Università degli Studi di Firenze
Ph.D. Cycle XXXVII
Doctoral Programme in Physics and Astronomy

Exploring exotic few- and many-body states in novel chromium-lithium Fermi mixtures

Strong interactions among fermionic particles constitute the key ingredient that might allow their binding into more complex aggregates, and which determines the behaviour of a wealth of physical many-body systems, spanning a wide range of energies: from ultracold gases and liquid Helium, to atoms, molecules and solids, all the way up to nuclear and quark matter. Importantly, a common set of ideas and concepts is applicable to these seemingly different frameworks, the understanding of one system providing information about the others. For instance, resonantly interacting ultracold Fermi gases and nuclear matter are both essentially non-relativistic quantum systems, in which interparticle interactions are characterized by a scattering length much larger than the mean interparticle distance. This has led in recent years to an interesting cross-fertilization between various fields, letting ultracold atomic Fermi mixtures emerge as ideal candidates for the exploration of a variety of strong correlation phenomena, in light of their unparalleled degree of cleanliness and versatility.

In this Ph. D. research project, I propose to experimentally unveil, and thoroughly characterize, a variety of elusive few- and many-body phenomena of highly-correlated fermions, by exploiting a new kind of atomic quantum simulator. This will be based on a heteronuclear Fermi mixture composed by lithium (^{6}Li) and chromium (^{53}Cr) atoms, uniquely available in the lab of Dr. Matteo Zaccanti at CNR-INO/LENS. In general, the introduction of a "heavy-light" mass asymmetry within a fermionic mixture is expected to promote a rich variety of exotic quantum states that are difficult to realize, or even unattainable, with currently available equal-mass systems. For few-particle physics, heteronuclear fermion mixtures are predicted to exhibit various $N > 2$–body cluster states and scattering resonances: Among others, a proper mass imbalance may lead to the existence of the Efimov effect [1, 2], as well as to the emergence of non-Efimovian clusters with universal properties [2, 3, 4]. At the many-body level, the natural mismatch of the Fermi surfaces of a mass-imbalanced Fermi mixture is expected to greatly enhance the observation of paradigmatic regimes of unconventional superfluidity [5]. A sufficiently large mass asymmetry may indeed promote pair condensation into non-zero momentum states, thereby leading to the celebrated FFLO-type ordering [6, 7], and it can favour the creation of "breached-paired" or Sarma superfluid states with exotic gapless excitations [8, 9], at experimentally achievable temperatures.
The specific choice for the chromium-lithium mixture is further motivated by the exceptional few-body properties of this system, which cannot be obtained with any other atom-atom combination, and that lay the ground to a wealth of possibilities, going well beyond the scope of presently available systems. The peculiar mass ratio of ^{53}Cr and ^{6}Li ($M/m = 8.8$) is predicted to support, in the region of repulsive Cr-Li interactions, three- and four-body cluster states [2, 3] with universal character and p-wave (i.e. $\ell = 1$) symmetry, never observed in any physical system so far. In turn, the availability of these exotic few-particle states near a Cr-Li Feshbach resonance will allow, for the first time, the resonant tuning of few-body (p-wave) elastic interactions, on top of the standard two-body (s-wave) ones. This will uniquely enable to controllably investigate novel many-body regimes of ultracold fermionic matter in the presence of non-perturbative few-body correlations. Besides these two main points, it is worth noticing that the Cr-Li system represents also an extremely appealing candidate for realizing ground state polar molecules with both electric and magnetic moment.

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