Frontiers in Nuclear Lattice EFT: From Ab Initio Nuclear Structure to Reactions

Saturday, 1 March 2025 - Monday, 3 March 2025

Baiyan Building

Book of Abstracts

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Ab initio calculation of hyper-neutron matter

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The equation of state (EoS) of neutron matter plays a decisive role to understand the neutron star properties and the gravitational waves from neutron star mergers. At sufficient densities, the appearance of hyperons generally softens the EoS, leading to a reduction in the maximum mass of neutron stars well below the observed values of about 2 solar masses. Even though repulsive three-body forces are known to solve this so-called "hyperon puzzle", so far performing \textit{ab initio} Monte Carlo calculations with a substantial number of hyperons has remained elusive. We address this challenge by employing Nuclear Lattice Effective Field Theory with up to 232 neutrons and 116 Λ hyperons in a finite volume. We introduce a novel auxiliary field quantum Monte Carlo algorithm, allowing us to simulate both pure neutron matter and hyper-neutron matter up to 5 times the density of nuclear matter using a single auxiliary field without any sign oscillations. Also, for the first time in {\em ab initio} Monte Carlo calculations, we not only include $N\Lambda$ two-body and $NN\Lambda$ three-body forces, but also $\Lambda\Lambda$ and $N\Lambda\Lambda$ interactions. Consequently, we determine essential astrophysical quantities such as the neutron star mass-radius relation and confirm the existence of the universal I-Love-Q relation.

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Carbon and Oxygen isotopes in NLEFT

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We study Carbon and Oxygen isotopes in NLEFT by using Wave Function Matching method with high fidelity Hamiltonian.

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Big Bang Nucleosynthesis and Deuteron-Deuteron reactions

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Big Bang or primordial nucleosynthesis (BBN) provides a fine laboratory for testing theories beyond the standard model. I present recent work on finding constraints on the variation of fundamental parameters like the Higgs VEV and the strange quark condensate from BBN. In order to match the

precision set by experiment for primordial abundances, we need to further improve our theoretical understanding of BBN. The biggest source of uncertainty are the nuclear reaction rates, mainly for the deuteron-deuteron reactions. I motivate my on-going work of calculating these reaction rates in the ab-initio framework of Nuclear Lattice Effective Field Theory (NLEFT) and present preliminary results. NLEFT has proven to be a powerful tool in predicting various nuclear properties and scattering rates, so calculating deuteron-deuteron rates will provide a reliable and necessary addition to theoretical simulations of BBN.

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Neural-network variational Monte Carlo for atomic nuclei

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Quantum Monte Carlo approaches based upon Feynman path integrals are powerful for addressing quantum many-body problems. However, they generally suffer from the "fermion-sign problem" that leads to exponential scaling of the computation effort with system size. As an alternative, the variational Monte Carlo (VMC) approach avoids such sign problems, but the challenge becomes how to construct an efficient and accurate variational ansatz. In this talk, I will introduce our recent developments in the neural-network ansatz for the VMC approach. I will show that the VMC calculations with neural-network ansatz can provide accurate solutions for the ground states of few- and many-body nuclei while keeping the computational cost polynomially scaling with system size, thanks to the strong expressive power of neural networks.

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Studying light hypernuclei based on chiral interactions

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Chiral interactions provide a systematic approach to baryonic interactions resulting in a high accuracy description of NN and YN interactions [1,2]. For a similar description of many-baryon systems at least 3BFs are necessary which can be consistently obtained using chiral effective field theory. In this contribution, I report on our recent progress to further constrain these interactions based on reliable results for light hypernuclei up to $A = 8$.
We use the hypernuclei data to determine the charge-symmetry breaking (CSB) of YN interactions and for exploring the results using and isospin multiplets of hypernuclei [3,4].
We then employ the results of different chiral orders to reliably estimate the theoretical uncertainty [5]. Finally, we use the separation energies of light hypernuclei to pin down the leading chiral YNN interaction [6].

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[4] H.Le, J.Haidenbauer, U.G.Meißner and A.Nogga, Phys. Rev. C 107 (2023), 024002 [arXiv:2210.03387 [nucl-th]].
[5] H.Le, J.Haidenbauer, U.G.Meißner and A.Nogga,Eur. Phys. J. A 60 (2024), 3 [arXiv:2308.01756

[nucl-th]].
[6] H.Le, J.Haidenbauer, U.G.Meißner and A.Nogga [arXiv:2409.18577 [nucl-th]].

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The three-body DD*K system on the lattice EFT

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We employ the nuclear lattice effective field theory (NLEFT), an efficient tool for nuclear ab. initio calculations, to solve the asymmetric multi-hadron systems. We take the DD*K three-body system as an illustration to demonstrate the capability of the method. Here the two-body chiral interactions between D, D* and K are regulated with a soft lattice regulator and calibrated with the binding energies of the Tcc, Ds0(2317) and Ds1(2460) molecular states. We then calculate the three-body binding energy using the NLEFT and analyze the systematic uncertainties due to the finite volume effects, the sliding cutoff and the leading-order three-body forces. Even when the three-body interaction is repulsive (even as large as the infinite repulsive interaction), the three-body system has a bound state unambiguously with binding energy no larger than the Ds1(2460)D threshold. To check the renormalization group invariance of our framework, we extract the first excited state. We find that when the ground state is fixed, the first excited states with various cutoffs coincide with each other when the cubic size goes larger. In addition, the standard angular momentum and parity projection technique is implemented for the quantum numbers of the ground and excited states. We find that both of them are S-wave states with quantum number JˆP = 1−. Because the three-body state contains two charm quarks, it is easier to be detected in the Large Hadron Collider.

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Nuclear Lattice EFT Simulation with Woods-Saxon Potential

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Experimental exploration of neutron dripline is very challenging, and neon is the heaviest nucleus measured neutron dripline experimentally. Prediction of dripline heavier nuclei than neon is currently depends on theoretical approaches. However, there exist strong model-dependence in the prediction of the dripline in theoretical approach. Nuclear Lattice Effective Field Theory is one of the ab initio approach to explore the quantum many-body systems. In this talk, I will give a talk about the nuclear properties of Oxygen isotopes under the Woods-Saxon potential which is semi ab initio near the neutron dripline using lattice Monte Carlo simulations.

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New Method for Determining Few-Body Resonance Poles in Finite Volume

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We introduce a new method, referred to as the persistent state method, for determining few-body resonance poles in a finite volume. The effectiveness of the method is demonstrated through explicit examples covering both continuum and lattice setups, as well as two- and three-body resonance cases.

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Nuclear charge radii from the partial pinhole algorithm

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Nuclear charge radii are among the most fundamental properties of atomic nuclei. In nuclear lattice effective field theory, charge radii are typically calculated using the pinhole method, where an A-body density operator (A being the mass number) is inserted at mid-time during the imaginary time evolution. However, this A-body density operator introduces significant sign oscillations, especially for heavy nuclei and large imaginary times. In this talk, I will present a novel approach called the partial pinhole method for calculating nuclear charge radii. By reducing the order of the density operators, this method significantly alleviates the sign oscillation issue. This method is then combined with the recently developed wavefunction matching technique, and the charge radii of oxygen isotopes are well reproduced using high-fidelity chiral effective field theory interactions.

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Introduction and welcome

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Advancing nuclear structure and scattering calculations using NLEFT

In this talk, I will present an overview of recent advances in nuclear lattice simulations, focusing on how the recently developed N3LO lattice action bridges the gap between QCD and nuclear interactions, enabling the formulation of a modern theory of nuclear forces. More specifically, I will discuss the determination of three-nucleon interactions, which has led to highly precise predictions and a deeper understanding of nuclear systems. Additionally, I will highlight the wave function matching method, an approach that significantly improves the convergence of perturbation theory for solving

quantum many-body systems. Finally, I will present recent ab-initio results from nuclear structure and nuclear scattering calculations.

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Alpha-alpha scattering using adibatic projecton method

I will present the alpha-alpha scattering results using the latest improved NLEFT interaction, including wavefunction matching, at N3LO. This will be an improvement to our previous results, where we had only up to N2LO and with a different interaction.

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Lattice simulation of nucleon distribution and shell closure in 22Si

In this report, we focus on 22Si, likely the lightest bound nucleus with Tz=−3, using Nuclear Lattice Effective Field Theory (NLEFT) with chiral forces. Our calculations agree with existing data and predict it as a proton-dripline nucleus, along with its 2+ state, radius, and spatial properties. Using nucleon ordering operators, we reveal nucleon spatial arrangement and localization, linked to shell closure features. Moreover, we introduce a novel pinhole method bridging NLEFT and shell model, offering new perspectives into a more comprehensive understanding of nuclear structure.

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Lattice calculation of nuclear magnetic moments

We present calculations of nuclear magnetic moments for light nuclei and aluminum isotopes using nuclear lattice effective field theory with the N3LO chiral interaction. Both one- and two-body electromagnetic current effects are included in the calculations. For all nuclei considered, the lattice results are generally consistent with experimental data. We find that the contribution from two-body currents is relatively small, typically below 10%. However, for magnetic moments of certain nuclei, nuclear structure effects play a significant role

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NLEFT calculations with perturbative QMC method

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NLEFT using quantum computation

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Hypernuclei on the lattice

Understanding the strong interaction beyond the up and down quark sector is crucial for an accurate and comprehensive description of nuclear forces. The inclusion of hyperons, in particular the Λ, extends the nuclear chart to a third dimension. We therefore present an extension of the NLEFT framework to the strangeness sector. In particular we focus on light to medium mass hypernuclei in the $S = -1$ sector.

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Exotic Nuclear Properties in Deformed Relativistic Hartree-Bogoliubov Theory

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Ab initio nuclear mass model and the emergence of nuclear magicity

How the nuclear magicity emerge from the underlying nuclear forces? Conventional understanding is based on the picture of the mean field, in which the nucleons move individually around onion-like orbits. Such a picture lacks the important many-body correlations and the connection to the bare nucleon-nucleon forces is obscure. We present a lattice nuclear force model capturing the essential elements of the nuclear binding and emergence of the magicity. Our model contains five adjustable parameters fitted to binding energies of medium-mass nuclei and can be solved non-perturbatively with sign-problem-free quantum Monte Carlo techniques. We obtain precision nuclear binding energies for A<=56 with an accuracy comparable with the state-of-the-art mean field models. Based on these numerial results, we discuss the dual role of the spin-orbit coupling in NN scattering and nuclear shell evolution.

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First lattice calculations of the threshold electroweak pion production from a nucleon

Nucleon pion production is an important process to study the low energy features, especially the chiral behaviours of QCD. The process receive strong attention since 1950s from experimental side, and would still play a crucial role to control the systematic effects in future neutrino-nucleus scattering experiments. Theoretically, though Chiral Perturbation Theory (Chipt) has given fruitful results, a first principle evaluation is still of great significance to understand QCD dynamics and to systematically control the errors. In this work, we present the first lattice calculations of both electro-production and weak-production process from a nucleon utilizing two domain wall fermion ensembles at physical pion mass. We analyze all the possible systematic effects, and the results show good consistency with Chipt at low energy region. The work shed light on future lattice calculations on electroweak pion production process.

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Discussion and farewell

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An accurate relativistic chiral nuclear force

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An Efficient Learning Method to Connect Observables

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Constructing fast and accurate surrogate models is a key ingredient for making robust predictions in many topics. We present a new model, the Multiparameter Eigenvalue Problem (MEP) emulator. Our new emulator connects emulators and can make predictions directly from observables to observables. We demonstrate that our MEP emulator can connect both Eigenvector Continuation (EC) and Parametric Matrix Model (PMM) emulators. We show an immediate application to the uncertainty quantification of valence-space in-medium similarity renormalization group calculations.