REACHING FOR THE HORIZON

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

Helen Caines and Karsten Heeger
with slides from Don Geesman, Brad Filippone, Bob McKeown, John Wilkerson
21st Century Nuclear Science: Probing nuclear matter in all its forms & exploring their potential for applications

How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

What is the nature of the different phases of nuclear matter through which the universe has evolved?

Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?

How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?

How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?

How can technologies developed for basic nuclear physics research be adapted to address society's needs?
Nuclear Science is at a Launching Point in Reaching for the Horizon

Valence quarks and gluons

Quark Gluon Plasma
The most perfect liquid

The Structure and Limits of Nuclei
The Origin of Nuclei

Unique Nuclear Probes of Physic beyond the Standard Model

Understanding the Glue that binds us all

JLAB 12 GeV Upgrade – Valence 3D Imaging and Valence Glue

RHIC – Low Energy Search for critical point
Exploit jets and high mass probes

FRIB – Twice the number of nuclei available

NSCL, ATLAS and University Facilities

Neutrinoless Double Beta Decay, Electric Dipole Moments
and other nuclear tests of the Standard Model

A future Electron Ion Collider
Nuclear Science in the U.S. has been guided by the NSAC Long Range Plans
Charge to NSAC to Develop a New Long Range Plan

“a framework of coordinated advancement of the Nation’s nuclear science research programs over the next decade”

“articulate the scope and scientific challenges”

“what progress has been made and the impact of these accomplishments both within and outside the field”

“identify and prioritize the most compelling scientific opportunities”

“coordinated strategy for the use of existing and planned capabilities, both domestic and foreign”

“what resources and funding levels would be required ... to maintain a world-leadership position in nuclear physics research”

“what the impacts are and priorities should be if funding provides for constant level of effort.”

“key element should be the Program’s sustainability under the budget scenarios considered”
The Role of the NSAC Long Range Plan in Projects

NSAC is asked to identify scientific opportunities and a level of resources necessary to achieve these. The recommendations express priorities. But, except for the largest-scale facilities, projects named in this report are given as examples to carry out the science. The funding agencies have well-established procedures to evaluate the scientific value and the cost and technical effectiveness of individual projects. There is a long-standing basis of trust that if NSAC identifies the opportunities, the agencies will do their best to address these, even under the constraints of budget challenges.

In this way our charge is different than that of the HEP Particle Physics Prioritization Panel which considers individual projects.
# The 2015 Nuclear Science Advisory Committee

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>Donald Geesaman (Chair)</td>
<td>Argonne National Laboratory</td>
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<td>Vincenzo Cirigliano</td>
<td>Los Alamos National Laboratory</td>
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<tr>
<td>Abhay Deshpande</td>
<td>Stony Brook University</td>
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<tr>
<td>Frederic Fahey</td>
<td>Boston Children's Hospital</td>
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<tr>
<td>John Hardy</td>
<td>Texas A&amp;M University</td>
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<tr>
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<td>Yale University</td>
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<td>Chair, American Chemical Society Division of Nuclear Chemistry and Technology</td>
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<tr>
<td>Suzanne Lapi</td>
<td>Washington University</td>
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<tr>
<td>Jamie Nagle</td>
<td>University of Colorado</td>
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<td>Filomena Nunes</td>
<td>Michigan State University</td>
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<tr>
<td>Erich Ormand</td>
<td>Lawrence Livermore National Laboratory</td>
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<tr>
<td>Jorge Piekarewicz</td>
<td>Florida State University</td>
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<tr>
<td>Patrizia Rossi</td>
<td>Thomas Jefferson National Accelerator Facility</td>
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<tr>
<td>Jurgen Schukraft</td>
<td>European Organization for Nuclear Research</td>
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<td>Kate Schoenberg</td>
<td>Duke University</td>
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<td>Matthew Shophord</td>
<td>Indiana University</td>
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<td>Raju Venugopalan</td>
<td>Brookhaven National Laboratory</td>
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<td>Michael Wiescher</td>
<td>Notre Dame University</td>
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<tr>
<td>John Wilkerson</td>
<td>University of North Carolina, Chair of American Physical Society Division of Nuclear Physics</td>
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A.2 The Long Range Plan Working Group Membership

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2015 Recommendations – in brief

The exact text is important!

- Recommendations
  - Follow the 2007 LRP
  - Lead a ton-scale neutrinoless double beta decay experiment
  - Build an Electron Ion Collider after FRIB construction is compete
  - Increase investment in small and mid scale projects and initiatives

- Initiatives
  - Theory and Theory Computing
  - R&D for the EIC and neutrinoless double beta decay

- Workforce, Education and Outreach
DOE Budget Projections

Modest Growth

- Facility Construction (EIC)
- Total Facility Ops
- Facility Construction (CEBAF + FRIB)
- Total Projects
- Total Research
- Total Other
- Constant Effort
- Modest Growth (FY16 PR + 1.6%)

FY15/1000

FY15, FY16, FY17, FY18, FY19, FY20, FY21, FY22, FY23, FY24, FY25
RECOMMENDATION I
The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.
- Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.
- The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained.
- The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.

Realizing world-leading nuclear science also requires robust support of experimental and theoretical research at universities and national laboratories and operating our two low-energy national user facilities —ATLAS and NSCL— each with their unique capabilities and scientific instrumentation.

The ordering of these four bullets follows the priority ordering of the 2007 plan.
Hot/Cold QCD - Future

- Do the initial conditions for the hydrodynamic expansion contain unambiguous information about saturated gluon fields in nuclei?
- What is the smallest collision system that behaves collectively?
- What does the QCD phase diagram look like? Does it contain a critical point in the HG-QGP transition region? Does the HG-QGP transition become a first-order phase transition for large $\mu_B$?
- What is the structure of the strongly coupled QGP at varying length scales? What makes it a liquid?
- What do Upsilon states tell us about quark deconfinement and hadronization?
- What do transversely polarized protons tell us about the coupled spin-momentum dynamics of QCD at different scales?
Hot QCD - Future

• Energy loss $\hat{q}$, $\eta/s$ Initial temperature $T_{\text{init}}$, $T_C$.

<table>
<thead>
<tr>
<th></th>
<th>$\hat{q}$</th>
<th>$\eta/s$</th>
<th>$T_{\text{init}}$</th>
<th>$T_C$</th>
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<tbody>
<tr>
<td>RHIC 200 GeV</td>
<td>1.2 ± 0.3</td>
<td>0.12</td>
<td>&gt; 300 MeV</td>
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<tr>
<td>LHC 2.67 TeV</td>
<td>1.9 ± 0.7</td>
<td>0.2</td>
<td>&gt; 400 MeV</td>
<td>~160 MeV</td>
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• RHIC and LHC Plans

RHIC

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LHC

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Heavy Flavor etc.

BES II

sPHENIX

From Photons

$T = 220$ MeV & $>300$ MeV

6.5–7.0 TeV Protons

LHC Upgrade

ALICE Upgrade

6.5–7.0 TeV Protons $p+p$, $p+Pb$, Pb+Pb
Toward critical fluctuations

Model independent structure of net baryon number kurtosis

Possible Scenario Near Critical Point
Completing the RHIC science mission

Status: RHIC-II configuration is complete
- Vertex detectors in STAR (HFT) and PHENIX
- Luminosity reaches 25x design luminosity

Plan: Complete the RHIC mission in 3 campaigns:
- 2014–17: Heavy flavor probes of the QGP using the micro-vertex detectors; Transverse spin physics
- 2018: Install low energy e-cooling
- 2019/20: High precision scan of the QCD phase diagram & search for critical point
- Install sPHENIX
- Probe QGP with precision measurements of jet quenching and Upsilon suppression
- Spin physics and initial conditions at forward rapidities with p+p and p+A collisions?
- Transition to eRHIC

STAR continued running? – proposal with PAC
sPHENIX final design - submission soon to BNL review
Completing the RHIC Science Mission

- A unique forefront science program with tremendous discovery potential that is ONLY possible with RHIC:
  - Quantify the transport properties of the QGP near $T_c$ using heavy quarks as probes (together with LHC)
  - Measure gluon and sea quark contributions to proton spin and explore coupled momentum-spin dynamics of QCD
  - High statistics map of the QCD phase diagram, including possible discovery of a critical point
  - Probe internal structure of the most liquid QGP using fully reconstructed jets and resolved Upsilon states as probes (together with LHC)
  - Refine the physics program of an EIC with studies of polarized pp and pA collisions in forward kinematics
  - RHIC enabled R&D to retire major risks of eRHIC design
RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.
Neutrinoless double beta decay

\[(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-\]

Lepton number changes by two units: \(\Delta L=2\)

Unique laboratory* to study lepton number violation (LNV)

*Enabled by nuclear physics energetics
Neutrinoless Double Beta Decay

Observation of Neutrinoless Double Beta Decay would

- Demonstrate the lepton number is not conserved
- Prove that a neutrino is an elementary Majorana particle, that is, its own antiparticle.
- Suggest that a new mechanism for mass generation, not the Higgs mechanism, is at work.
- Provide evidence for one of the key ingredients that could explain the preponderance of matter over antimatter in the universe, leptogenesis.
Why is it a big deal?

- B-L conserved in the Standard Model \( \Rightarrow \) Observation of NLDBD would be direct evidence of new physics, with far-reaching implications

- The proposed ton-scale experiments will probe LNV violation at the level of \( T_{1/2} \sim 10^{27} \text{yr} \) (100x improvement): a discovery would have major impact on our understanding of fundamental interactions

- To assess the discovery potential, need to take a look inside the blob
Lepton Number Violation and $0\nu\beta\beta$

- Ton-scale $0\nu\beta\beta$ probes LNV from a variety of mechanisms and scales of masses (M) and couplings (g)

Diagram:
- $M_{GUT}$
- TeV
- eV
- standard mechanism (see-saw)
- left-right SM RPV SUSY
- light sterile $\nu$'s

V. Cirigliano

10/15/15 NSAC Meeting
New Physics and LHC

arXiv:1508.07286
The role of nuclear structure

- Connecting experimental rates to parameters of LNV interactions ($m_{\beta\beta}$, ...) requires mechanism-dependent nuclear matrix elements

- Available model results differ by factors of 2-3

- Discovery goals set by taking “pessimistic” matrix elements

- Improvement is highly desirable: the matrix elements are essential for interpretation

Matrix elements for “standard mechanism”
## Current Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Isotope</th>
<th>Isotope Mass (kg fiducial)</th>
<th>Currently Achieved ($10^{26}$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>206</td>
<td>&gt;0.028</td>
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<tr>
<td>MAJORANA</td>
<td>$^{76}$Ge</td>
<td>26.9</td>
<td></td>
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<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>35</td>
<td>&gt;0.21</td>
</tr>
<tr>
<td>EXO200</td>
<td>$^{136}$Xe</td>
<td>79</td>
<td>&gt;0.11</td>
</tr>
<tr>
<td>NEXT-10</td>
<td>$^{136}$Xe</td>
<td>10</td>
<td></td>
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<tr>
<td>SuperNEMO</td>
<td>$^{82}$Se+</td>
<td>7</td>
<td>&gt;0.001</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}$Xe</td>
<td>434</td>
<td>&gt;0.19</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{130}$Te</td>
<td>160</td>
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**Primary goals:**
- Demonstrate background reduction for next generation experiment
- Extend sensitivity to $T_{1/2} \sim 10^{26}$ years.
Preparations for an NP Stewardied Neutrino-less Double Beta Decay Experiment

With techniques that use nuclear isotopes inside cryostats, often made of ultra-clean materials, scientists are “tooling up” to study whether neutrinos are their own anti-particle. NSAC charged to provide additional guidance on effective strategy for implementing a possible 2nd generation U.S. experiment.

“Grand Challenge” science questions that will be addressed:

- Is the neutrino its own anti-particle?
- Why is there more matter than antimatter in the present universe?
- Why are neutrino masses so much smaller than other elementary fermions?

Fermion masses

Mandrel insertion in MJD electroforming lab
International Program in $0\nu\beta\beta$

- Previous Expts.
  - $T_{1/2} \sim 10^{24}$ y
  - ($\sim 1$ eV)
  - $\sim$ kg scale

- Quasi-degenerate
  - $T_{1/2} \sim 10^{25} - 10^{26}$ y
  - ($\sim$ 100 meV)
  - 30 - 200 kg
  - $\sim$ 8 expts

- Inverted hierarchy
  - $T_{1/2} \sim 10^{27} - 10^{28}$ y
  - ($\sim$ 15 meV)
  - Tonne (phased)
  - $\sim$ 3 experiments
  - All international in scope
  - U.S. involvement in $\sim$ 2

Timeline:
- 1980 - 2007
- 2007 - 2017
- 2015 - 2025
International Program in $0\nu\beta\beta$

**Previous Expts.**
- $T_{1/2} \approx 10^{24}$ y
  - $\approx 1$ eV
  - $\approx$ kg scale

**Quasi-degenerate**
- $T_{1/2} \approx 10^{25} - 10^{26}$ y
  - $\approx 100$ meV
  - 30 - 200 kg
  - $\approx 8$ expts

**Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques**
- $\approx$ tonne scale

**Inverted hierarchy**
- $T_{1/2} \approx 10^{27} - 10^{28}$ y
  - $\approx 15$ meV
  - tonne (phased)
  - $\approx 3$ experiments
  - All international in scope
  - U.S. involvement in $\approx 2$

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**0$\nu\beta\beta$-decay — experiments**

1980 - 2007

2007 - 2017

2015 - 2025

LRP Resolution Meeting
April 18, 2015
Ton-scale Neutrinoless Double Beta Decay (0νββ) - A Notional Timeline

Search for Lepton Number Violation

- Current generation experiments
- NSAC 0νββ decay Subcommittee
- R&D: Pre-technology selection
- R&D & Project Eng.: Post-technology selection
- Ton-scale Construction
- Data Taking

Timeline:
- 2015
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025

Ton-scale Milestones:
- Mission Decision
- Technology Selection
- Construction
- Data
RECOMMENDATION III

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new Electron Ion Collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC’s unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.
Investigate with precision the universal dynamics of gluons and sea quarks that fundamentally make up nearly all the mass of the visible universe.

All strongly interacting matter is an emergent consequence of many-body quark-gluon dynamics.

Understanding the origins of matter demands that we develop a deep and varied knowledge of these emergent dynamics.

Two branches -> polarized ep and eA
Electron Ion Collider

a) incident electron → scattered electron
b) virtual photon → magnetic moment
c) gluon proliferation
d) gluon saturation
Driving Fundamental Questions in ep

How do quarks and gluon dynamics generate the proton spin?

What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?

How are the sea quarks and gluons distributed in space and transverse momentum inside the nucleon?
Driving Fundamental Questions in eA

What is the fundamental quark-gluon structure of atomic nuclei?

What is the role of saturated strong gluon fields and what are the relevant degrees of freedom in this strongly interacting regime?

Can nuclear color filter provide novel insight into propagation, attenuation and hadronization of colored probes?

eA: Unprecedented study of matter in a new regime of QCD.
US Based EIC – Two competing designs

**eRHIC**
- upgrade to RHIC hadron beam,
- add ERL and FFAG Recirculating electron ring,
- 6.3 - 15.9 and 21.2 GeV e energy, - Heavy Ions up to 100 GeV/u
- √s up to 93 GeV
- L ~ 1033 cm-2s-1/A base design.

**MEIC**
- upgrade to CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration, - 3-12 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy,
- L ~1034 cm-2s-1/A
The Science Case

arXiv:1212.17010

Unification of Hot and Cold QCD programs
RECOMMENDATION IV

We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

Innovative research and initiatives in instrumentation, computation, and theory play a major role in U.S. leadership in nuclear science and are crucial to capitalize on recent investments. The NSF competitive instrumentation funding mechanisms, such as the Major Research Instrumentation (MRI) program and the Mathematical & Physical Sciences mid-scale research initiative, are essential to enable university researchers to respond nimbly to opportunities for scientific discovery. Similarly, DOE-supported research and development (R&D) and Major Items of Equipment (MIE) at universities and national laboratories are vital to maximize the potential for discovery as opportunities emerge.
Neutrinos & Fundamental Symmetries

next-generation nEDM experiment

R&D towards direct measurements of neutrino mass
SNS-nEDM Experiment

HV FEED
MAGNETIC SHIELD HOUSE

3He ATOMIC BEAM SOURCE
3He DILUTION REFRIGERATOR
PURIFIER MODULE
INJECTION MODULE

VARIBLE CAPACITOR
MEASUREMENT CELLS
CENTRAL DETECTOR SYSTEM
MAGNET PACKAGE

Neutron beam is into page
A: Theory Initiative
Advances in theory underpin the goal that we truly understand how nuclei and strongly interacting matter in all its forms behave and can predict their behavior in new settings.

To meet the challenges and realize the full scientific potential of current and future experiments, we require new investments in theoretical and computational nuclear physics.

- We recommend new investments in computational nuclear theory that exploit the U.S. leadership in high-performance computing. These investments include a timely enhancement of the nuclear physics contribution to the Scientific Discovery through Advanced Computing program and complementary efforts as well as the deployment of the necessary capacity computing.
- We recommend the establishment of a national FRIB theory alliance. This alliance will enhance the field through the national FRIB theory fellow program and tenure-track bridge positions at universities and national laboratories across the U.S.
- We recommend the expansion of the successful Topical Collaborations initiative to a steady-state level of five Topical Collaborations, each selected by a competitive peer-review process.
B: Initiative for Detector and Accelerator Research and Development

U.S. leadership in nuclear physics requires tools and techniques that are state-of-the-art or beyond. Targeted detector and accelerator R&D for the search for neutrinoless double beta decay and for the Electron Ion Collider is critical to ensure that these exciting scientific opportunities can be fully realized.

- We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the Electron Ion Collider.