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From Nuclei to Neutron Stars with a Microscopic Approach

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Neutron-rich systems are associated with a variety of important and still open questions such as: the location of neutron drip lines, the thickness of neutron skins, and the structure of neutron stars. Common to these diverse situations is the equation of state (EoS) of neutron-rich matter, namely the energy per particle in isospin-asymmetric matter as a function of density (and other thermodynamic quantities as appropriate, such as temperature). In the presence of different neutron and proton concentrations, the symmetry energy emerges as an important component of the EoS and plays an outstanding role in the physics of neutron-rich systems.

Our predictions of the EoS are based on microscopic high-precision nuclear interactions derived from chiral Effective Field Theory (EFT) [1]. In recent years, chiral EFT has evolved into the authoritative approach to construct nuclear two- and many-body forces in a systematic manner [1, 2].
We apply the microscopic EoS of symmetric nuclear matter and the ones of pure neutron matter as derived in Ref. [3]. The derivation is based on high-precision chiral nucleon-nucleon potentials at next-to-next-to-next-to-leading order (N3LO) of chiral perturbation theory [1, 4]. The leading three-nucleon force, which is treated as an effective density-dependent force [5], is included.

It is well known that the available information on neutron radii and neutron skins is scarce and carry considerable uncertainty. Although future experiments are anticipated which should provide reliable information on the weak charge density in 208Pb and 48Ca, the identification of other "observables"whose knowledge may give complementary information on neutron skins would be most welcome. An issue of current interest is whether information on the neutron skin can be obtained through the knowledge of proton radii alone, specifically those of mirror nuclei. In particular, the difference between the charge radii of mirror nuclei in relation to the slope of the symmetry energy, and, in turn, to the neutron skin, was nvestigated in Ref. [6]. Although phenomenological analyses are a useful exploratory tool to gain some preliminary insight into sensitivities and interdependences among nuclear properties, only through microscopic predictions can we understand a result in terms of the physical input. We will explore, from the microscopic point of view in contrast to the phenomenological one, the relation between the neutron skin of a nucleus, on the one hand, and the difference between the proton radii of the mirror pair with the same mass, on the other.

Moving on to a dramatically different scale, it is remarkable that the relation between the mass and the radius of neutron stars is uniquely determined by the EoS together with their self-gravity. In fact, these compact systems are intriguing testing grounds for nuclear physics. Most recently, the detection by LIGO of gravitational waves from two neutron stars spiraling inward and merging has generated even more interest and excitement around these exotic systems. In fact, the LIGO/Virgo [7] detection of gravitational waves originating from the neutron star merger GW170817 has provided new and more stringent constraints on the maximum radius of a 1.4 M⊠ neutron star, based on the tidal deformabilities of the colliding stars [8]. We will present and discuss predictions of neutron star masses and radii based, as far as possible, on state-of-the-art nuclear forces. The focal point is the radius of a star with mass equal to 1.4 M⊠ (the most probable mass of a neutron star), which we wish to predict with appropriate quantification of the theoretical error.

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