theory needs for rare isotope science

Topic	Theory development needed
T1: Forces	Effective field theory (EFT) constants from LQCD; Improved chiral forces, with and without Δs plus UQ; Consistent operators and power counting
T2: Nuclear structure	Connect realistic nuclear forces to shell model and DFT; Microscopic optical potential that incorporates many-body correlations; Proper treatment of collective, cluster and continuum degrees of freedom Masses and beta-decay rates
T3: Medium-mass nuclei	Properties of nuclei with validated ab-initio techniques; Shell-model effective interactions and operators derived and/or constrained from microscopic interactions, with controlled uncertainties; Unified treatment of structure and reactions.
T4: Heavy nuclei	DFT constrained by rare isotope data and ab-initio theory; Beyond-DFT treatment of open shell systems; calculations of Schiff and anapole moments. Improved DFT-based adiabatic models of the large-amplitude collective motion; Implementation of TDDFT and multi-reference DFT approaches; Effective field theory for collective nuclear phenomena based on powerful existing phenomenology. Implementation of proton-neutron, symmetry-projected multi-reference DFT and large-scale shell model to compute nuclear matrix elements for double-beta decay.
T5: Neutron stars	Controlled calculations of the nuclear equation of state for all relevant densities including extrapolations to high densities with known uncertainties; Improve constraints on nuclear EOS by identifying observables most sensitive to the high-density behavior of the nuclear symmetry energy; Calculate structure in the neutron star crust at various densities (ground state and response functions).

Table from FRIB-TA proposal – last updated Sep 2021

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T6: Reactions	Ab-initio reaction theory, consistent with nuclear structure, with quantified uncertainties, adequate for many domains of experimental interest, including radiative capture, transfer, breakup of dripline nuclei, knockout, alpha-induced reactions in intermediate-mass nuclei, and superheavy synthesis to estimate production of nuclei at and beyond the dripline and to extract structural information. Nuclear reactions study at the limits of stability to extract crucial isovector indicators such as neutron skins; Reaction theory with quantified uncertainties for charge-exchange. Reaction observables to isolate the role of pairing correlations and characterize the pairing interaction. Microscopic theory of spontaneous and neutron-induced fission; Ab-initio theory for light-ion fusion. Reaction theory for compound nucleus formation consistent with structure. Consistent reaction theory for single-nucleon transfer and radiative capture reactions on medium mass and heavy nuclei; Reliable transport theory with quantified errors, including a quantum formulation with correlations, for heavy-ion reactions from low to intermediate energies.
T7: Astrophysics	Advanced simulations of compact objects; supernova, binary neutron star mergers and related explosive phenomena; Nucleosynthesis and chemical evolution simulations with up-to-date nuclear input; Neutrino interactions with nuclei in hot and dense nuclear matter, including neutrino oscillations; Hydrodynamics and neutrino transport in stars; Screening in stellar plasma consistent with reaction theory.

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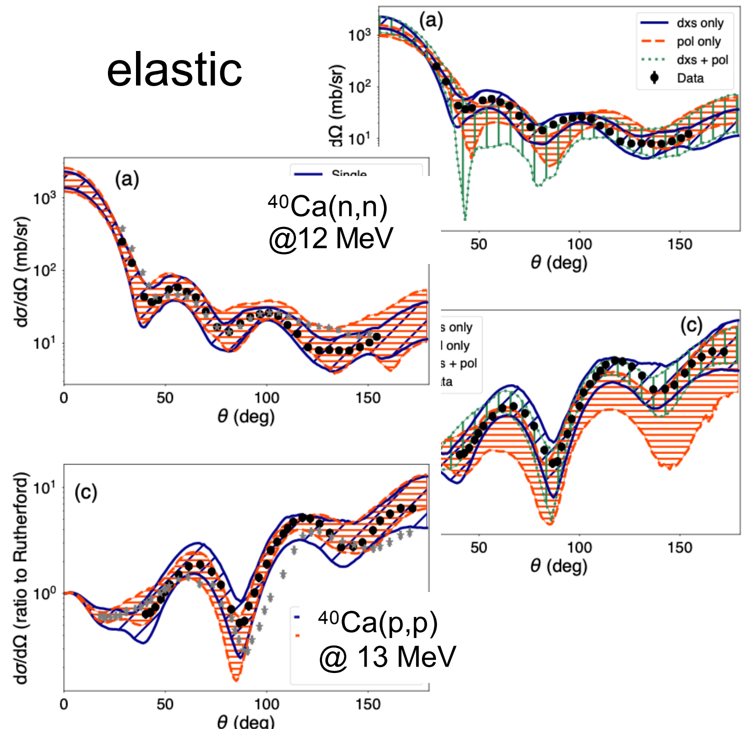
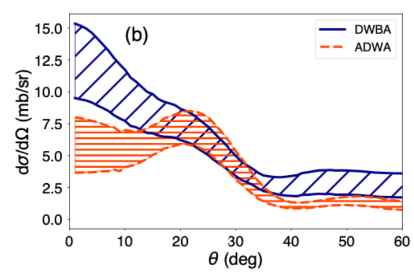
Bayesian analysis as a tool for nuclear reactions

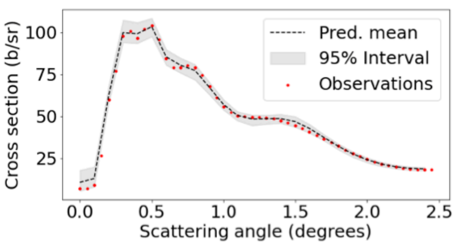
- Use for calibration of the effective interactions in the model
- Propagation to all desired observables
- Exploration of parameter sensitivities
- Versatile approach to experimental design
- Quantitative method for model comparison
- Quantitative method for model mixing
- Emulators for complex reactions

elastic

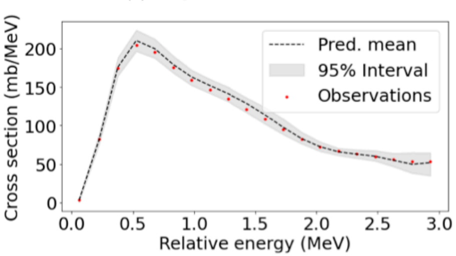


transfer





(a) Angular distribution.



(b) Energy distribution.

^{8}B breakup on ^{208}Pb

Surer et al., PRC 106, 024607 (2022)

King et al. PRL (2019)
Lovell et al. , JPG (2020)
Catacora-Rios et al. PRC 100, 064615 (2019)
PRC 104, 064611 (2021)

DNP Fall meeting 2015 – LRP presentation We expect much progress in the next decade!

From theory we will have:

- Microscopic reaction theories applicable to heavy nuclei and rooted in QCD with predictive power for transfer, breakup and fusion.
- A spectroscopic-quality nuclear energy density functional rooted in QCD
- Few percent uncertainties in the prediction of the symmetry energy for the equation of state of nuclear matter, including its isospin and density dependence.
- Few percent uncertainties in the prediction of nuclear matrix elements relevant for the neutrinoless double better decay tonne scale experiment.

- Plus all the surprises along the way…