

M2 internship/PhD Project 2026-2029

Ultracold dysprosium atoms: a giant spin for quantum simulation and metrology

Laboratory: Laboratoire Kastler Brossel, Collège de France, Paris

Master internship/PhD Advisor: Sylvain Nascimbene, Professor at ENS Paris

We offer a Master's 2 internship in spring 2026, which will be followed by a three-year PhD from 2026 to 2029. During the internship, the student will work on developing a technical upgrade of the experiment in collaboration with the supervisor, while also becoming familiar with the experimental apparatus to ensure a smooth and efficient start to the PhD.

Scientific Context

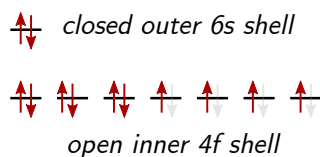
Ultracold atomic gases have become a cornerstone of modern quantum many-body physics, providing highly controllable platforms for exploring fundamental quantum phenomena. In recent years, energy bands with non-trivial topological properties have been engineered for neutral atoms, enabling the simulation of exotic condensed matter systems such as those exhibiting the quantum Hall effect [1]. Moreover, interactions between atoms can generate entanglement between their internal spins, paving the way for the realization of quantum-enhanced sensors and precision measurements where quantum correlations play a central role [2].

Project specificity: using dysprosium, an atom with a giant spin

The originality of this PhD project lies in the use of ultracold gases of dysprosium atoms. Dysprosium possesses a **large internal spin degree of freedom**, with a total angular momentum $J = 8$ (see Figure 1). This high-dimensional spin manifold offers unprecedented opportunities for quantum simulation and quantum sensing.

The research group of S. Nascimbene has pioneered two complementary research directions exploiting these properties. First, the coupling between atomic spins and light fields can induce nonlinear spin dynamics, leading to the generation of **non-classical spin states** [3, 4, 5, 6]. Such states enable the detection of magnetic fields with sensitivities beyond the standard quantum limit, holding promise for next-generation quantum magnetometers. Second, atom–light momentum exchange can simulate the effect of artificial magnetic fields on neutral atoms, enabling the study of **topological band structures** and analogues of the quantum Hall effect [7, 8]. The group has realized a variety of topological phases, including a system effectively evolving in four dimensions [9], where two synthetic dimensions are encoded in atomic spin states. Recently, spatial entanglement properties in such systems have also been probed experimentally [10].

Until now, these experiments have focused on dilute regimes where interatomic interactions were negligible. This PhD project aims to extend these investigations to **interacting** systems, where controlled spin-exchange interactions can give rise to correlated and entangled many-body states.



Key property of Dysprosium

electronic structure with 2 valence shells

→ spin $J = 8$ strongly coupled to light

Figure 1: Electronic structure of dysprosium, a lanthanide atom with two valence shells, a fully filled 6s outer shell, and a partially filled submerged 4f shell. This structure leads to numerous optical resonances and strong spin-light coupling, central to this PhD project.

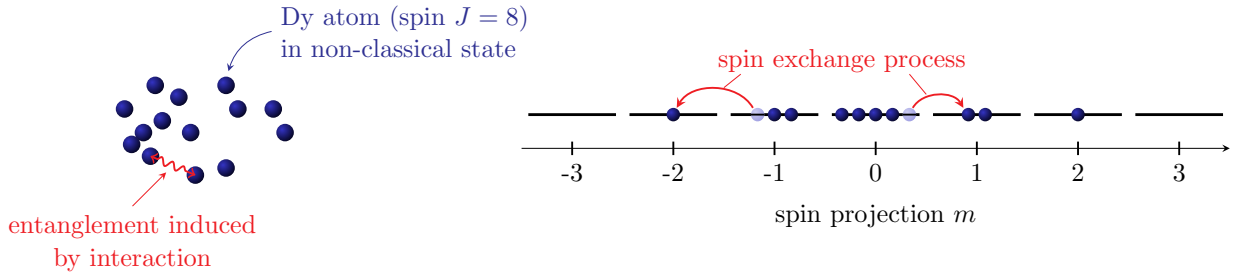


Figure 2: Left: Representation of the system studied in this thesis—a dysprosium condensate exhibiting both atom–atom entanglement and non-classical single-atom spin states. Right: Diagram of a spin-exchange process generating interatomic entanglement.

Objective 1: Entangled dysprosium atoms for quantum sensing

The first goal of the project is to combine non-classical spin dynamics within individual atoms with entanglement generated through interatomic elastic collisions. These collisions drive spin-exchange processes such as (see Figure 2):

$$(m = -1) + (m = 0) \rightarrow (m = -2) + (m = 1).$$

Such processes have been used in low-spin systems to generate entanglement [11, 12]. Extending them to a high-spin system like dysprosium opens new possibilities for realizing complex multi-particle entangled states, where each atom itself occupies a non-classical spin state. The long-term goal is to produce states with enhanced magnetic sensitivity, which could serve as prototypes for advanced quantum sensors.

Objective 2: Interacting Condensates in Topological Bands

The second objective is to study interacting dysprosium gases confined in topological bands. We will first explore the weakly interacting regime, where a Bose–Einstein condensate is expected to form a regular lattice of quantized vortices (see Figure 3). The project will then progress toward the strongly interacting regime, where we anticipate the emergence of many-body states analogous to those in the fractional quantum Hall effect, providing a bridge between atomic and electronic topological matter.

Experimental Setup and Thesis Organization

The experimental setup is fully operational and currently capable of producing ultracold samples of dysprosium. The PhD student will join an active research team consisting of two permanent researchers, one postdoctoral fellow, and two other PhD students. The project will combine experimental work, theoretical modeling, and numerical simulations to interpret and guide the experiments.

Funding of the Thesis

We plan to apply for funding from Ecole Doctorale EDPIF (as well as specific funding depending on the student’s origin). If unsuccessful, the group can cover the PhD using its own funds.

Candidate Profile

We are seeking a highly motivated student with a strong background in quantum physics and hands-on laboratory experience. The selected candidate will participate in all aspects of the experiment: daily operation of the ultracold atom apparatus, design and construction of new optical systems, data acquisition and analysis, and numerical modeling for interpreting results. The student will work within a collaborative team environment, typically comprising three PhD students and two permanent researchers.

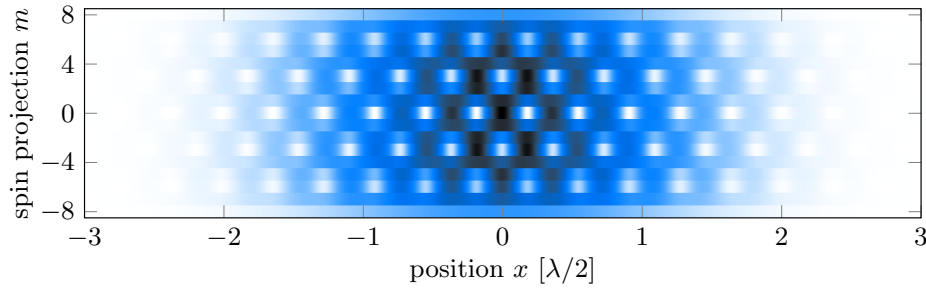


Figure 3: Expected atomic density distribution in an interacting Bose–Einstein condensate within a topological band. One of the two spatial dimensions is encoded in the atomic spin projection m [7]. The density minima correspond to quantized vortices arranged in a regular lattice.

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