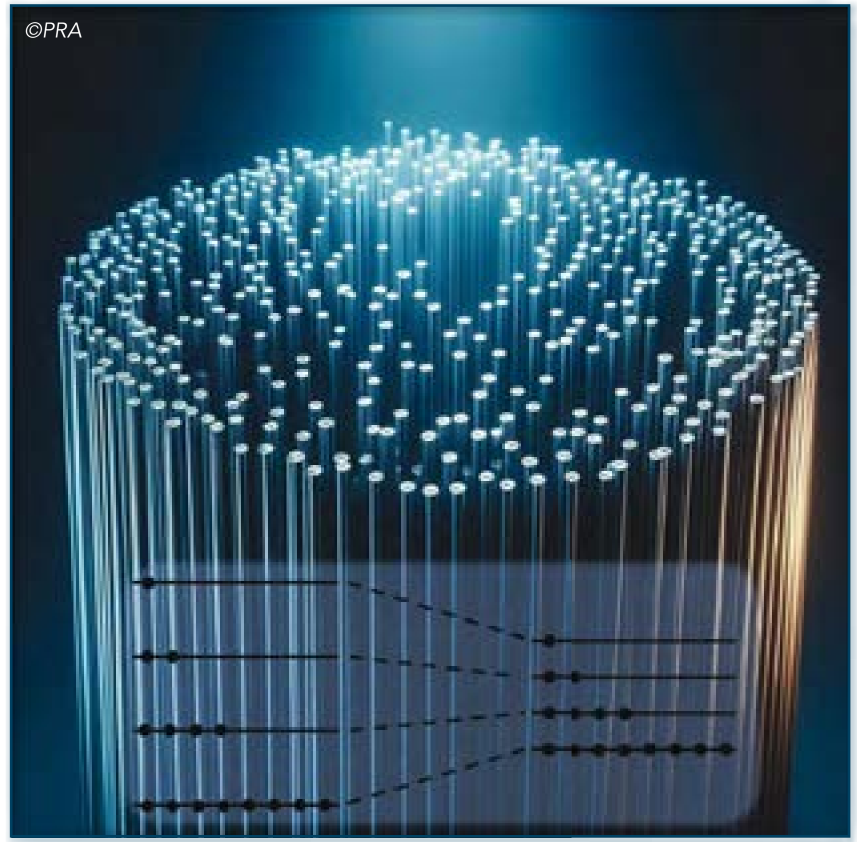
Starting with the discovery of superfluid ^{3}He in the 1970s, cooling condensed matter well below 10 mK has yielded fascinating discoveries up to the present day in areas including nanomechanical resonators, low dimensional electron systems, amorphous solids, electronic transport in nanostructures and dark matter searches.

Sub-mK temperatures in condensed matter are obtained using adiabatic nuclear demagnetization. The refrigerant of a nuclear demagnetization refrigerator (NDR) is a metal containing nuclei with non-zero spin. First, a magnetic field is applied to the refrigerant while it is in contact with a precooling dilution refrigerator at ~10 mK, causing the spins to align with the magnetic field. Then the refrigerant is thermally isolated from the precooler and the applied field is decreased. The thermal isolation implies that the degree of alignment of the spins remains constant. Thus the temperature of the spins ideally decreases in proportion to the field. Once the desired temperature is achieved, heat leaks are balanced by further demagnetization.

Until now, NDR have had to return to the precooler temperature for regeneration when the magnetic field reaches zero. The autonomy of such NDR is particularly limited when precooled by dry dilution refrigerators, partly because of their vibrations. Thus researchers working at sub-mK temperatures have not fully benefited from cryogen-free technologies.

We recently reported the performance of a new aluminum nuclear demagnetization refrigerator, whose design simultaneously maximizes the thermal conductance along the nuclear stage and minimizes eddy current heating. It is optimized for powerful continuous cooling when part of a proposed dual stage NDR, which will maintain temperatures below 1 mK indefinitely. The two stages are installed in parallel, so that one stage maintains the sample temperature while the other stage is regenerated. The high thermal conductance of our nuclear stage and its thermal links yields rapid thermalization, so that the continuous refrigerator can be rapidly cycled, maximizing its cooling power. Furthermore, its low susceptibility to eddy currents yields a low parasitic heat load. We expect this innovation to broaden the field of microkelvin physics, accelerating the rate of discovery and increasing its technological potential.

Figure 1



Caption

Figure 1: Artist's impression of the aluminum wire refrigerant. The inset indicates the Zeeman levels of nuclei at high (left) and low (right) magnetic fields. The population of the Zeeman levels remains constant under adiabatic demagnetization, implying a decrease in temperature.

Contacts

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Further reading...

"Aluminum nuclear-demagnetization refrigerator for powerful continuous cooling"
M. Raba et al.
Physical Review Applied **22**, 024027 (2024)

Growth of nanowires of compound semiconductors: slow wins the race

Motivated by the emergence of new devices and by the search for topological superconductivity, there is an urgent need to master the growth of nanowires made of a compound semiconductor such as InAs. We give a simple answer to a long-standing question: how can one describe the growth of such nanowires, where the two components, indium and arsenic, feature very different behaviors as adatoms on the surface. However, a simple answer may have multiple consequences.

A crucial parameter governing the growth of compound semiconductors by molecular beam epitaxy is the stoichiometry at the growing surface. In the case of layers, two molecular beams are sent directly to the surface and the stoichiometry is controlled by the intensity ratio of the two beams.

Controlling the stoichiometry during growth of self-organized nanostructures is more complex. The growth of nanowires usually proceeds through a seed, for instance a gold droplet: the constituents reach the droplet via different paths, such as direct impingement or formation of adatoms on the nanowire sidewalls and diffusion toward the droplet. In the diffusion-limited description, the growth rate is determined by the current of adatoms which reach the droplet.

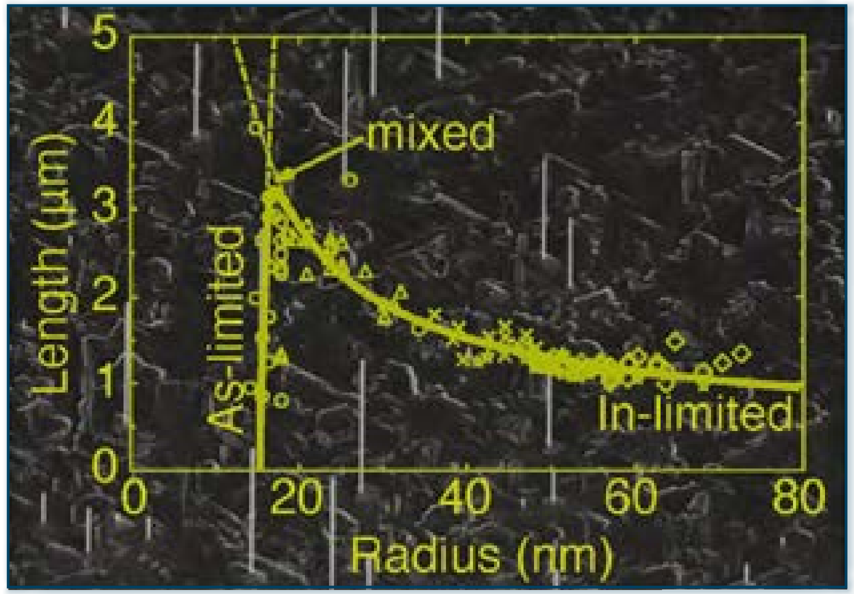
An efficient method to determine the dominant path is to plot the growth rate as a function of the nanowire radius *R*. Species with a long diffusion length λ are captured on a sidewall area $2R\lambda$, and as they contribute to the layer by layer growth at the nanowire-droplet interface of area $\sim R^2$, we expect a characteristic $1/R$ dependence of the growth rate. Volatile species have a negligible diffusion length and are essentially captured by direct impingement onto the droplet, but the evaporation from small droplets is increased (this is the so-called Kelvin effect) so that the growth rate vanishes below a threshold in radius. All this is easy if only one chemical species is involved.

The description of the growth of compound nanowires most often remains in the frame of this one-species model. If the two species behave very differently, this approach is hopeless. This is the case, for instance, for our InAs nanowires: arsenic is volatile with a small or negligible diffusion length, while indium features a diffusion length of several micrometers.

We have shown that a good approach is to determine for each species, at each time of the growth of a nanowire of given radius, the current of adatoms which can reach the droplet. Then the minority current determines the instantaneous growth rate.

This approach allows us to model the final length of an InAs nanowire as a function of its radius (Figure). For any fixed ratio of In and As flux from the effusion cells, for large radius the growth rate is limited by the indium current with the characteristic $1/R$ dependence, and for low radius it is limited by the arsenic current with the impact of the Kelvin effect. For intermediate radius values, the currents are not balanced, but the nature of the minority current is either In or As, depending on the instantaneous length of the nanowire.
The next step is to understand the role of the currents' stoichiometry on the formation of defects and the impact for eventual devices.

Figure 1



Caption

Figure 1: InAs nanowires: scanning emission microscopy image, and length-radius plot. Symbols are experimental, dashed lines correspond to maximum calculated currents of each type, solid line is calculated using the instantaneous minority currents.

Contacts

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Collaboration with Edith.Bellet-Amalric@cea.fr

Further reading...

"Dual-adatom diffusion-limited growth model for compound nanowires: Application to InAs nanowires"
D. Mosiiets, Y. Genuist, J. Cibert, E. Bellet-Amalric, and M. Hocevar
Crystal Growth and Design, **24**, 3888 (2024)

Decoupling between dynamics and density in high-pressure glasses

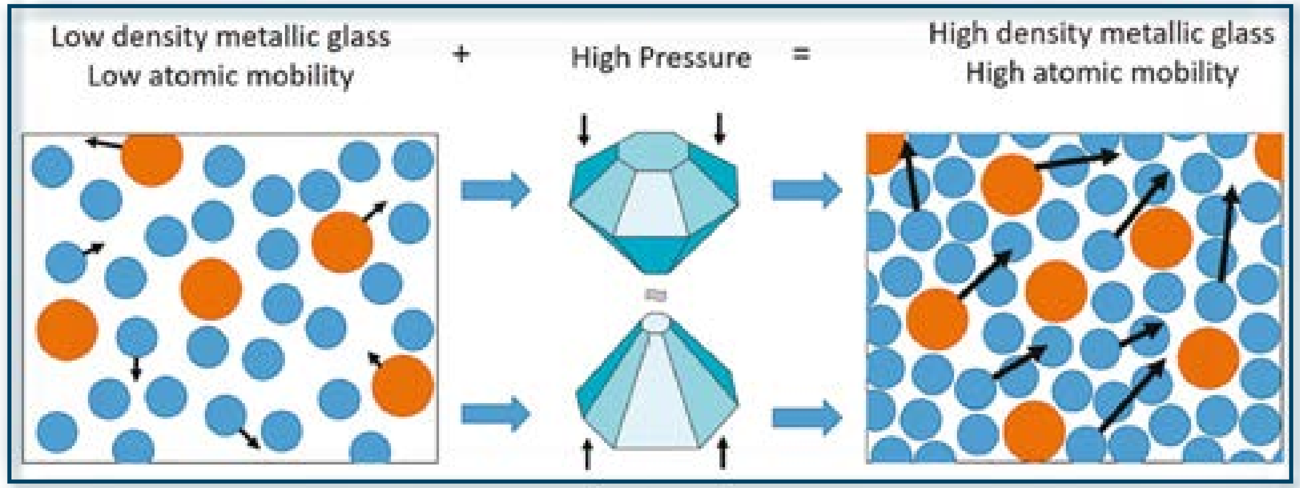
Glasses are liquid frozen in an amorphous state, far from thermodynamic equilibrium: they flow on timescales larger than device life, human life or even thousands of years depending on compositions and temperatures. As a consequence, all properties of glasses have a memory of the thermo-mechanical treatments applied to the material, making difficult their control during processing and applications. By coupling extreme pressures to coherent x-ray scattering in one of the world most brilliant x-ray sources (ESRF), we made possible density dependent observations of the microscopic "atomic rearrangements" within glasses. Our results reveal a counter-intuitive behavior in a model metallic glass: under pressure, atoms actually.

Despite being the oldest man-made materials, and being ubiquitous in our daily lives, glasses remain puzzling to researchers. In particular, we still lack a comprehensive microscopic theory to understand how they form from their liquid parents and their spontaneous evolution with time. Everything starts during cooling a liquid below its melting temperature fast enough to avoid crystallization. In this case, the system enters a metastable state called supercooled state where the liquid viscosity increases by up to 16 orders of magnitude until the liquid flow is not measurable in typical observation times and a glass is formed.

As such, glasses are out-of-equilibrium materials (one would see a normal liquid behavior if the observation time is long enough, in the order of 104 years for silicate glasses at room temperature!) and are defined dynamically (their structure is virtually indistinguishable from that of the liquid). This implies that we need a dynamical description of glasses, a quest far more complex than getting an averaged structural description. Coherent x-rays can help: when they are scattered by the sample, they form a scattering pattern which is a footprint of the exact, non-averaged structure. Following this scattering pattern over time provides information on the temporal evolution, and thus the dynamics, of the constituents (atoms, molecules…). Yet, so far, only light sample environments could be used with coherent x-rays, enabling mainly temperature dependent studies. Here, we manage to investigate the dynamical properties of a model metallic glass at extreme pressures (comparable to that of the earth upper mantle) at the atomic scale, by placing our sample in a specific high-pressure apparatus: a Diamond Anvil Cell, which allows for the pressure generation, the preservation of the x-ray's coherence, and the required sample stability below the micron scale. This enables the study of the density dependence of the microscopic relaxation processes which control the macroscopic properties of the glass. Our results highlight a complex behavior under pressure: while the density increases monotonously as expected, the microscopic dynamics shows a two-stages evolution, including an acceleration of the atomic motion in the first part. This acceleration is really counter-intuitive: it's like people moving faster in a crowded environment.

Our analysis suggests that this strange dynamical behavior is stress driven, and characterized by sudden relaxation events involving a large ensemble of atoms, a feature visible in simulations and called cascade relaxations. This eventually disappears at large pressures, when pressure dramatically slow down the particle motion, and is in agreement with a recently developed theoretical model.

Figure 1



Caption

Figure 1: Sketch of the pressure induced acceleration of the atomic motion. At high pressure, the density increases and the dynamics is hyper-diffusive with a collective ballistic-like atomic motion.

Contact

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Further reading...

"Denser glasses relax faster: Enhanced atomic mobility and anomalous particle displacement under in-situ high pressure compression of metallic glasses"
A. Cornet, G. Garbarino, F. Zontone, Y. Chushkin, J. Jacobs, E. Pineda, T. Deschamps, S. Li, A. Ronca, J. Shen, G. Morard, N. Neuber, M. Frey, R. Busch, I. Gallino, M. Mezouar, G. Vaughan, and B. Ruta
Acta Materialia **255**, 119065 (2023)

"High-pressure X-ray photon correlation spectroscopy at fourth-generation synchrotron sources"
A. Cornet, A. Ronca, J. Shen, F. Zontone, Y. Chushkin, M. Cammarata, G. Garbarino, M. Sprung, F. Westermaier, T. Deschamps, and B. Ruta
J Synchrotron Rad **31**, (2024)

Epitaxial growth of $RbTiOPO_4$ thin films for confined nonlinear optics

Laser frequency conversion using a nonlinear process has to be carried out at high intensity. Waveguides are therefore the preferred media when low energies are considered. The Pulsed Laser Deposition technique was used to fabricate thin films based on isotype crystals of $KTiOPO_4$.

Second-harmonic (ω + ω → 2ω) and third-harmonic (ω + ω + ω → 3ω) generation, as well as the inverse processes of photon pair generation (2ω → ω + ω) and photon triplet generation (3ω → ω + ω + ω) respectively, require pump laser intensities of several hundred Mega Watt/cm². Micrometer-sized crystalline waveguides allow such interactions to be achieved at relatively low energies by taking advantage of the confinement of light.

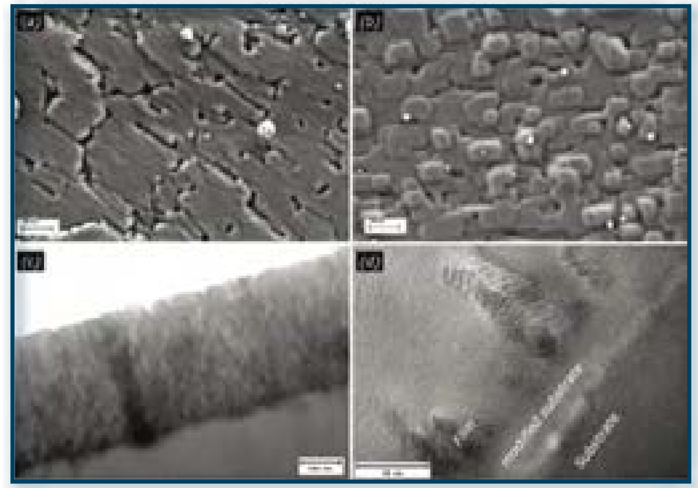
In 2021, a new collaboration within the OPTIMA team was initiated to reduce the size of waveguides to the minimum required to obtain optimum frequency conversion, known as phase-matching, involving the Telecom wavelength at 1.5 micrometers. Among the techniques available for growing crystalline materials, PLD (Pulsed Laser Deposition) is the technique of choice because it offers the possibility of obtaining homogeneous layers of high crystalline quality with a perfect thickness control.

The materials selected for this study are all from the titanyl phosphate family, with $KTiOPO_4$ (KTP) at the forefront, the latter being a privileged material for nonlinear optics. The architecture of the proposed waveguide is a thin layer of a few hundred nanometers of $RbTiOPO_4$ (RTP) on a KTP substrate. These two isostructural materials have a low lattice parameter mismatch, making it possible to achieve high-quality epitaxial growth. In addition, the refractive index of the RTP, which is slightly higher than the KTP substrate one, will allow light to be guided into the deposited layer.

The study of the deposition parameters and associated characterizations conclude that a homogeneous 500-nm-thick layer could be obtained by PLD [2]. However, High Resolution X-ray Diffraction and X-ray Photoelectron Spectroscopy measurements show that the alkaline ions, *i.e.* K^+ and Rb^+, present in the layer and in the substrate, inter-diffuse, leading to a solid solution with a composition of $K_xRb_{(1-x)}TiOPO_4$.
However, the layer retains a single-crystal character. This preliminary validation of the PLD technique provide the basis for further experiments to deposit $KTiOAsO_4$ (KTA) rather than RTP to avoid any inter-diffusion [3].

Figure 1

Figure 2



Captions

Figure 1: Principle of second-harmonic generation in a 1-Dimension nonlinear waveguide where ω and 2ω are the fundamental and second-harmonic circular frequencies, respectively

Figure 2: SEM surface images of the morphologies of the RTP layer before (a) and after annealing (b). TEM images of the cross-section of the layer (c), (d).

Contacts

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Further reading...

"Birefringence phase-matched direct third-harmonic generation in a ridge optical waveguide based on a $KTiOPO_4$ single crystal"
A. Vernay, V. Boutou, C. Félix, D. Jegouso, F. Bassignot, M. Chauvet, and B. Boulanger
Optics Express **29**, 22266-22274 (2021)

"Growth and characterization of rubidium titanyl phosphate thin films by pulsed laser deposition"
M. Salaün, A. Thiam, S. Kodjikian, and B. Boulanger
Materialia **34**, 102068 (2024)

"Epitaxial growth and characterization of (100) oriented Potassium Titanyl Arsenate ($KTiOAsO_4$) thin film by Pulsed Laser Deposition"
A. Clavel, M. Salaün, and B. Boulanger
The 8th European Conference on Crystal Growth - ECCG8, Warsaw, 21-25 July 2024

Origin of second harmonic generation in gold plasmonic nanostructures

Can we optically detect the difference in physical properties of identically shaped nanostructures fabricated through different processes? In our work, we found that the crystallinity or the surface roughness dramatically changes the second harmonic response of metal nanostructures under identical excitation field conditions. Consequently, by comparing numerical simulations and experimental data we were able to identify the origin of the second harmonic response in terms of the underlying current sources.

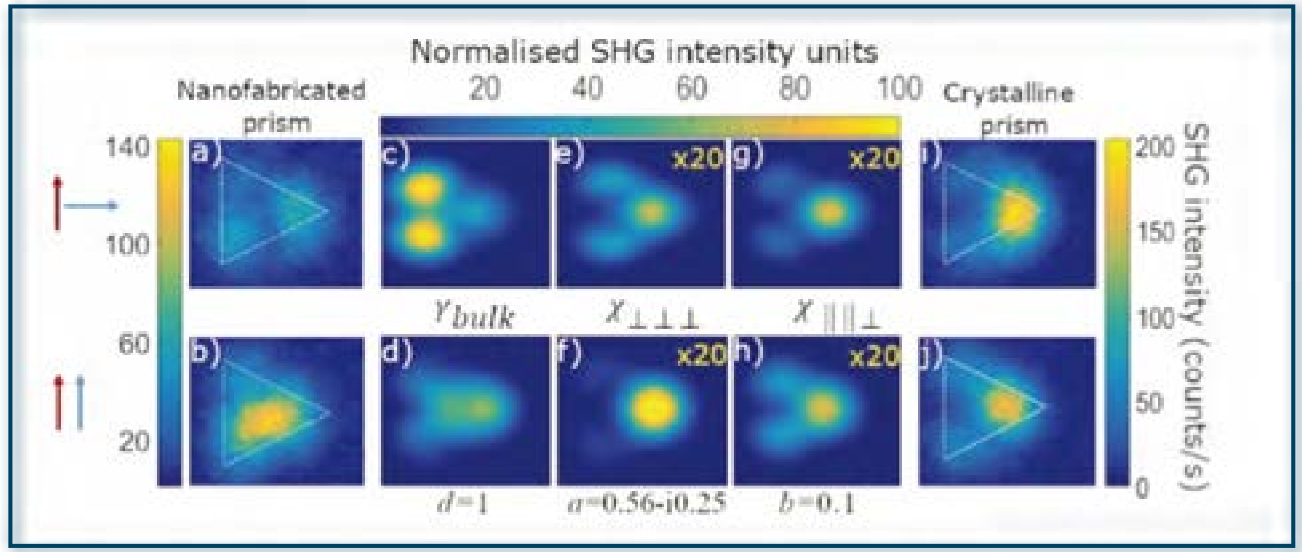
Metal nanostructures provide an interesting platform to study various phenomena of nanoscale light matter interaction. The coherent excitation of conduction electrons in a metal nanoparticle due to incident light wave, also known as a localised surface plasmon, leads to local electromagnetic field enhancement larger than the excitation field confined to the nanoparticle size. We can leverage this property to enhance nonlinear optical response, in our case, second harmonic generation (SHG) response whereby the frequency of the emitted light is twice the frequency of the incident light.

Although the lattice symmetry of metals inherently forbids second order nonlinear response such as SHG, the observation of SHG from metals since several decades has spawned several studies in order to understand their origin. As inversion symmetry is clearly broken at the interface separating the metal and its environment, it is understood that surface current sources can play an important role. In addition to it, higher order effects in the electron fluid motion can lead to SHG signal from within the bulk. The deviation of electronic currents by the magnetic field of light is one example. As a result, three nonlinear sources have generally been accepted as the main current sources to the SHG response. These are namely, bulk current, normal surface current and tangential surface current sources. Despite this, several studies have reported conflicting conclusions and assumptions regarding the dominant current source without sufficient justification.

In collaboration with NPSC and NOF teams within Institut Néel through Nanofab platform as well as CEMES, Toulouse, our recent work sheds new light on the discussion by reporting, to our knowledge, the first evidence of the dominant nature of the usually neglected tangential surface current source.

We fabricate Au nanoprisms of similar dimension either by chemical synthesis (crystalline prism) or e-beam lithography (nanofabricated prism) followed by sputtering. In Fig. 1 a)-b) and i)-j), are the experimentally acquired cartographic SHG response from different harmonic field polarizations for the two systems respectively. We can note these maps are clearly different from each other despite the identical experimental conditions of light exposition implying that the underlying nonlinear sources are different. To identify further the nonlinear sources, we can compare these maps with the numerically simulated cartographic responses for the three previous source terms in Fig. 1 c)-h). As the crystalline nanoprism has an atomically smooth surface, we expect the current source parallel to the surface to flow freely without hindrances. Consequently, we can see that the cartographic response among the sources that matches the most with Fig. 1 i) and j) are g) and h). Using a similar analysis, we can conclude that, in the case of the nanofabricated prism, the dominant contribution comes from both the bulk source and the tangential surface source. Hence, our work clarified one of the still debated fundamental aspects concerning the origin of SHG in plasmonic nanostructures.

Figure 1



Caption

Figure 1: Polarization resolved experimental SHG maps of nanofabricated prism (a-b) and crystalline prism (i-j) corresponding to an excitation wavelength of 1000 nm polarised normal to the horizontal axis of the nanoprisms (red arrows) and detected at the harmonic wavelength for two orthogonal polarisations (blue arrows). They are compared with simulated second harmonic source contributions (c-h) for the same configurations. The intensity of the maps corresponding to normal surface current $\chi_{\perp\perp\perp}$ (e-f) and tangential surface current $\chi_{\parallel\parallel\perp}$ (g-h) are multiplied by a factor of 20 for better visibility to be compared with the maps obtained for the bulk current γ_{bulk} (c-d). Their relative weights are given by the so-called "Rudnick and Stern" parameters entering in the evaluation of $\chi_{\perp\perp\perp}$, $\chi_{\parallel\parallel\perp}$ and γ_{bul} relative to a hydrodynamic model describing the electron dynamics. The dotted white lines on the experimental maps are guides to the eyes.

Contacts

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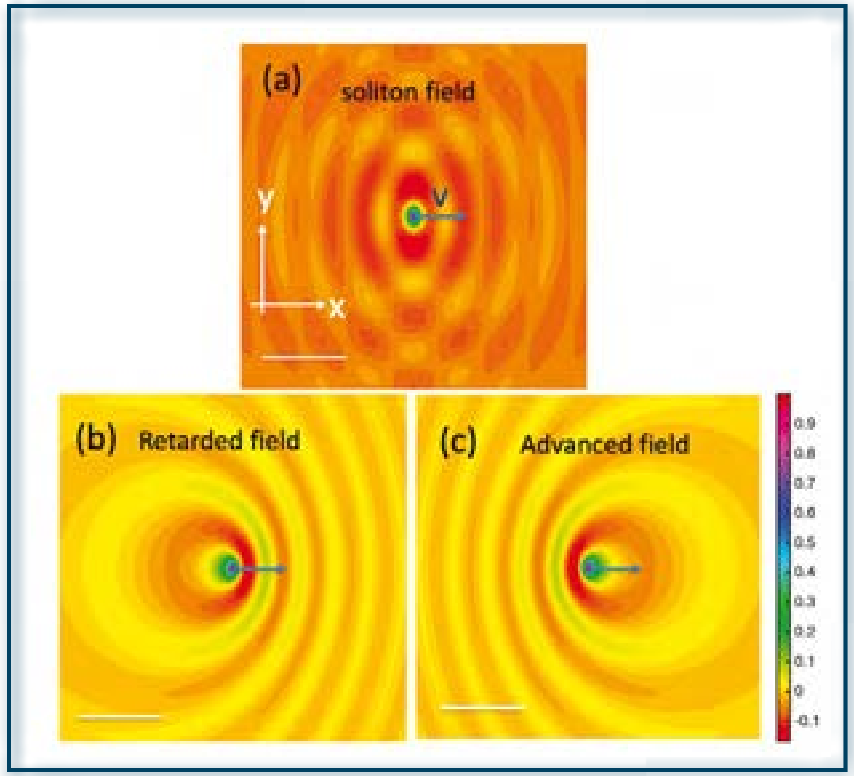
De Broglie's wave mechanics 100 years on: the return of quantum realism

100 years ago, in a series of seminal works, Louis de Broglie developed the wave mechanics at the heart of the quantum revolution. De Broglie did not, however, share the blind confidence of other founders (Bohr, Heisenberg, Born, etc.) who, through the instrumentalist and positivist Copenhagen interpretation, accepted that quantum mechanics be opposed to classical space-time causality and determinism.

Far from this, de Broglie, in line with a 'realist' vision championed by Einstein, proposed a hidden-variable pilot-wave theory, completed by Bohm into the de Broglie-Bohm mechanics (dBB). This theory, while re-establishing classical determinism and the notion of particle trajectories, makes it possible to recover all the probabilistic results of quantum mechanics.
We have recently developed a new de Broglie-type approach in which particles appear as small localized waves (solitons), propagating in space-time, and solutions of local, non-linear, wave equations. Each soliton is composed of a very sharp central peak on top of extended stationary waves (see Figure). The whole structure is oscillating in time at a frequency proportional to the particle mass and more generally involves a strong time-symmetry associated with waves emitted and absorbed by the soliton. The soliton peaks follow complex trajectories that identify with those predicted by dBB mechanics, and enable supposedly inexplicable quantum results (wave-particle duality, non-locality à la EPR-Bell ...) to be exactly recovered using a classical-like deterministic theory without the need of the Copenhagen quantum magic.
Of course, there is a price to pay for this return to ontological clarity in space-time. Indeed, the hidden variables of the dBB theory are known as non-local, because they assume instantaneous interactions at a distance that allow Bell's inequalities to be violated, in line with Alain Aspect's experiments. Our approach is completely local and also recovers the observed results at the cost of adding additional hidden variables describing the extended waves. We demonstrate that, thanks to the non-linearity of the wave equations generating our time-symmetric solitons, the initial conditions of the entangled quantum particles cannot be chosen arbitrarily. This is the key for an effective nonlocality of the measurements.
Such a theory is not only a return to the ideal of ontological clarity of 19th-century physics: It has many consequences, both physical and philosophical, which are being studied at Institut Néel.

Figure 1



Caption

Figure 1: Soliton profile for a particle moving with a uniform velocity v=0.6c (c is the light velocity) in the direction x. (a) cross-cut map of the real part of the soliton field in the x-y plane (the 3D soliton wave is rotationally invariant around the x axis). The field amplitude decreases with the distance to the central peak, and the asymmetry between the x and y axes is a relativistic effect related to the soliton motion. (b-c) retarded and respectively advanced fields associated with the moving soliton. Due to time-symmetry the full soliton field (a) is the half sum of (b) and (c) and is stationary in the rest frame of the soliton (where v=0). The scale has been chosen for the illustration (the particle peak could be much more pronounced). The oscillation period of the stationary field surrounding the central soliton peak in (a) is related to the Compton wavelength of the particle.

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Further reading...

"Whence Nonlocality? Removing spooky action at a distance from the de Broglie Bohm pilot-wave theory using a time-symmetric version of de Broglie double solution"
A. Drezet
Symmetry **16**, 8 (2024)

Unconventional Superconductivity in Infinite-Layer Nickelates

The discovery of superconductivity in the infinite-layer nickelates ($RNiO_2$, with R=La,Nd, Pr) has uncovered a new family of nickel-based superconducting materials, that show intriguing similarities to high-temperature cuprates. However, the exact nature of their superconducting mechanism remains uncertain. Researchers are questioning whether the traditional electron-phonon interaction is sufficient to explain this phenomenon or if a more complex mechanism is at play.

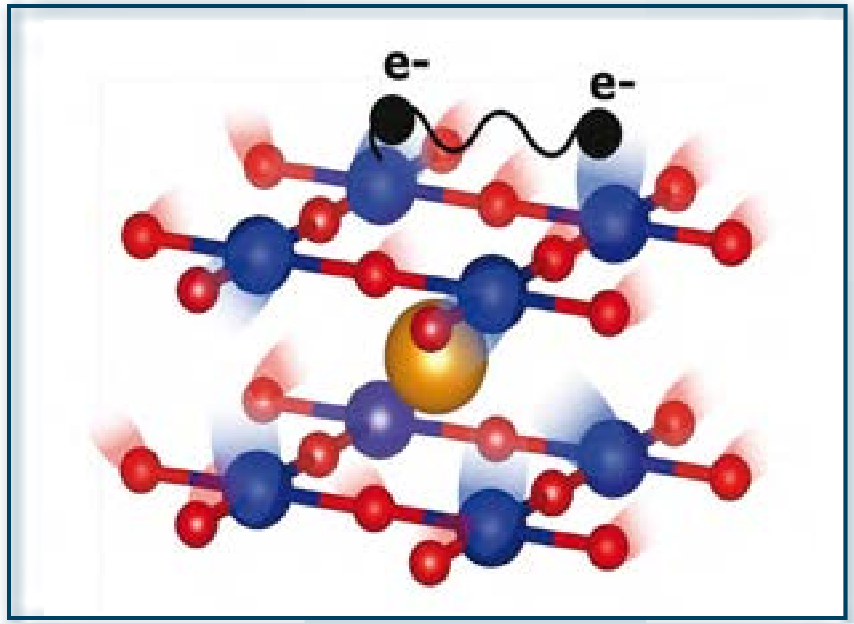
In this study, we used advanced computational methods, such as many-body perturbation theory, to closely examine possible mechanisms of superconductivity in infinite-layer nickelates. These materials, with their layered structure similar to that of cuprates, provide a valuable opportunity to understand how superconductivity emerges. A key question is whether electron-phonon coupling, known to be the source of conventional superconductivity, plays a significant role in these systems. Based on our ab initio calculations, we found that the improved treatment of electronic correlations using manybody perturbation theory enhances the electron-phonon coupling compared to results obtained from simpler methods, such as pure density functional theory (DFT). However, despite this enhancement, the calculations show that this coupling remains too weak to explain the high critical temperatures observed experimentally, which can reach up to 20 K in doped nickelates. This weakness suggests that another mechanism, different from conventional electron-phonon coupling, is responsible for superconductivity.

We then turned our attention to the parent compounds of the nickelates, which are undoped materials like $NdNiO_2$ and $LaNiO_2$. Interestingly, these compounds also show signs of superconducting instabilities at very low temperatures. Although these instabilities lead to significantly lower critical temperatures (below 1 K), they support the idea that superconductivity in these systems may be driven by more complex electronic correlations.

For further clarifications, we performed electron-phonon coupling calculations under pressure. The results showed that applying pressure increases the stiffness of vibrational modes (phonons) and reduces the electronic density of states near the Fermi level. Consequently, instead of enhancing phonon-mediated superconductivity, pressure seems to reduce it, which contradicts current experimental data showing that superconductivity increases with pressure. This inconsistency further supports the hypothesis that superconductivity in nickelates is dominated by an unconventional mechanism, though the exact nature of this mechanism remains undetermined, with magnetic interactions suspected to play a role.

In conclusion, this study highlights that while electron-phonon interactions are present, they cannot solely account for superconductivity in infinite-layer nickelates. Another coupling mechanism, likely linked to strong electronic correlations and doping effects, appears to dominate in these materials. These findings pave the way for further studies to better understand this unconventional superconductivity.

Figure 1



Caption

Figure 1: Illustrative representation of phonon-mediated cooper-pair formation in an infinite-layer nickelate crystal"

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Further reading...

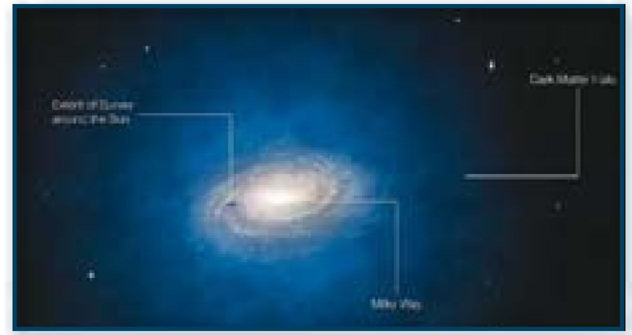
Q. N. Meier, J-B. de-Vaulx et al
Phys. Rev. B, **109**, 184505 (2024) Editors' suggestion

The GrAHal Project: In Search of Dark Matter

"Dark matter" is that mass present in the cosmos that reveals itself through its gravitational effects but remains invisible to all means of observation. Although it makes up the majority of the mass content of the universe, its nature has remained elusive for over 80 years. The GrAHal project, involving the Néel Institute, LNCMI, and LPSC in Grenoble, aims to test with the highest sensitivity the hypothesis that dark matter is made up of a new particle called the axion.

A "missing" mass has been invoked to explain the dynamic anomalies observed by astronomers since the 1930s. The stability of most galaxies raises questions: the gravitational pull generated by the observed matter is not sufficient to counterbalance the centrifugal force experienced by peripheral stars as they orbit the galactic center. To restore balance, an additional invisible mass must be invoked. Dark matter also reveals itself through its gravitational lensing effects (bending the light from distant sources) and certain properties of the cosmic microwave background radiation. But what is it made of? Various candidates have been considered and sought after, so far in vain.
The axion, meanwhile, is a particle introduced in the late 1970s to solve a puzzle related to the symmetry properties of the strong interaction (the "strong CP problem," i.e., the absence of CP symmetry, or equivalently time reversal, violation). It turns out that the axion is an ideal candidate for dark matter if its mass is within a certain range: it could then have been produced in sufficient amount during the universe evolution to make up the main part of dark matter. It interacts very weakly with other particles, making it extremely difficult to detect. Advantage can however be taken of the fact that the axion can be converted into a photon in a space where a magnetic field prevails. The putative axions of our dark matter halo, illustrated in Figure 1, have non-relativistic velocities so the expected photon's energies correspond to their rest mass energy. Given cosmological constraints, these energies are expected to fall within the microwave range (100 MHz to 100 GHz).
The principle of the haloscope is therefore simple (Figure 2): maintain a microwave cavity at low temperatures within a strong magnetic field and search for a faint quasi-monochromatic signal of relative spectral width of 10^{-6}. However, the exact mass of the axion is not known, which requires a methodical frequency sweep. Despite the expected axion density (between 10^{12} and 10^{15} per cm^3 depending on their mass), the expected signal is extremely weak: from 10^{-21} to 10^{-25} watts, depending on the haloscope design and the frequency investigated. This is where the competitiveness of the Grenoble site comes into play, combining recognized expertise in cryogenics and ultra-low noise microwave amplification (I. Néel), axion theory (LPSC), and the new hybrid magnet at LNCMI, whose superconducting outsert allows for the installation of the most powerful haloscope in the world (Figure 3). In an increasingly competitive international context, the Grenoble collaboration has partnered with a key player: CAPP, the large Korean center for dark matter axion research. In its first phase, the joint detector project will explore the 0.3-0.6 GHz range "definitively" before moving to higher frequencies. It was recently presented to the international community of "axion hunters."

Figure 1



Captions

Figure 1: Artist's view of our galaxy, the Milky Way, and its dark matter halo (in blue).

Figure 2

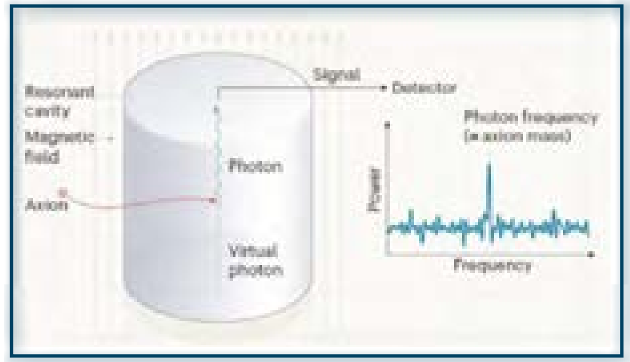


Figure 2: Left: Principle of the haloscope – an axion is converted into a photon within a resonant cavity placed in a magnetic field and at low temperature. Right: Spectrum of the signal emitted by the cavity, where axion-photon conversions should appear as a small monochromatic peak, with a height proportional to the square of the magnetic field and the cavity volume, superimposed on the thermal signal.

Figure 3

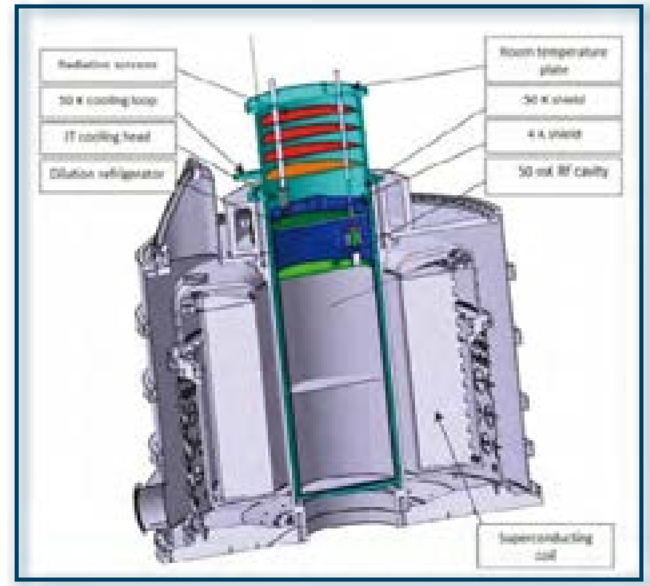


Figure 3: Schematic diagram of the GrAHal haloscope installation within the superconducting outsert of LNCMI's new hybrid magnet. The specific cryogenic system is designed at Néel Institute. The resonant cavity for the GrAHal-CAPP collaboration will measure approximately 700mm in diameter and 1.2m in height.

Contact

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Further reading...

"GrAHal-CAPP for axion dark matter search with unprecedented sensitivity in the 1–3 μeV mass range"
P. Pugnat, P. Camus, O. Kwon, R. Ballou, C. Bruyère, H. Byun, W. Chung, T. Grenet, P. Perrier, Y. K. Semertzidis, A. Talarmin, and J. Vessaire
Frontiers in Physics (2024), https://doi.org/10.3389/fphy.2024.1358810

The quest for Room Temperature Superconductors

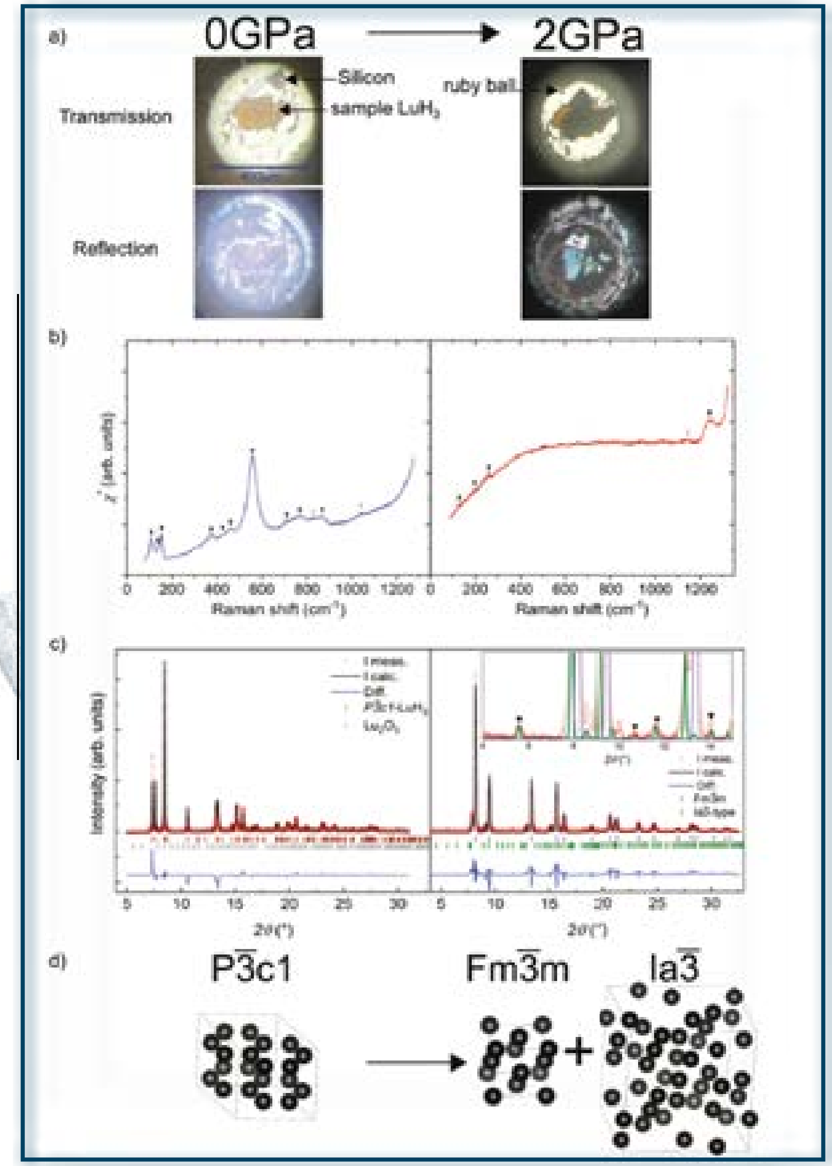
Pressure-induced formation of cubic lutetium hydrides derived from trigonal LuH_3

Room temperature superconductivity has become a Holy Grail of condensed matter physics with the current record held by LaH_{10} with a T_C of 260K around 200GPa, a pressure comparable to the Earth's core. Determining the precise structure of these compounds is always challenwging due to the presence of very light-elements and the extreme conditions of their stability. Current efforts target the promising family of metallic hydrides, but, as the number of untested binary hydrides dwindled, it became natural to search within the ternaries. In March 2023, this led to the controversial discovery of room-temperature superconductivity at a staggeringly low pressure of 1GPa in nitrogen-doped lutetium hydride, in a now-retracted Nature paper.

This discovery was not only met with uncertainty but drew suspicions of fraud from the scientific community, which urged us to investigate these precocious claims. Besides the controversy about existence of superconductivity in this compound, there was a clear inconsistency in the retracted paper but also in subsequent reports between the reported structures and the number of Raman active phonon modes. The presence of nitrogen in the structure was also doubtful, due to molecular nitrogen's inherent stability, evidenced by previous attempts to synthesise metal nitrides. Thanks to a collective effort within the Néel Institute together with ESRF facility, we show the compound is in fact a mixture of lutetium-hydrogen cubic compounds, without nitrogen, and we solve their structures consistently with X-ray diffraction and Raman spectroscopy measurements.

High-quality starting samples of trigonal LuH_3 were grown using hydrogen absorption. However, to synthesise the desired nitrogen-doped lutetium hydride, the diamond anvils cell (DAC) was sealed with a mixture of helium and nitrogen, the former being inert. X-ray diffraction directly probes the lutetium sublattice, whilst Raman spectroscopy measures the vibrational excitations (phonons) of the crystal. We performed both measurements at each step. For pressure measurements, we used a DAC, which takes advantage of the ideal properties of diamonds: their ability to withstand extreme pressure, and they are transparent to both X-rays and visible light.

The photos in Fig.(a) show the sample as it is pressurised from ambient pressure to 2GPa, where we immediately saw a distinct change in its colour and transparency. Figure.(b) shows the Raman spectra, and at 0GPa, we observed many features, almost all of which vanished upon pressurisation and indicate a structural and/or chemical transformation. Similarly, Figure.(c) shows the X-ray diffraction patterns at two pressures, and we once again see a drastic change; the application of pressure has resulted in the decomposition of the initial LuH_3 into two different compounds with distinct crystal structures (as shown in figure.(d)). The first corresponds to cubic LuH_{2+x} with an *Fm$\bar{3}$m* structure, whilst the second is a novel *Ia$\bar{3}$* compound of unknown stoichiometry, though no nitrogen was observed by our X-ray spectroscopy measurements, in disagreement with the original *Nature* publication. Most importantly, this last *Ia$\bar{3}$* structure can now explain the Raman results as reported by us and by few groups worldwide.



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PhD Student
Owen Moulding

Further reading...

https://www.lemonde.fr/sciences/article/2023/03/20/doutes-en-serie-autour-d-un-article-sur-un-materiau-supraconducteur_6166278_1650684.html

https://www.lemonde.fr/sciences/article/2023/09/04/materiau-supraconducteur-soupcons-de-fraude-sur-une-etude-americaine_6187791_1650684.html

https://www.nature.com/articles/d41586-023-02733-z

https://lejournal.cnrs.fr/articles/supraconductivite-la-temperature-monte

The art of contacting and of chasing losses:
Processing aluminum and gold air bridges

Micrometric air-bridges were shown to be an essential component and an elegant technique to design microscale circuits such as superconducting coplanar waveguides for example. With the density of features increasing over the past years on these chips, being able to limit at maximum the losses and the parasitic signals, coming from the asymmetry encountered due to the confined design, was a challenge.

Chips that include several superconducting quantum devices are composed of multiple electrodes, each of which must have precisely defined electrical potentials, especially at very high frequencies (in the range of several tens of gigahertz). If the potentials are not properly defined, unwanted parasitic modes may arise, negatively affecting the electrical performance of the quantum chip. Therefore, reliable connections are essential for ensuring proper electrical contact between these electrodes. Suspended bridges are the preferred solution, as they can be made very short, thereby minimizing stray inductance and ensuring optimal electrical performance. Several procedures were developed at Nanofab to optimize the lead fabrication.

A first one was dedicated to micrometric air-bridges built up on metallic pillars. This technique managed to get really good electrical contacts of hundreds of nm features. Its challenging aspect was to find the best compromise between the doses used for electron beam exposure for the different parts of the bridge: the aerial one, and the one sitting on the pillars for which an optimum electrical contact was required (Figure 1). This was made possible thanks to the use of a trilayer of different resists with diverse sensitivities.

Moving forward, the second technique that was developed managed to reduce the number of process steps to one only, improving yield and bridges quality. A full bridge feature was built by only one electron beam lithography step (Figure 2). This exposure was based on an incrementing dose factor between the base of the bridge and the top part associated with a following reflow.
The challenge of this procedure was to find the best compromise between the dose increment and the reflow temperature chosen to keep a continuous metallic bridge and to make it resistant mechanically.
Again, these micrometric bridges were able to contact features of only a few tens of nm wide.

Finally, a last technique was developed to reach a much larger scale. Indeed, bridges of tens of micrometers were designed to connect different parts of a superconducting coplanar circuit.
This last technique was based on the evolution of the contact angle of a reflowed resist, leading to a curved profile being optimal for further metal deposition without inducing any strain in the metal, even for heights reaching 1-3µm (Figure 3).
This last technique was proved to be really versatile as it can be transferred to every microfabrication techniques found at the institute (**UV and electron e-beam lithography can both be employed**).
It is a though technique requiring two steps of lithography: one designing the boxes for the reflow, and the other one to design the final bridges.
All these different techniques could be employed to contact various types of designs, chips and materials, giving a complete picture of the possibility of 3D contacting at the Institute.

Figure 1

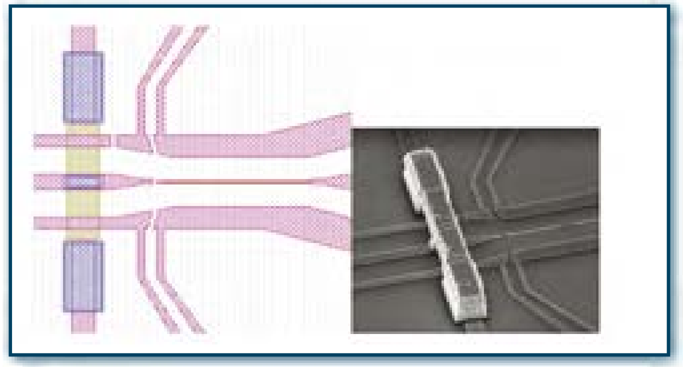


Figure 2

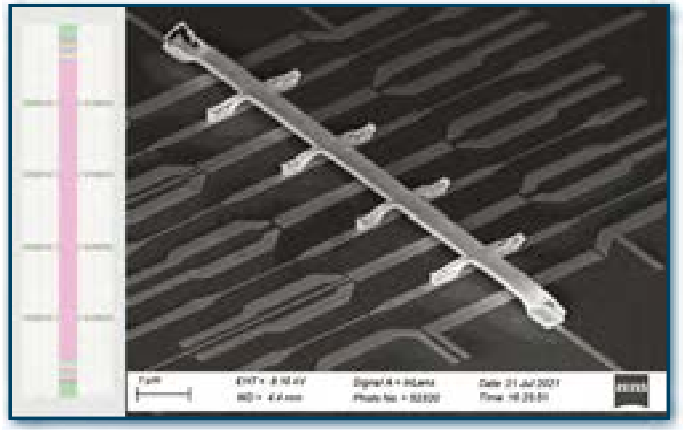
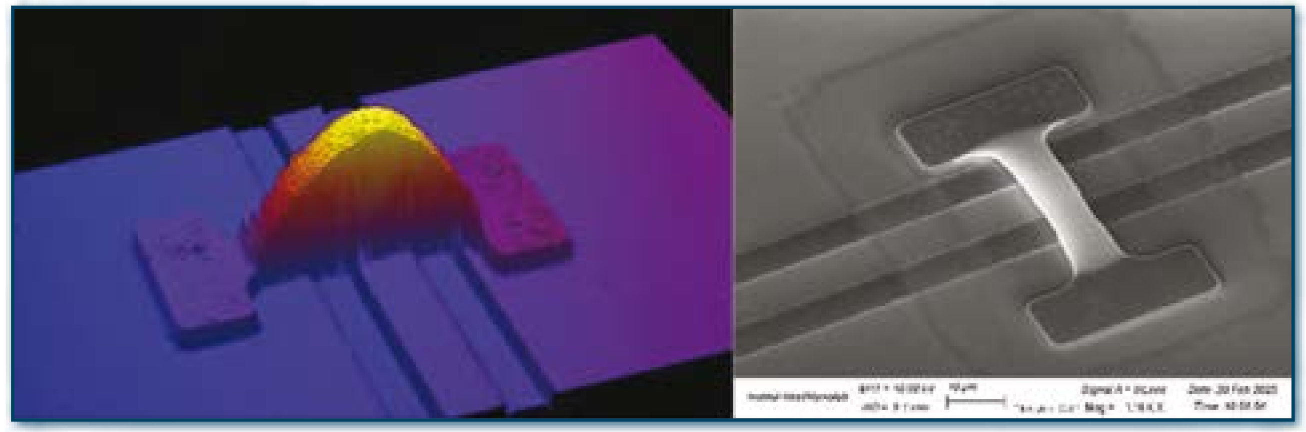


Figure 3



Captions

Figure 1: Micrometric pillar bridge (Ti_{30}/Au_{200}) and its design.

Figure 2 Micrometric dose increment bridge (Ti_{6}/Au_{95}) and its design.

Figure 2 Long micrometric bridge based on resist reflow procedure (Al_{350}) and its 3D profile.

Thicknesses are given in nm.

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• Journées du laboratoire •
• Laboratory days •
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