Nuclear reactions
Filomena Nunes
### theory opportunities with FRIB

**DOE Nuclear Physics Mission** is to understand the fundamental forces and particles of nature as manifested in nuclear matter, and provide the necessary expertise and tools from nuclear science to meet national needs. **DOE Nuclear Physics Mission** is accomplished by supporting scientists who answer overarching questions in major scientific thrusts of basic nuclear physics research.

<table>
<thead>
<tr>
<th>Science Drivers (Thrusts) from NRC RISAC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nuclear Structure</strong></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td><strong>Overarching Questions from NSAC 2007 LRP</strong></td>
</tr>
<tr>
<td>What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?</td>
</tr>
<tr>
<td>What is the origin of simple patterns in complex nuclei?</td>
</tr>
</tbody>
</table>

**Overarching questions are answered by rare isotope research**

<table>
<thead>
<tr>
<th>17 Benchmarks from NSAC RIB TF measure capability to perform rare isotope research</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Shell structure</td>
</tr>
<tr>
<td>2. Superheavies</td>
</tr>
<tr>
<td>3. Skins</td>
</tr>
<tr>
<td>Pairing</td>
</tr>
<tr>
<td>5. Symmetries</td>
</tr>
<tr>
<td>13. Limits of stability</td>
</tr>
<tr>
<td>15. Weakly bound nuclei</td>
</tr>
<tr>
<td>17. Mass surface</td>
</tr>
</tbody>
</table>

**FRIB-CDR, 2010**
4N bound state

TABLE I. The expectation values $\langle T \rangle$ and $\langle V \rangle$ of kinetic and potential energies, the binding energies $E_b$ in MeV, and the radius in fm.

<table>
<thead>
<tr>
<th>Method</th>
<th>$\langle T \rangle$</th>
<th>$\langle V \rangle$</th>
<th>$E_b$</th>
<th>$\sqrt{\langle r^2 \rangle}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY</td>
<td>102.39(5)</td>
<td>-128.33(10)</td>
<td>-25.94(5)</td>
<td>1.485(3)</td>
</tr>
<tr>
<td>CRCGV</td>
<td>102.30</td>
<td>-128.20</td>
<td>-25.90</td>
<td>1.482</td>
</tr>
<tr>
<td>SVM</td>
<td>102.35</td>
<td>-128.27</td>
<td>-25.92</td>
<td>1.486</td>
</tr>
<tr>
<td>HH</td>
<td>102.44</td>
<td>-128.34</td>
<td>-25.90(1)</td>
<td>1.483</td>
</tr>
<tr>
<td>GFMC</td>
<td>102.3(1.0)</td>
<td>-128.25(1.0)</td>
<td>-25.93(2)</td>
<td>1.490(5)</td>
</tr>
<tr>
<td>NCSM</td>
<td>103.35</td>
<td>-129.45</td>
<td>-25.80(20)</td>
<td>1.485</td>
</tr>
<tr>
<td>EIHH</td>
<td>100.8(9)</td>
<td>-126.7(9)</td>
<td>-25.944(10)</td>
<td>1.486</td>
</tr>
</tbody>
</table>

H. Kamada, et al, PRC 64, 044001 (2001)

TABLE III. AV18 $n^{-3}H$

<table>
<thead>
<tr>
<th>$E_{\text{c.m.}}$</th>
<th>$\sigma$ (b)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>1.73</td>
<td>AGS</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>FY</td>
</tr>
<tr>
<td></td>
<td>1.76</td>
<td>HH</td>
</tr>
<tr>
<td>0.75</td>
<td>1.79</td>
<td>AGS</td>
</tr>
<tr>
<td></td>
<td>1.78</td>
<td>FY</td>
</tr>
<tr>
<td></td>
<td>1.79</td>
<td>HH</td>
</tr>
<tr>
<td>1.50</td>
<td>2.22</td>
<td>AGS</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>FY</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>HH</td>
</tr>
<tr>
<td>2.625</td>
<td>2.51</td>
<td>AGS</td>
</tr>
<tr>
<td></td>
<td>2.24</td>
<td>FY</td>
</tr>
<tr>
<td></td>
<td>2.24</td>
<td>HH</td>
</tr>
<tr>
<td>3.0</td>
<td>2.48</td>
<td>AGS</td>
</tr>
<tr>
<td></td>
<td>2.21</td>
<td>FY</td>
</tr>
<tr>
<td></td>
<td>2.21</td>
<td>HH</td>
</tr>
</tbody>
</table>

Ab-initio reactions with 3N forces

PRC 88, 054622 (2013)

FIG. 5. (Color online) Dependence of the $n^{-4}$He phase shifts on the considered target eigenstates. Results with only the g.s. of $^{4}$He (thin gray long-dashed lines) are compared to those obtained by including in addition up to the $0^+ 0^{-}$ (thin black dashed lines), $0^+ 0^{-}$ (thin violet lines), $2^{-} 0$ (thick brown dotted lines), $2^{-} 1$ (thick green long-dashed lines), $1^{-} 1$ (thick blue dashed lines), and $1^{-} 0$ (thick red lines) excited states of $^{4}$He, respectively. The model space is truncated at $N_{\text{max}} = 13$. Other parameters are identical to those of Fig. 2.

- he4+n elastic scattering

FIG. 10. (Color online) Comparison of the $n^{-4}$He (a) and $p^{-4}$He

FIG. 4
Ab-initio reactions for heavier nuclei

- ab-initio coupled cluster calculations
- single nucleon correlations insufficient

FIG. 5. (Color online) Differential cross section from coupled-cluster calculations divided by Rutherford cross section for elastic proton scattering on $^{40}$Ca at $E_{\text{c.m.}} = 9.6$ MeV (solid line), experimental data (dots), and optical model potential fits (dashed line), taken from Ref. [31].

FIG. 6. (Color online) Same caption as in Fig. 5 except that the energy is $E_{\text{c.m.}} = 12.44$ MeV.
reducing the many body to a few body problem

- isolating the important degrees of freedom in a reaction
- keeping track of all relevant channels
- connecting back to the many-body problem

- effective nucleon-nucleus interactions (or nucleus-nucleus)
  (energy dependence/non-local)
- many body input
picture for scattering

Incoming plane wave \( \exp(ikz) \)

Outgoing spherical waves \( \exp(ikR)/R \)

Beam direction \(+z\)
classification of reactions

Direct reactions
transfer momentum is small compared to initial momentum
typically peripheral
short timescale (10^{-22} s)
E>10 MeV
mostly one step
final states keep memory of initial states

Resonance reactions
reactions that go through a resonance (peak in the cross section)
intermediate step in the reaction
longer time scale

Compound reactions
longer timescale
many steps in the reaction
all nucleons share the beam energy
loss of memory from the initial state
low energy reactions
direct reactions

Capture

\[ \phi_{k\ell j}^m(\vec{r}) \]

Inelastic excitations (bound to bound states)

\[ \phi_{n\ell j}^m(\vec{r}) \]
\[ \chi_{k,\sigma}(\vec{R}) \]

\[ \phi_{n'\ell' j'}^m(\vec{r}) \]


target
direct reactions

**Inelastic excitations (breakup)**

\[ \phi_{n_\ell j}^m (r) \xrightarrow{\chi_{k,m}} \chi_{k_v,\sigma_v} \xrightarrow{\phi_{k_\ell' j'}^m} (r) \xrightarrow{\chi_{k_c,\sigma_c}} \chi_{k_c,\sigma_c} \xrightarrow{\phi_{k_\ell_1 j}^m} (r) \xrightarrow{k, j'} \]

**Transfer reactions**

\[ \phi_{n_i \ell_i j_i}^m (r) \xrightarrow{\chi_{k_i,m_i}} \chi_{k_f,m_f} \xrightarrow{\phi_{n_f \ell_f j_f}^m} (r) \xrightarrow{k_f, j_f} \]

k, j'
why do reactions? elastic

![Graph showing elastic scattering for $^{6}\text{He} + ^{12}\text{C}$ at 38.3 MeV/nucleon in comparison with the OM results given by the real folded potential (obtained with the CDM3Y6 interaction and the Gaussian $ga$ density for $^{6}\text{He}$). The dashed curve is obtained with the unrenormalized folded potential only. The solid curve is obtained by adding a complex surface polarization potential to the real folded potential. Its parameters, and those of the imaginary part, are explained in the text. The dotted line is obtained by folding the CDM3Y6 interaction with the compact Gaussian density $ro$.]

[La poux et al, PRC 66 (02) 034608]
why do reactions? inelastic

traditionally used to extract electromagnetic transitions or nuclear deformations

Fig. 2. Comparison of $B(E1)$ values obtained from lifetime and Coulomb excitation measurements. The weighted average of lifetime measurements [3] (open circle) is plotted on the left along with the weighted average (solid circle) of three Coulomb excitation measurements (solid symbols). The individual Coulomb excitation measurements, GANIL (this work, square), MSU (up triangle) [6], RIKEN (down triangle) [7], and a previous GANIL experiment (diamond) [4], are plotted versus the beam energy.
why do reactions? transfer

traditionally used to extract spin, parity and spectroscopic factors

\[ d(^{132}\text{Sn},^{133}\text{Sn})p@5\text{ MeV/u} \]

why do reactions? transfer

\[ ^{11}\text{Li}(p,t)^{9}\text{Li} @ 3 \text{ A MeV} \]

measured both ground state and excited state \(^{9}\text{Li}\)

[Tanihata et al, PRL 100, 192502 (2008)]

\[ ^{11}\text{Li}(p,t)^{9}\text{Li} @ 3 \text{ A MeV} \]

*traditionally used to study two nucleon correlations and pairing*
why do reactions? breakup

\[ ^{14}\text{Be} \rightarrow n+n+^{12}\text{Be} \]

two nucleon correlation function

\[ ^{23}\text{O}(_{\text{Pb,Pb}})^{22}\text{O}+n+\gamma \]

[Marques et al, PRC 64 (2001) 061301]

Fig. 1. Doppler corrected \( \gamma \)-ray spectra measured in coincidence with an \(^{22}\text{O}\) fragment and one neutron for \( \text{Pb} \) (symbols) and \( \text{C} \) (shaded area) targets. Arrows indicate the strongest \( \gamma \) transitions as expected from the \(^{22}\text{O}\) level scheme of Ref. [10] (partial level scheme shown as inset; level energies are in keV).

[Mariforo et al, PLB 605 (2005) 79]
why do reactions? knockout

Fig. 14.9. Schematic of a nuclear knockout reaction. Reprinted from [3] with permission.

Includes elastic and inelastic breakup as well as transfer

traditionally used to extract spin and parity as well as shell occupancy
why do reactions? Charge exchange

\[ \frac{d\sigma}{d\Omega}(q=0)_{(t^3He)} = \hat{\sigma} B(GT) \]

traditionally used to extract GT and F strengths

\[ ^{56}\text{Ni}(t,^3\text{He}) \]

\[ E(t)=115 \text{ MeV/nucleon} \]

\[ 1.75 \text{ MeV}<E_x(^{56}\text{Co})<2.0 \text{ MeV} \]

\[ \theta_{\text{c.m.}}(^3\text{He}) \text{ (deg)} \]

FIG. 5. The differential cross sections for the energy bin 1.75 < \( E_x(^{56}\text{Co}) < 2.0 \text{ MeV} \) and the result of the MDA (solid line) using a linear combination of \( 1^+ \) (dashed line) and \( 2^+ \) (dotted line) components. The error bars in the data are of statistical nature only.

FIG. 6. (Color online) (a) Large-scale shell-model calculations for the Gamow-Teller strength distribution in \(^{56}\text{Co}\) using the KB3G [69] interaction [37,38,70] (black) and GXPF1 [71,72] interaction [38] (gray, green online). (b) Gamow-Teller strength distribution extracted from the \(^{56}\text{Ni}(t,^3\text{He})\) data compared with the theoretical distributions that were folded with the experimental resolution (250 keV) and binned in the same manner as the data.

Cole et al., Phys. Rev. C 74, 034333
why do reactions? fusion

Fig. 8. Reduced cross sections for the fusion of halo, normal/weakly bound, and strongly bound nuclei. (Courtesy of Kolata).

After geometric effects are scaled out, fusion enhanced for halo nuclei!

Superheavies
Halos
Applications: energy
why reactions?

- shell structure
- correlations
- pairing
- weakly bound systems
- role of continuum
- ...

need accurate reaction models!

[Jenny Lee et al, PRL 2009]

[Gade et al, Phys. Rev. Lett. 93, 042501]
why do reactions? astrophysics

- direct measurement $^{14}\text{C}(n,\gamma)^{15}\text{C}$
- transfer reaction $^{14}\text{C}(d,p)^{15}\text{C}$
- Coulomb dissociation

14C(d,p)15C

$^{15}\text{C}$

$^{208}\text{Pb}$

n

low relative energy

14C

$^{15}\text{C}$

$^{14}\text{C}$

$^{208}\text{Pb}$

$\gamma$