Nuclear Physics Beyond the JLab (and QCD) Borders

R. Tribble
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Nuclear Physics Beyond the JLab (and QCD) Borders
The Context

‘Guidance’ provided by the recent Long Range Plan: The Frontiers of Nuclear Science

LRP focus is on new science opportunities for nuclear physics

Requires upgrading facilities, constructing new facilities and detectors
U.S. Nuclear Science
[Today and for the Next Decade]

General goal:
Explain the origin, evolution, and structure of the visible matter of the universe—the matter that makes up stars, planets, and human life itself.

Frontiers:
• Quantum Chromodynamics (QCD)
• Physics of Nuclei and Astrophysics
• Fundamental Symmetries and Neutrinos
The Science – QCD

- What are the phases of strongly interacting matter and what roles do they play in the cosmos?
- What is the internal landscape of the nucleons?
- What governs the transition of quarks and gluons into pions and nucleons?
- What is the role of gluons in nucleons and nuclei and where do their self-interactions dominate?
- What does QCD predict for the properties of strongly interacting matter?
- What determines the key features of QCD and what is their relation to the nature of gravity and spacetime?
The Science – QCD

• Theory
• U.S. facilities
  &
• Recent Results
**RHIC:** the Relativistic Heavy Ion Collider
Hot QCD

Recent Successes:

• Discovery of a Near Perfect Fluid – enormous collective motion found in the (QGP) medium

• Jet Quenching – large energy loss that shows up as shock wave

• Novel Hadronization (unexpected baryon/meson ratio appears to follow constituent quark scaling)

• Novel phenomena at high parton density (particle yields in central Au-Au collisions smaller than expected – saturation effects?)
Jefferson Lab Today

Hall A
Two high-resolution
4 GeV spectrometers

Hall B
Large acceptance spectrometer
electron/photon beams

Hall C
7 GeV spectrometer,
1.8 GeV spectrometer,
large installation experiments
QCD and Hadron Structure

Recent Achievements:

- New era - precision predictions of QCD from the lattice
- New constraints on the origin of the nucleon spin
- PV electron scattering – strange quark contribution to electric and magnetic properties of the proton
- Mapping of charge distribution of neutron
- Observation of three-nucleon short range correlations in nuclei
- Initial constraints on Generalized Parton Distributions
- Proton quark distributions are modified by spin orbit correlations
The Science – Fundamental Symmetries and Neutrinos

• What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?

• Why is there now more matter than antimatter in the universe?

• What are the unseen forces that were present at the dawn of the universe but disappeared from view as it evolved?
The Science – Fundamental Symmetries and Neutrinos

• Uses wide range of facilities

• Many recent successes
## Activities in the field (accelerators)

<table>
<thead>
<tr>
<th>Neutrons</th>
<th>nEDM</th>
<th>BSM, BAU, CP ...</th>
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<tbody>
<tr>
<td>NIST</td>
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<td>LANSCE</td>
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<td>SNS FnPB</td>
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<td></td>
<td>Lifetime</td>
<td>( g_A, (\lambda), V_{ud}, BSM )</td>
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<tr>
<td></td>
<td>GO, Happex</td>
<td>( \alpha ) running; BSM</td>
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<tr>
<td></td>
<td>Qweak</td>
<td>( \rho, \delta, \eta, P_{\mu \xi}, (\div 10) )</td>
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<tr>
<td></td>
<td>Möller ee</td>
<td>( G_F ) (1 ppm)</td>
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<td>PVDIS</td>
<td>( \Lambda_s \to g_p )</td>
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<th>Michel parm</th>
<th>( \mu \to e ) capture</th>
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<td>( \rho, \delta, \eta, P_{\mu \xi} )</td>
<td>( G_F ) (1 ppm)</td>
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<td>( \Lambda_s \to g_p )</td>
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<td>( \mu \to e ) capture</td>
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<tr>
<td>FNAL ?</td>
<td>( \mu A \to e A )</td>
<td>( \mu A \to e A )</td>
</tr>
</tbody>
</table>

\( \nu \) connect | SUSY, BSM | LFV, BSM
DoE Division of Nuclear Physics
Returns from investments in Neutrino Physics

SNO

KamLAND

Solar neutrino problem resolved
Precise values of mass and mixing
LMA solution of the Solar Neutrino problem established
Open Questions

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \]

\[
= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}
\]

\[ \theta_{23} = (45 \pm 7)^\circ \]
\[ \theta_{13} < 13^\circ \]
\[ \theta_{12} = (33.9^{+2.4}_{-2.2})^\circ \]
\[ \delta = ? \]
\[ \alpha = ? \]
\[ \beta = ? \]

Normal or Inverted?

Majorana or Dirac?
Fundamental Symmetries and Neutrinos – the Future

- $\beta\beta$ decay
- $\theta_{13}$ (Daya Bay with HEP)
- CP violation – neutron EDM ($\beta$ decay)
- new solar neutrino detector
- muon (g-2)
- ...
DUSEL Site Selection

- Cascades
- SNOLAB
- Soudan
- Homestake
- Henderson
- San Jacinto
- WIPP
- Kimballton
Double Beta Decay

As a result of the review-panel recommendations, DOE has approved CD-0, a statement of mission need, for a generic double-beta-decay program. The EXO $^{136}$Xe double beta decay experiment is under construction at the 200-kg level. CUORE is a European double-beta-decay experiments with substantial US involvement; US capital for CUORE is in the FY08 Presidential Budget. The COBRA CdTe double-beta decay experiment is receiving R&D support. A European $^{76}$Ge experiment, GERDA, is moving ahead towards a 45-kg enriched isotope array. In the US, the Majorana collaboration is now requesting support for a 60-kg enriched array in an aggressive R&D program aimed at a future 1-ton Ge experiment. In Japan, the MOON and CANDLES double beta decay experiments ($^{100}$Mo and $^{48}$Ca respectively) are under construction at the several-Kg scale.
The Science – Physics of Nuclei and Nuclear Astrophysics

- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?
- What is the nature of neutron stars and dense nuclear matter?
- What is the origin of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?
What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?

Goal: describe all nuclei with interactions rooted in QCD: major progress within reach! Connect with reaction theory (example: ab initio calculations of $^7\text{Be}(p,\gamma)$ … )

Need experimental data to
- to assess validity of theoretical approximations
- to test validity of extrapolations - data need to span significant area on chart
- to understand nature of inter-nucleon interactions by revealing and isolating aspects of it in nuclear properties and phenomena
Examples of new phenomena that reveal aspects of the nuclear force in new ways

- shell structure changes with neutron excess
  - accomplished: major changes occur, correlations, role of tensor interaction, impact of continuum
  - future: heavier shells far from stability (astrophysics!) incl. precision mass measurements

- neutron skins and halos
  - accomplished: precision measurements in light systems
  - future: halos: search in heavier nuclei <A~100 find the most extreme skins
  PREX at JLAB

- location of n-drip line
  - accomplished: up to O
  - future: up to ~Zr with FRIB

- new radioactive decay modes: 2p decay
  - accomplished: discovered several cases
  - now underway: measure correlations->pairing

- weakening of spin-orbit force with n-excess?
  - accomplished: hints from a few isolated cases
  - future: broader picture, find microscopic origin

→ Vast majority of these far from stability – that’s the frontier
→ but just at the beginning: great discovery potential for the future
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What is the origin of simple patterns in complex nuclei?

Shape evolution with N,Z

Described as phase transition
Can understand behavior at critical Point with X(5) symmetry

New collective modes

Mixed-Symmetry States

Future: systematic study → far from stability
impact of n/p ratio on phase transitions

Future: signature at large N?
decoupling of n & p deformations?
new symmetry or breakdown of algebraic picture
(fragmentation)
Return of collectivity at the highest spins, in a regime where it had been thought to be destroyed
→ Triaxial shapes

K-isomers in very heavy nuclei:
→ Direct proof of axial symmetry
→ Information on $E_{sp}$ → gaps and spacings
→ Shell stabilization → SHN
What is the nature of neutron stars and dense nuclear matter?

- What is the maximum mass of a neutron star?
- What is the mass-radius relationship?
- How do neutron stars cool?
- What is the core made of?
- What is the origin of transient phenomena?
  (bursts, superbursts, transient cooling)
- What is the EOS of nuclear matter
  in particular the density dependence of asymmetry?

→ These are as much nuclear physics questions as they are astrophysical questions.
Recent accomplishments:
• first NS seismology
• massive (>1.4 solar masses) neutron stars discovered
• first hints for non-standard cooling
• ground state at extreme densities: color superconductor with CFL phase
• consistent values for compressibility from Giant Resonances and HI collisions
  \[ K = 230 \pm 10 \text{ MeV} \text{ (Giant Resonance Studies)} \]
  \[ K = 233 \pm 39 \text{ MeV} \text{ (Multi-Fragm. HI collisions)} \]

But: long way to go … Better theory (interpolation from finite nuclei to nuclear matter) Better observations, Neutron skin measurements (PREX), HI collisions with large asymmetry (FRIB)…
What is the origin of the elements in the cosmos?

NAS report: “Connecting Quarks with the cosmos”
11 questions for the 21st century
• how where the elements from iron to uranium made?

Lots of precision data on the r-process yields:
much more to come from ongoing campaigns

→ Experimental data needed to interpret astronomy data
and to test various r-process models against data
(~20 r-process nuclei have been reached by experiments incl $^{78}$Ni)
Goals:
- Understand the origin of all the elements – chemical history of the Galaxy
- Use nucleosynthesis processes as diagnostics for other physics

Owing to decades of experimental work this has been accomplished for some processes involving stable nuclei or nuclei close to stability:

- Still lots of work to be done – need stable and neutron beam facilities
- Vision for the future: achieve same for processes with unstable nuclei

Fusion reactions in the sun:
Constrains neutrino physics

Big Bang nucleosynthesis:
Determined baryon contents of the universe

s-process:
Constrains mixing processes in AGB stars
What are the nuclear reactions that drive stars and stellar explosions?

Stars

Accomplishment: new measurements of $^{14}\text{N}(p,\gamma)$ rate show rate is x2 smaller
  $\rightarrow$ Globular cluster ages increase by $\sim 1$ Gyr

Future: many challenges, for example $^{12}\text{C}(\alpha,\gamma)$ $\rightarrow$ need stable beam facilities

Supernovae:
Accomplishments: major progress in modeling (though explosion mechanism is still unknown) identified critical weak interactions

Need EC rates on unstable nuclei

$\nu$-physics is also critical
X-ray bursts (and Novae)

Many open questions from X-ray observations:
superbursts, constraints on neutron star, ejected composition, …

Accomplishments:
• use indirect techniques to obtain first constraints on many rates
• pioneered techniques to directly measure reaction rates with rare isotope beams
many exciting results but field is strongly limited by selection of available beams and beam intensities

Future:
FRIB will have sufficient beam intensities to apply techniques to most reactions (need stopped, reaccelerated, and fast beam capabilities)
A Digression
Direct and **Indirect** Techniques to get N.A. reaction rates

- **Direct measurements:**
  - stable beam and targets ‘going underground’

- **Widths** \((\gamma \text{ and 'p')}\) of resonance rates
  - populate resonance state and measure decay
  - now extending to radioactive beams

- **Resonance energies** – determine \(E_R\)

- **Coulomb dissociation**

- **Trojan Horse Method**
  - unique way to understand screening

- **Asymptotic Normalization Coefficients**
  - use with stable and radioactive beams
Reactions studied relevant to:
- $p$-$p$ chain
- rapid $\alpha$-$p$ reactions
- CNO cycle
- HCNO cycle
- Breakout from CNO cycle
- Ne-Na cycle

= studied at TAMU
The Science – Physics of Nuclei and Nuclear Astrophysics

• U.S. facilities
NSCL Coupled Cyclotron Facility (CCF)

Primary beams (He–U): E/A ≤ 200 MeV
Fast and stopped rare isotopes beams
Reaccelerated beams in 2010
The ATLAS Facility Today

8.5-MV Tandem Injector
Important for:
Beams of A<58
Long-lived RIB’s

12-MV Positive Ion Injector (PII)
Required for:
Beams with A>58
Noble gases
High current

18 Quarter-wave SC resonators

World-Class Equipment & Advanced Penning Trap

2 ECR Ion Sources on HV platform

24-Resonator Booster
19-Resonator ATLAS
**88-Inch Cyclotron - Facilities**

- **BASE Facility**
  - Space radiation effects

- **LIBERACE**
  - Laser Trapping

- **Berkeley Gas-filled Separator**
  - 3 ECR ion sources including VENUS

### Table: Particle Energies

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<tr>
<th>Particle</th>
<th>Energy (MeV)</th>
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<tr>
<td>Proton</td>
<td>55</td>
</tr>
<tr>
<td>Alpha</td>
<td>130</td>
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<tr>
<td>Li to S</td>
<td>32 MeV/A</td>
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<tr>
<td>Kr</td>
<td>20 MeV/A</td>
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<tr>
<td>Xe</td>
<td>14 MeV/A</td>
</tr>
<tr>
<td>U</td>
<td>5 MeV/A</td>
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- **K-140 separated sector cyclotron**
  - High intensity light and heavy ions
US Mid-Size Nuclear Physics Facilities

- **CENPA**: FN Tandem in low and high energy LINAC post-acceleration mode
- **FSU**: FN Tandem with LINAC post-acceleration radioactive beam facility
- **RESOLUT**
- **Notre Dame**: FN Tandem, KN & JN single ended accelerators radioactive beam facility TWINSOL
  AMS facility with gas filled spectrometer
- Stony Brook: FN Tandem with LINAC post-acceleration
- Francium trap
- TAMU: K-500 cyclotron
- Radioactive beam facility MARS
- TUNL: FN Tandem, neutron beam facility
- LENA laboratory, JN single ended machine
- HIGS photon beam facility
- Yale: MP Tandem
- Sasyer Separator
- Yrast Ball
Present and Future Direction in Physics of Nuclei and Nuclear Astrophysics

Rare Isotope Beams
Basic Techniques for Producing RIBs

ISO

L

Ion Source

Electromagnetic Separator

Ion Trap

Post Accelerator

Secondary Experiment

Primray Source

Production Target

In Flight

Fragmentation, Reactions

In Flight + Stopping

Gas Stopping

Ion Trap

Primary Experiment
RIB Facilities
(Operating or Under Construction)
Primary Beams

- $^{40}\text{Ar}^{18+}$: $2 \times 10^{12} / \text{s}$ @ 1 – 2 AGeV
- $^{238}\text{U}^{28+}$: $5 \times 10^{11} / \text{s}$ @ 1 – 2 AGeV
- $^{40}\text{Ar}^{18+}$: $2 \times 10^{10} / \text{s}$ @ 1 – 45 AGeV
- $^{238}\text{U}^{92+}$: $1 \times 10^{10} / \text{s}$ @ 1 – 35 AGeV

100 x 1000 times present intensity

- Protons: $2 – 5 \times 10^{13} / \text{s}$ @ 30 GeV

Secondary Beams

- Broad range of radioactive beams up to 1 – 2 AGeV
- RI- Intensities up to 10 000 over present
- Antiprotons

Storage and Cooling of Beams

- Radioactive beams
- $e^-$ – A (or antiproton – A) collider
- Antiprotons: $> 10^{11}$ at 0.8 – 15 GeV/c
- Future: Polarized antiprotons
RIKEN RI-Beam Factory (RIBF)

- Fast RI beams (RIPS) - $v \sim 0.3c$
- SHE (e.g. $Z=113$)
- $\sim 5$ MeV/nucleon
- RILAC
- AVF
- RRC
- IRC
- SRC
- BigRIPS
- pol. d beams
- $135$ MeV/nucleon for light nuclei (1986-)
- $350$ MeV/nucleon up to U
- 350 MeV/nucleon
- 1st beam in Dec. 2006
- U beam in Mar. 2007
- 1st new isotope ($^{125}$Pd): May 2007

June 2008
A(nother) Digression
The European ISOL Road Map

- Vigorous exploitation of current ISOL facilities: EXCYT, REX/ISOLDE, SPIRAL
- Construction of intermediate generation facilities: SPIRAL2, HIE-ISOLDE, SPES
- Design and prototyping in the framework of EURISOL Design-Study (20 Labs, 14 Countries, 30M€)
The Science of FRIB

Overarching Goal: A predictive model of nuclei and their reactions.

SCIENCE OF THE SMALL: The atomic nucleus is a unique laboratory of interdisciplinary sciences related to quantum, many-body, open systems

UNDERSTANDING THE UNIVERSE: Nuclei determine the chemical history of the Universe and drive stellar explosions. Connection of models of novae, supernovae, X-ray bursts etc. to observations require rare isotopes.

TESTING SYMMETRIES IN NATURE: Rare isotopes provide complementary information to high-energy experiments at, e.g., LHC

NUCLEI MATTER: Nuclei have applications to medicine, energy, industry, other sciences, and national security
FRIB General Features

- Driver linac with 400 kW and greater than 200 MeV/u for all ions
- Ions of all elements from protons to uranium accelerated
- Space included for upgrade to 400 MeV/u, ISOL, and multiple production targets
Superconducting Heavy Ion Driver Linac

- 4 cavity types required
- Prototypes of all cavities except $\beta = 0.53$ complete
- Alternative analysis underway

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<th>Type</th>
<th>$\beta$</th>
<th># per Cryomodule</th>
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<tr>
<td>Totals</td>
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<td>336</td>
<td>81</td>
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ReA12 and Experimental Areas

• A full suite of experimental equipment will be available for fast, stopped and reaccelerated beams

• New equipment developed in collaboration with users

• These will likely include
  – Stopped beam area (LASERS)
  – ISLA Recoil Separator
  – Solenoid spectrometer
  – Active Target TPC
ISOL and Multi-user Capability

- Harvesting for off-line use of isotopes in focal plane chambers
- Catcher/ion source system in focal plane
  - Low-energy ISOL-type beams
  - Stopped and reaccelerated beams simultaneous to fast beams for experiments
- Additional production stations could be added
  - 2 ISOL stations or 2\textsuperscript{nd} fragment separator
  - Single-beam and multiple-beam option for primary beams
Isotope Production
– a new program for DOE NP

The FY09 budget request for DOE includes a transfer of the Isotope Production program from Office of Nuclear Energy to Office of Nuclear Physics in Office of Science.

The budget line for this program is about $20 M.

An additional $3 M R&D was added for new isotopes.

Program also sells about $20 M of isotopes in a year – funds stay in the program to support production costs.
Isotope Related Activities

• Workshop on Nations Needs for Isotopes: Present and Future

• NSAC established NSACI subcommittee
  – Asked to prioritize how to spend R&D funding
  – Asked to develop an Isotopes Program LRP due in July, 2009
The U.S. Nuclear Science Program

DOE and NSF support a very diverse program in nuclear science that cover the three frontier areas.

With funding profile endorsed by Congress to double science budgets, the program will flourish over the next decade.
MR. KABLIHNICK HAS DEVELOPED THE QUANTUM LECTURE... IT HAS NO REAL POINT.

MR. KABLIHNICK'S PROBLEM IS THAT HE HAS A GENIUS COMPLEX... AND HE ISN'T ONE.