# MASTER THESIS PROJECT FOR HANS MATHIAS MAMEN VEGE: QUANTUM-MECHANICAL STUDIES OF INFINITE NUCLEAR MATTER AND NEUTRON STAR MATTER AND NEUTRINOS

## I. INTRODUCTION

Bulk nucleonic matter is interesting for several reasons. The equation of state (EoS) of neutron matter determines properties of supernova explosions [1], and of neutron stars [2–7], and it links the latter to neutron radii in atomic nuclei [8–10] and the symmetry energy [11, 12]. Similarly, the compressibility of nuclear matter is probed in giant dipole excitations [13], and the symmetry energy of nuclear matter is related to the difference between proton and neutron radii in atomic nuclei [14–16]. The saturation point of nuclear matter determines bulk properties of atomic nuclei, and is therefore an important constraint for nuclear energy-density functionals and mass models (see, e.g., Refs. [17, 18]).

The determination and our understanding of the EoS for nuclear matter is intimately linked with our capability to solve the nuclear many-body problem. Here, correlations beyond the mean field play an important role. Theoretical studies of nuclear matter and the pertinent EoS span back to the very early days of nuclear many-body physics. Early computations are nicely described in the 1967 review by Day [19]. These early calculations were performed using Brueckner-Bethe-Goldstone theory [20, 21], see Refs.[3, 22, 23, 39] for recent reviews and developments. In these calculations, mainly particle-particle correlations were summed to infinite order. Other correlations were often included in a perturbative way. Coupled-cluster calculations of nuclear matter were performed already during the late 1970s and early 1980s [24, 25]. In recent years, there has been a considerable algorithmic development of first-principle methods for solving the nuclear many-body problem. A systematic inclusion of other correlations in a non-perturbative way are nowadays accounted for in Monte Carlo methods [26–30], self-consistent Green's function approaches [23, 31–34] and nuclear density functional theory [16, 18].

## MANY-BODY APPROACHES TO INFINITE MATTER

This project is based on existing many-body codes for infinite matter using coupled cluster theory, see for example the recent article in `http://lanl.arxiv.org/abs/1611.06765`.

The first step of the thesis is to perform a coupled-cluster calculations at the coupled-cluster with doubles excitations, the so-called CCD approach [40], using the nuclear matter code from `http://lanl.arxiv.org/abs/1611.06765`. The next step is to include triples correlations and perform full doubles and triples calculations (CCDT) for neutron matter using a simplified model for the nuclear force, the so-called Minnesota potential. This allows for a benchmark of codes to infinite nuclear matter. After having developed the necessary formalism, the next step is to include realistic models for the nuclear forces and study the EoS for pure neutron matter, asymmetric nuclear matter (for different proton fractions) and symmetric nuclear matter. With this one can study $\beta$-stable neutron star matter and extract important information about the symmetry energy in infinite matter and the composition of a neutron star. The resulting effective interactions at the two-body level can then be included in the study of neutrino emissivities in dense matter represented by the neutrino production processes

$$n+n \to p+n+e+\overline{\nu}_e, \qquad p+n+e \to n+n+\nu_e. \quad (1)$$

These reactions correspond to the processes for $\beta$-decay and electron capture with a bystanding neutron. The calculation of neutrino spectra has important consequences for our basic understanding on how neutron stars cool, the synthesis of the elements and neutrino oscillations in dense matter and an precise determination of neutrino spectra is the final goal of this thesis project.

The results will be published in scientific journals, if possible.

## PROGRESS PLAN AND MILESTONES

The aims and progress plan of this thesis are as follows

- Spring 2017 and partly fall 2017: Finalize courses and start developing a coupled cluster for infinite nuclear matter.
- Fall 2017: The next step is to include a proper treatment of periodic boundary conditions using the twisted boudary condition approach described in Refs. [35–37], triples correlations and realistic nuclear forces.
- Spring 2018: With a functioning code the final aim is to perform systematic studies of $\beta$-stable nuclear matter and to estimate the production rates of neutrinos in dense matter by studying various neutrino emitting processes.
- Spring 2018: The last part deals with a proper write-up of the thesis.

The thesis is expected to be handed in May/June 2018.


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