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LIST OF ACRONYMS AND ABBREVIATIONS

EDF	Energy Density Functional
EFT	Effective Field Theory
EOS	Equation of State
BMF	Beyond Mean-Field
MBPT	Many-body Perturbation Theory
YGLO functional	Yang, Grasso, Lacroix, Orsay functional

Executive Summary

This deliverable report describes the status of the development of new effective interaction to be used in existing and future many-body theories beyond the independent particle picture within the framework of the energy density functional theory developed by members of the TheoS-JRA. The main objective of the deliverable is to develop new approaches based on well-founded power counting leading to new effective interaction that can be safely used to describe atomic nuclei at the mean-field level and beyond. Along the line of the deliverables, two main achievements were made.
First, techniques from EFT have been used to properly treat unwanted UV divergence in beyond mean-field calculations using zero-range interactions. This leads to a new generation of renormalized interaction directly usable in beyond mean-field calculations.
Second, a systematic strategy has been developed to define a power counting for the energy density functional approach. Using this proposal of power-counting, counter-terms are gradually introduced to absorb divergence order by order. This has led to a new generation of effective interaction directly applicable to nuclear matter and finite nuclei.

Introduction

During the first two years of this project, we investigated connections between the energy-density-functional (EDF) theory and techniques currently used within effective field theory (EFT). This is particularly important because the empirical ingredients used in most cases to build nuclear EDF reduce its predictive power in the yet scarcely explored physics of exotic nuclei. Such investigations opened several lines of research. The ones that we judge particularly promising and challenging aim to connect modern microscopic analyses performed in nuclear physics through *ab initio* methods with the nuclear EDF theory, with the goal of rendering EDF approaches less empirical and of relating EDF ingredients to properties of underlying quarks and hadrons. This connection will ultimately contribute to reduce uncertainties in the construction of a nuclear density functional for finite nuclei and for nuclear systems of astrophysical interest, and will offer a practical unambiguous and ambitious tool to describe nuclear systems with many-body techniques for both structure and reaction applications.

We worked on properties of nuclear matter, which may guide us in constraining effective interactions within the EDF theory, especially close to the equilibrium density of symmetric matter. Reproducing simultaneously the equation of state (EOS) of symmetric and pure neutron matter is an important step for producing interactions tailored to treat both stable and neutron-rich unstable nuclei or even, in the most extreme cases, the isospin-asymmetric systems located in the crust of neutron stars.

Section 1: UV-divergent free effective interaction in EDF-MBPT approach

First, we worked on the development of the nuclear interaction for beyond-mean-field applications in the EDF theory. In particular, we computed the EOS of symmetric, neutron, and asymmetric matter up to second order (beyond the mean-field level, that corresponds to the first order) in the case of zero-range Skyrme-type interactions. These beyond-mean-field calculations generate an ultraviolet divergence related to the zero range of the interaction. Such a divergence, together with the double counting of correlations, were removed by employing **regularization procedures (EFT techniques)** [1,2]. With this work, we aim to design **functionals for**

beyond-mean-field EDF models, based on EFT techniques. Such an activity is strongly related to the task 1.2 of the TheoS-JRA 3 and directly produces new effective interactions designed for beyond mean-field theories based on MBPT approaches.

SECTION :2 POWER COUNTING FOR NUCLEAR EDF AND SYSTEMATIC CONSTRUCTION OF EFFECTIVE INTERACTION FOR BMF THEORIES

The methodology proposed in section 1 leads to a natural extension of widely used zero-range interaction to treat perturbative many-body effects. Therefore, it leads already to a practical tool to construct new effective interactions suited in MBPT. A study on the **renormalizability of the nuclear many-body problem** with Skyrme interactions has been first made in [3] and a **first steps towards a power-counting** defined for EDF functionals was made in [4]. After these formal analysis, a new technique has been developed to construct effective interaction consistent with the underlying power-counting. In this approach, at each order, **counter-terms** are introduced **to absorb possible divergences**. The form of the counter-terms is imposed by the type of divergence at this order. This technique that is standardly used in renormalization group theory provides a systematic constructive framework to design completely new effective interactions for BMF calculations. An illustration of applicability has been made in Ref. [4]. With this, we directly deliver a new generation of effective interactions for MF and BMF directly usable for infinite nuclear matter and finite nuclei.

SECTION 3 NEW FUNCTIONAL THEORIES INCLUDING DIRECTLY BEYOND MEAN-FIELD EFFECTS

Although this was not the direct subject of the deliverable D11.1, the new developments made on effective interaction has considerably impacted the proposal of new density functional theories for atomic nuclei that directly incorporate BMF effects. Indeed, with the expertise acquired with second-order calculations, we addressed another facet of phenomenological EDFs, that is related to the description of the low-density regime of neutron matter. In most cases, EDFs do not correctly describe such a regime. Only density scales of interest in nuclear phenomena are explored and, due to the large value of the scattering length in nuclear systems, standard density-functional theories based on effective interactions usually fail to reproduce the nuclear Fermi-liquid behavior both at very low densities and close to equilibrium. The first achievement of our project in this direction was the introduction of the functional YGLO (Yang, Grasso, Lacroix, Orsay). Guided on one side by the success of the Skyrme density functional and inspired, on the other side, by second-order calculations for the EOS of nuclear matter and by resummation techniques used in EFTs for systems with large scattering lengths, **a new energy-density functional was proposed**, called YGLO [5], adjusted on microscopic calculations. It reproduces the **nuclear EOSs of neutron and symmetric matter at various densities.** Furthermore, it provides reasonable saturation properties as well as appropriate density dependence for the symmetry energy.

Then, resummed formulas were used to explore a different direction. We analyzed the **emergence of some universal behavior in nuclear systems**, especially in the context of neutron matter (neutron stars) and introduced a resummed functional adapted to reproduce the unitary limit of neutron matter [6,7].

We also worked on the extension of Lee-Yang-type functional by defining a way to impose a low-density regime at all density scales for both neutron and symmetric matter. We introduced a **Lee-Yang inspired functional** where, owing to a neutron-neutron scattering length which is rendered density dependent, the Lee-Yang low-density regime is automatically satisfied at all density scales [8].

CONCLUSION

The deliverable D11.1 has been completed successfully without encountering unexpected problem. Two different approaches have been proposed and developed leading to two types of new effective interactions directly applicable in state of the art mean-field and beyond mean-field calculation. The inherent difficulty of using zero-range interaction at the BMF level, has been solved both formally and technically. In particular, the technique consisting in introducing counter-terms together with the definition of power counting leads to a completely new and versatile approach to construct a new generation of interaction that could be directly be used in finite nuclei.