SORBONNE UNIVERSITÉ

# PROGRAMME INTITUTS ET INITIATIVES

## Appel à projet – campagne 2021

## Proposition de projet de recherche doctoral (PRD)

## IPhyInf - Initiative Physique des infinis

**Intitulé du projet de recherche doctoral (PRD): X-ray metrology for astrophysical and fundamental physics applications**

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Intitulé : Laboratoire Kastler Brossel
Code *(ex. UMR xxxx)* : UMR 8552

**École Doctorale de rattachement de l'équipe (future école doctorale du.de la doctorant.e) :** **ED564-Physique en IdF**

**Doctorant.e.s actuellement encadré.e.s par la.e directeur.rice de thèse (préciser le nombre de doctorant.e.s, leur année de 1<sup>e</sup> inscription et la quotité d'encadrement) : 1 doctorant, 2020, 100%**

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**École Doctorale de rattachement :** **Choisissez un élément :**
Ou si ED non Alliance SU :

**Doctorant.e.s actuellement encadré.e.s par la.e co-directeur.rice de thèse (préciser le nombre de doctorant.e.s, leur année de 1e inscription et la quotité d'encadrement) :**

**Cotutelle internationale :** ☒ Non ☐ Oui, précisez Pays et Université :

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# X-ray metrology for astrophysical and fundamental physics applications

## Introduction and context

High-precision atomic physics measurements allow to probe a multitude of fundamental physics questions, from quantum electrodynamics to astrophysics, to tests of the standard model. Precision spectroscopy in muonic hydrogen, to which the LKB group has been a main contributor, have led to the “proton size puzzle”, where the proton size obtained from muonic and normal hydrogen showed a 7 standard deviation disagreement[1-3]. The problem is still not fully understood [4]. We just published the He nuclear radius[5], obtained by the same method, which agrees with electron scattering results. High-precision measurements with crystal spectrometers in highly charged ions (HCI) have also improved our understanding of bound state quantum-electrodynamics—BSQED (see Ref. [6] for a recent review), and LKB has a world-leading facility in Paris for highest-precision x-ray spectroscopy of HCI.

On the astrophysics side, improved knowledge of x-ray transition energies and intensities in highly charged ions has become critical for understanding stellar emissions and searching for dark matter. There is an ongoing debate surrounding a possible dark matter signal at 3.5 keV extracted from the HITOMI satellite data[7-9], show to be most probably x-ray lines from hydrogenlike sulfur in an ion source based atomic physics experiment[10]. Another interesting unsolved problem concerns the intensities of the brightest iron lines emitted by some astrophysical objects[11], the Ne-like iron L lines. Their relative intensities have long posed a problem for plasma models, a problem has finally been traced back to a strong disagreement between the most advanced atomic theoretical calculations and experiments[12]. We have observed similar discrepancies in high-precision reference-free measurements carried out on core-excited Li-like Ar and S ions with our double crystal x-ray spectrometer on SIMPA (Source d’Ions Multichargés de Paris) in Jussieu[13]: theoretical predictions do not agree with the measured line intensity ratios.

Similar x-ray spectroscopy techniques applied to “exotic atoms” where an electron is replaced by a muon, electron, pion, or antiproton, have allowed us to test Chiral Perturbation theory for the strong interaction[14], and the nucleon-antinucleon interaction[15]. We have recently demonstrated a new paradigm, wherein measurements of transition energies in circular Rydberg states in muonic and antiprotonic atoms can provide better tests of QED than HCI[16]. Atomic system and precision measurements may also contribute to tests of physics beyond the standard model (BSM), see e.g., Ref. [17] for a review.. Our group is currently working at evaluating limits on coupling constants and masses of possible BSM bosons which can be extracted from all the precision measurements on hydrogen and deuterium, highly-charged ions spectroscopy, laser spectroscopy of muonic H, D and He, laser spectroscopy of antiprotonic[18] and pionic[19] He.

New quantum technologies are now available for atomic physics that can shed light on these outstanding problems. The project proposed here will use both world-leading x-ray metrology techniques and new quantum transition edge sensor (TES) microcalorimeter detectors to make precision measurements of highly charged and exotic atoms for multi-faceted fundamental physics studies. This novel combination of expertise will directly benefit astrophysical applications, as one of the members of the muonic atom collaboration described below (S. Watanabe) is also part of the design group in charge of the new x-Ray Imaging and Spectroscopy Mission satellite—XRISM (http://xrism.isas.jaxa.jp/en/), which will be equipped with a TES detector and launched in 2021.

## Project

The PhD project has two parts. First, highest-precision reference-free measurements on few-electron heavy ions will be performed with the crystal spectrometer at SIMPA in Paris, to test QED and relativistic many-body physics, and explore the problem of line intensity ratios and energies important for astrophysical studies and plasma physics. The candidate will then combine his/her new expertise with both quantum sensing detectors and crystal spectrometers for precision measurements of transitions between Rydberg states in muonic atoms at J-PARC in Japan. Advanced calculations by the LKB team have shown as presented in Ref. [16], that these transitions offer a complementary and more accurate probe of QED contributions than highly-charged ions, as the nuclear size and nuclear polarization effects are very small in these systems.

### Highly charged ions at SIMPA

The first part of the project consists in improving and making measurements with the double crystal x-ray spectrometer at SIMPA in Paris to measure highly charged ions (HCI). This spectrometer is a world-unique facility, allowing to perform reference-free ppm-accuracy measurements on highly-charged middle-*Z* ions[13,20,21]. The only other instrument allowing such measurements is at the Max Planck Institute in Heidelberg, but it uses a different instrument, of lower metrological reliability. The candidate will work on improving the spectrometer, to gain at least a factor of two in accuracy, which is necessary to measure higher-energy lines. These improvements will be done in collaboration with the NIST Dosimetry group, which has performed similar improvement to their DCS, which is used to make high-precision measurements of x-ray [22] from solid targets.

The improved setup should boast a factor of two gain in accuracy, and the student will then use it to do energy measurements in highly-charged ions for QED tests and astrophysics. We will perform high-precision measurements of the $1s2s2p\ ^2P_J \to 1s^2 2s\ ^1S_{1/2}$ , transitions where intensity ratio discrepancies have been identified, as well as the $1s2s^2 2p\ ^1P_1 \to 1s^2 2s^2\ ^1P_0$ in Be-like Cl and S as a measurement we performed in sulfur seems to indicate an increased disagreement with theory[13]. For that purpose, we will use organometallic compounds which are either gaseous at ambient temperature or easily vaporized to make, for example iron beams with the ECRIS. This will improve our knowledge in particular of the Auger shifts and widths of the observed lines. For the astrophysical problem identified in Ne-like iron, we will extend the measurements to Mo and Xe. The study of the evolution of the intensity ratio and energies as a function of Z will enable to better understand the reason for the large observed disagreement.

### Muonic atom precision experiments at J-PARC

In April 2019, we performed a preliminary experiment for QED tests with muonic atoms at J-PARC in Japan, in collaboration with Pr. Azuma and his group from RIKEN, researchers from the university of Tokyo and of the Kavli Institute, and from the NIST in Boulder in the framework of the High-resolution Exotic Atoms x-ray spectroscopy with Transition Edge Sensor microcalorimeter (HEATES) international collaboration. We did the first observation ever of a transition in muonic atoms[23] using a high-performance, new-generation quantum sensing TES microcalorimeter detector[23,24]. A 5-year measurement program has been accepted to measure high-n circular Rydberg states in muonic atoms, with gains of 2-3 over existing sensitivity to higher-order QED effects. We did a first high-precision measurements on Ne and Ar in January 2020, in the 3-10 keV range [23]. Two new detectors, intended to the 3-35 keV and 3-100 keV range will allow to study heavier elements, Kr and Xe, available for the next run in the fall of 2021. One key to experimental success is the calibration of the TES detector, which is extremely sensitive. We used a combination of many metallic targets excited with an x-ray tube during our January run. We plan to improve our calibration procedure by measuring transition energies in HCI with the Paris spectrometer, and compare them with the measurements performed with the TES. The candidate will play a central role in designing and performing this new calibration procedure, which will have important implications for our physics program, allowing us to gain another order of magnitude in sensitivity. He will them participate to the implementation of these new calibration procedure during the experiment at JPARC. Another important progress will be to apply modern Bayesian techniques to the analysis of the lines observed at JPARC, as they are the sum of several partially resolved lines corresponding to transitions between the different fine-structure sublevels. This will provide quantitative evaluation of the quality of the fit, providing a check of the line intensity ratios.

## Conclusion

This project is thus, both by its physics objectives and applications, at the interface between atomic physics, low-energy particle physics, tests of the standard model and astrophysical applications. The PhD candidate will perform complementary experiments with advanced, state-of-the art, world unique technologies and instruments to provide the most-accurate atomic data available to date in highly-charged and exotic atoms. The project builds on the world-recognized expertise in relativistic atomic structure and QED calculations of the LKB group to provide the necessary information to exploit the experimental results to their fullest.

## Role of the two PhD supervisor

P. Indelicato will be in charge of x-ray metrology on highly-charged ions and muonic atom experiments at J-PARC, and of providing theoretical support in QED and relativistic many-body calculations. M.

Trassinelli will oversight the analysis of the data and developing tools for data analysis with Bayesian techniques.

## Student profile

The PhD student hired in the framework of this project must be interested in fundamental physics. He/She will participate in the conception, construction, improvements, and use of the different experimental set-ups in Paris and JPARC. He must be interested in learning advanced x-ray metrology and the use of state-of-the art quantum x-ray detectors, as well as collaborating with research engineers to develop high-precision mechanics. Basic programming competencies in ROOT/C++ and Python are appreciated to analyze the TES and DCS data, as well as to use the Bayesian analysis techniques for disentangling complicated atomic spectra, developed by M. Trassinelli at INSP. [25,26]. LABVIEW is used for control of some of the instruments. Good mastering of English is also necessary for working in the international collaborations with NIST (Gaithersburg and Boulder implantations) and with Japan.

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