Nuclear structure theory at UT/ORNL

Who are we?
What are the major questions in our field?
What research do we perform, and how?
What might be in for you?
Curious? Intrigued? Want to know more?
Who are we?

Group consists currently of

• 4 PhD students (Michael Bertolli, Jordan McDonnell, Nikola Nikolov, George Papadimitriou)
• 6 Postdocs (J. Holt, R. IdBetan, M. Kortelainen, T. Lesinski, J. Pei, N. Schunck)
• 2 Visiting professors/scientists (J. A. Sheikh, M. Stoitsov)
• 4 permanent researchers (Dean, Hagen, Nazarewicz, Papenbrock)
• Several short and long-term visitors

with offices at UT and ORNL
Energy scales and relevant degrees of freedom

Our focus

Degrees of Freedom

- quarks, gluons: 940 MeV (neutron mass)
- constituent quarks: 140 MeV (pion mass)
- baryons, mesons
- protons, neutrons
- nucleonic densities and currents
- collective coordinates

- proton separation energy in lead: 8 MeV
- vibrational state in tin: 1.32 MeV
- rotational state in uranium: 0.043 MeV
BIG questions in our field

1. What binds protons and neutrons into stable nuclei and rare isotopes?
2. What is the origin of simple patterns in complex nuclei?
3. When and how did the elements from iron to uranium originate?
4. What causes stars to explode?

To address these questions, experiment must be guided by theory!
Roadmap for Theory of Nuclei

Nuclear Landscape ...provides the guidance

- Ab initio
- Configuration Interaction
- Density Functional Theory

Density Functional Theory and Extensions

Coupled Cluster Method

Interacting Shell Model
Shell Model Monte Carlo
Gamow Shell Model
Local interests

1. Building nuclei from scratch
2. Global properties (masses, deformations) across the nuclear chart
3. Drip-line nuclei and superheavy nuclei
4. Fission
5. Interdisciplinary research: ultracold atom gases and quantum chaos

\[ \hat{H} |\psi\rangle = E |\psi\rangle \]

\[ \left( -\frac{\hbar^2}{2m} \Delta + F(\rho) - \mu \right) \Phi(r) = 0 \]

The problem consists of the determination of the nuclear Hamiltonian (or energy functional) and the solution of the Schrödinger (or Kohn-Sham) equation.
Local research: Building nuclei from scratch

Previous ab-initio calculations are restricted to light nuclei $\sim^{12}\text{C}$.

Our method (coupled-cluster theory) can be employed for much heavier nuclei! Recently, we computed $^{48}\text{Ca}$. 
True a Sum of its Pieces?
Computing Medium-Mass Atomic Nuclei from Scratch

Atomic nuclei consists of protons and neutrons, and the forces that bind these constituents are better known today than ever before. A stringent test of our understanding of the nuclear interactions is thus the computation of increasingly heavier nuclei. For light nuclei, this program has been very successful, and this approach is now extended toward heavier nuclei by researchers at the University of Tennessee (UT) and Oak Ridge National Laboratory (ORNL). First-principles calculations of medium-mass nuclei such as $^{48}$Ca from modern nucleon-nucleon forces are missing about 0.5MeV per nucleon in binding energy. The missing energy contributions are mainly attributed to presently omitted three-nucleon forces.

The coupled-cluster calculations were performed on Cray XT5 computers Kraken at UT and Jaguar at ORNL. The figure shows the ground-state energy of the $^{40}$Ca nucleus as a function of model-space parameters.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Λ-CCSD(T) Theory</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{4}$He</td>
<td>6.39</td>
<td>7.07</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>7.56</td>
<td>7.97</td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>8.63</td>
<td>8.56</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>8.28</td>
<td>8.67</td>
</tr>
</tbody>
</table>

Superheavy elements
method: density-functional theory

Left: Superheavy nuclei come in prolate and oblate deformed shapes!

Bottom: Fission path in $^{258}\text{Fm}$. Energy as a function of deformations.
Local research:
Global deformation from nuclear density-functional theory
What’s in for you?

- Participate in cutting-edge research in nuclear theory.
- Study the interdisciplinary quantum many-body problem.
- Work in an internationally recognized and world-leading research group.
- Develop new ideas and models, and solve them on desktops to supercomputers.
- Participate in international collaborations and workshops.
- Meet visitors from many places at UT/ORNL.

Numerous collaborations across the globe
Japan-US Theory Institute for Physics with Exotic Nuclei (JUSTIPEN)

Location: RIKEN (near Tokyo) at new radioactive ion beam facility RIBF.
US provides travel and local support for visitors from US institutions.

http://www.phys.utk.edu/JUSTIPEN/
Nuclear theory for students

Research at UT and ORNL
usually first half at UT and second half at ORNL
work involves analytical derivations and numerical implementations

Four students now
Michael Bertolli, Jordan McDonnell, Nikola Nikolov, George Papadimitriou

Possibly one more student at the end of this academic year!

Requirements: Interest / passion / talent to solve problems in nuclear theory

We have several sources of funding (2 DOE grants, 1 NNSA grant)
Curious? Intrigued? Want to know more?

• Talk to us! Nazarewicz and Papenbrock are located in the South College (ground floor)

• Attend the Nuclear Physics Seminar: Monday 2:20PM
  http://web.utk.edu/~rgrzywac/UTNPSem2009fall.html

• 600-level Nuclear physics course in 2010 by Nazarewicz.

• Quantum Mechanics I and II in Fall 2009 and Spring 2010 by Papenbrock.

• Suggested Reading:

• Suggested listening: Rare Isotope Rap http://www.youtube.com/watch?v=677ZmPEFIXE