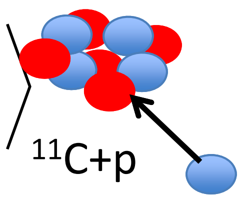
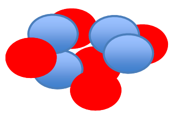
TRIUMF

Represents $H\left|\Psi^{J\pi T}\right\rangle = E\left|\Psi^{J\pi T}\right\rangle$ using the over-complete basis:

$$\left|\Psi^{J\pi T}\right\rangle = \sum_\lambda c_\lambda \left|E_\lambda\ \lambda\ J^\pi T\right\rangle + \sum_\nu \int dr r^2 \frac{\chi_\nu(r)}{r} \hat{A}_\nu \left|\xi^{J\pi T}_{\nu r}\right\rangle$$



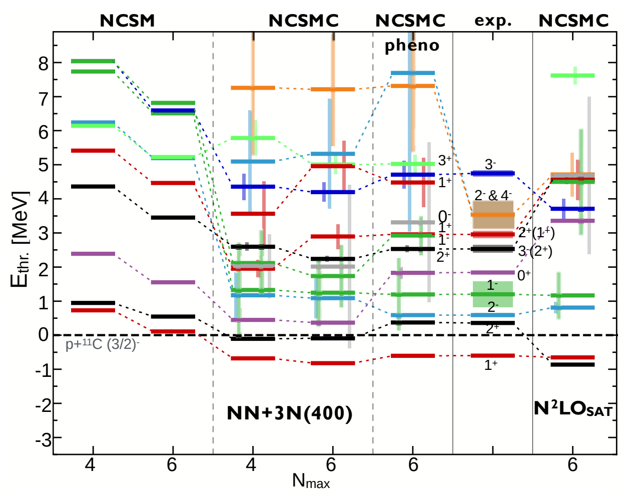
^{12}N

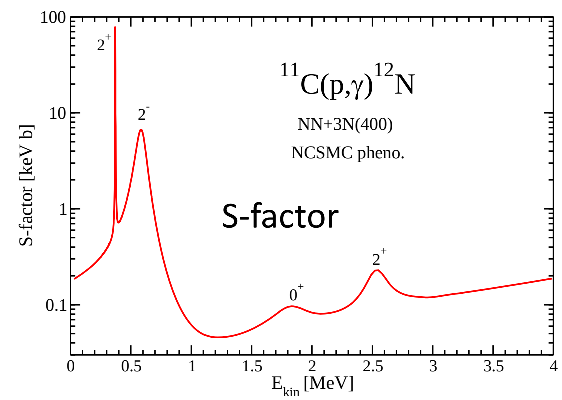


Expansion in A-body NCSM eigenstates

Relative motion of clusters

Example of ongoing application aligned with TRIUMF experimental efforts: ^{11}C(p,p), structure of ^{12}N, & ^{11}C(p,γ)^{12}N
FRIB: sd-shell





LLNL/TRIUMF collaboration: S. Quaglioni, P. Navratil *et al.*

Currently most suited for reactions with light nuclei

Developments for going to heavier nuclei: use symmetry adapted NCSM (LSU)

Nuclear Lattice EFT applied to reaction theory
Collaboration projects ongoing and planned

- **Ab initio calculations of transfer reactions using the adiabatic projection method.**

  approach is suited for e.g. alpha transfer reactions

- **Ab initio calculations of effective interactions:**

  Derivation of a shell model interaction from ab initio nucleon + nucleus elastic scattering and chiral effective field theory.

  Testing new Monte Carlo algorithms for computing ab initio
  - nucleon-nucleus effective interactions
  - alpha-nucleus effective interactions

Lattice sizes and corresponding cpu time limiting factors for heavy nuclei

FRIB Day-1 Science: challenges for nuclear reactions

Ca Isotopes: Where is the dripline? Are ^{61}Ca or ^{62}Ca bound?

here current mean field and ab-initio approaches show large differences and will help inform the current many-body Hamiltonian.

Theory: will be sorted out in the next 4 years

Exp: How far can FRIB go and are the rates enough for Day 1?

Sn isotopes: Chain is very long – how far in N can be measured?

Exp: Perform interaction cross-section measurements to extract neutron skins consistently all they way from ^{118}Sn to ^{132}Sn?

Theory: predictions for neutron skins
is predicted skin large enough to compete with uncertainties in reaction theory analysis?

Heavier isotopes: (d.p) transfer to probe single particle behavior?

how about ^{238}Th for (d,p)?

FRIB science and effective interactions

Current status:

Empirical effective nucleon-nucleus interactions

- only contain E>0 information and do not connect to structure
- are local but should be nonlocal
- should be dispersive, but are not

Ab initio effective nucleon-nucleus interactions

- Currently not adequate to be used in reaction calculations

Further development of

- Nonlocal dispersive optical model
- Multiple scattering approach
- Nuclear lattice approach
- Structure + RGM approach

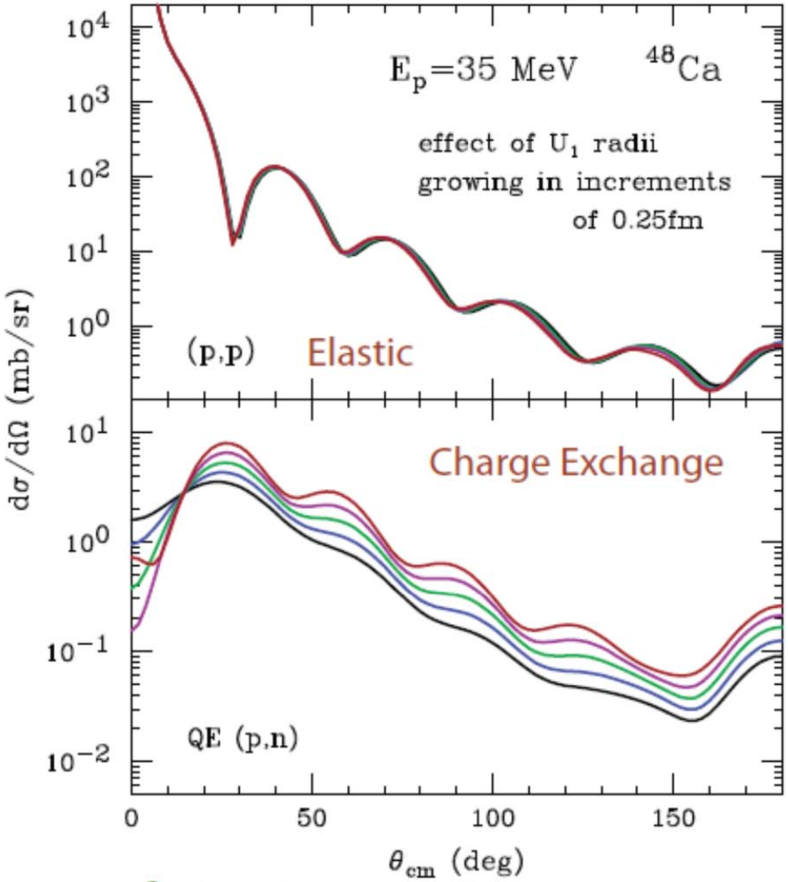
To effective interactions nucleon-nucleus, deuteron-nucleus, alpha-nucleus needed.

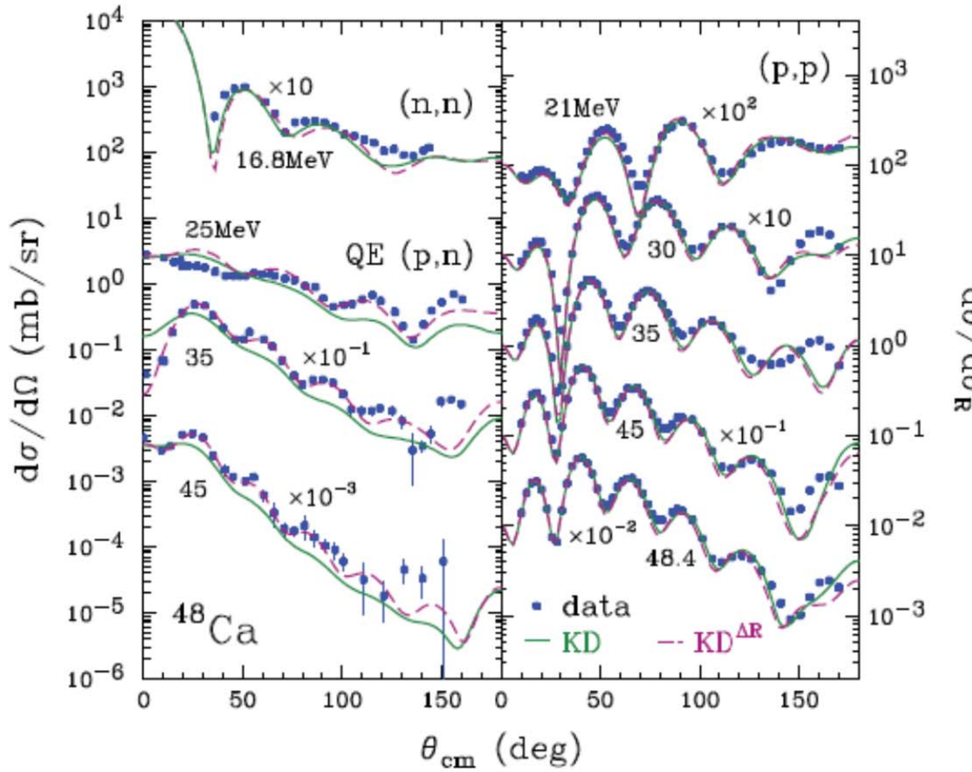
Impact on experiment: Elastic scattering cross sections (inverse kinematics)
Provide essential constrains on effective interactions.

Need to be measured!

Skins/Aura from Charge-Exchange Reactions

Skins more accessible from quasielastic exchange reactions + elastic scattering than electron or nucleon scattering alone





(^{3}He, *t*) could be used and even heavy ions

Danielewicz, Sing & Lee NPA958(17)147

Theory for reactions above 50 MeV/u beam energy

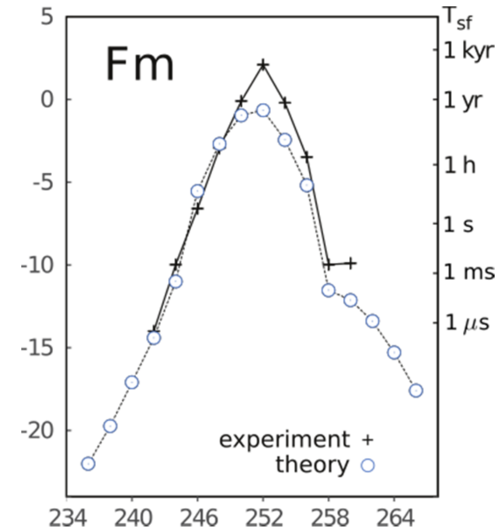
- Priority: Reactions with fast beams (e.g. performed at the S800 and the HRS) have **enormous discovery potential** due to the high luminosity afforded by the use of thick targets and the resulting reach on the nuclear chart. Nuclear structure information is extracted most often in comparison to reaction theory
- Need: The only developments in the corresponding reaction theory have been driven by less than a handful of theorists, mostly based outside of the US, and several of them will be retired by the time FRIB comes online
- Opportunity: Fast-beam reaction theory developments, if started now, would be extremely relevant and are truly needed for FRIB experiments at the frontier of discovery. This is an opportunity for the US theory community to lead

Alexandra Gade and Remco Zegers

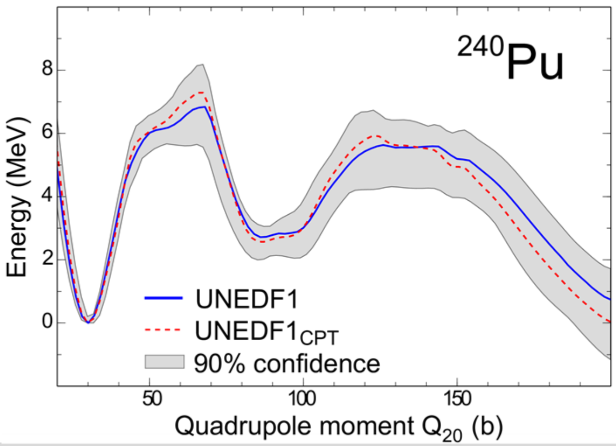
Nuclear fission is one of the most complex, unsolved science problems: FRIB can help

- Developing a predictive theory of fission based on nuclear forces and quantum many-body methods is needed to explain the decay of superheavy elements and the r-process
- Our best description of fission is based on time-dependent extensions of density functional theory
  - Need to better understand dissipation (coupling between intrinsic and collective motion)
  - Need for high-precision, fast time-dependent solvers
- FRIB data that can help
  - Deformation properties of neutron-rich nuclei: superdeformed and hyperdeformed isomers
  - Evolution of shell structure with neutron number: single-particle states, 2+ energie, etc.
  - Direct measurements of fission half-lives

Spontaneous fission half-lives in Fm isotopes from DFT calculations



Quantified statistical uncertainties in predictions of fission barriers in DFT



FRIB Day-1 Science: challenges for nuclear reactions

Priorities for FRIB theory

General Goal: Develop many-body theory that will unify nuclear structure and reactions

- Develop quantified microscopic effective interactions as input to describe direct reactions
- Develop exacts methods for solving reactions and test reliability across the nuclear chart
- Develop predictive model of excitation functions/production cross sections
- Explain properties of many-body systems around the reaction threshold. This includes microscopic picture of cluster structures

Ideas/needs for achieving them

- Reaction cross sections based on different approaches
  - Continuum shell models (different realizations) with RGM
  - Green's function approach based on NN and NNN interactions
  - Spectator approach with continuum shell models
- Heavy Ion fusion and quasi-fission reactions from Time-Dependent DFT and DFT
- Advanced statistical tools for uncertainty quantification, model development, data selection, and identification of key experimental data needed
- Development of databases of
  - theoretical results
  - Nuclear matrix elements and codes to process them
  - open-source reaction codes and corresponding user groups

W. Nazarewicz, LECM 2017 – augmented Ch. Elster

FRIB Day-1 Science: nuclear reaction challenges

Impact on/alignment with the experimental effort. Experimental data needed.

- Key measurements:
- reaction mechanism involving neutron-rich projectiles
- Cross sections/excitation functions; angular and energy correlations of light particles (to probe, e.g., di-neutron or di-proton structures);
- Benchmark cross sections for theory approaches
- Pair transfer with exotic projectiles to probe pairing channel

W. Nazarewicz, LECM 2017 -- augmented Ch. Elster