The 2015 Long Range Plan for Nuclear Science

Nuclear Science Advisory Committee

October 2015

USA: LRP 2007, LRP 2015

(working group of 58 members)

Europe: LRP 2010, LRP 2017

Nuclear Physics European Collaboration Committee (NuPECC)

LRP for Nuclear Science in Europe

GSI-FAIR, Darmstadt, January 2017

The 2015 Nuclear Science Advisory Committee

- **Donald Geesaman (Chair)** Argonne National Laboratory
- **Vincenzo Cirigliano** Los Alamos National Laboratory
- **Abhay Deshpande** Stony Brook University
- **Frederic Fahey** Boston Children’s Hospital
- **John Hardy** Texas A&M University
- **Karsten Heeger** Yale University
- **David Hobart** Chair, American Chemical Society Division of Nuclear Chemistry and Technology
- **Suzanne Lapi** Washington University
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- **Filomena Nunes** Michigan State University
- **Erich Ormand** Lawrence Livermore National Laboratory
- **Jorge Piekarewicz** Florida State University
- **Patrizia Rossi** Thomas Jefferson National Accelerator Facility
- **Jurgen Schukraft** European Organization for Nuclear Research
- **Kate Scholberg** Duke University
- **Matthew Shepherd** Indiana University
- **Raju Venugopalan** Brookhaven National Laboratory
- **Michael Wiescher** Notre Dame University
- **John Wilkerson** University of North Carolina, Chair of American Physical Society Division of Nuclear Physics

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- **International Observers**
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- **Frank (Ted) Barnes,** DOE
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- **Tim Hallman,** DOE
- **Ken Hicks,** NSF
- **Bogdan Mahalia,** NSF
- **Gulsham Rai,** DOE
- **Allena Opper,** NSF
- **James Sowinski,** DOE

2. Quantum Chromodynamics

The fundamental description of the heart of visible matter

- QCD and the structure of hadrons and nuclei
- QCD and the phases of strongly interacting matter
- Understanding the glue that binds us: The next QCD frontier in nuclear physics

- Structure of hadrons with Lattice QCD

  Example: Mass differences between isospin pairs of baryons (proton-neutron, for example), can be calculated from first principles at the level of one part in a thousand

- Structure of light nuclei with Lattice QCD

  Example: Magnetic moments of proton, neutron, deuteron, triton (3H), 3He

3D pictures of the nucleon

- New concept: Generalized parton distributions

- Computed tomography (CT) scan

  (minute cancer tumors, tiny broken bones, early signs of osteoporosis)

  Example: 3D views of the spatial charge density of the proton

Phases of QCD matter

- Emergent phenomena

- High temperature superconductivity

  Strongly correlated, electromagnetically interacting matter

  Strange metal phase

- Quark gluon plasma

  Strongly interacting matter

  Color superconductor

Jetting through the quark gluon plasma

- Ernest Rutherford

  Alpha particles through gold foil

  Sometimes scattered at large angles

  Atomic nuclei discovered

- Jets: high-energy quark probes

  Sent through quark gluon plasma (RHIC, LHC)

  Look for jets or partons scattered at large angles

  Individual quarks and gluons to be seen

Nucleon spin

- Simple properties from complex QCD interactions

- Proton: composite system

  Quark and gluon constituents

- Spin of all quarks + spin of gluons

  + angular momentum of all quarks

  + angular momentum of gluons $= \frac{1}{2}$

An evolving picture of nuclei

- Tool: electron scattering
  Increasing energy and momentum transfer
- Overall electric charge and magnetic moment
- Spatial distribution of electric charge and magnetization (Robert Hofstadter, Nobel 1961)
- Individual nucleons seen (Deep Inelastic Scattering; Friedman, Kendall, Taylor; Nobel 1990)
- Proliferation and saturation of gluons (Electron Ion Collider)

High-energy nuclear physics / QCD facilities

- Continuous Electron Beam Accelerator Facility (CEBAF)

  Newport News, Virginia 12 GeV upgrade

  Thomas Jefferson National Accelerator Facility (JLab)

- Relativistic Heavy Ion Collider (RHIC)

  Upton, Long Island, New York

  Brookhaven National Laboratory (BNL)

- Electron Ion Collider (EIC) future

U.S. participation abroad – Hadron physics

Europe

- Mainz, Germany
- COMPASS-II experiment at CERN
- PANDA experiment at GSI/FAIR
- Paul Scherrer Institut (PSI), Switzerland

Asia

- J-PARK facility, Japan
- BES-III facility, China
- Super-KEKB electron-positron collider, Japan

U.S. participation abroad – Heavy ion physics

- Large Hadron Collider (LHC) at CERN

  Heavy-ion detectors at the LHC ALICE, CMS, ATLAS

- GSI/FAIR at Darmstadt, Germany

  Heavy ion experiment Compressed Baryon Matter (CBM) planned

3. Nuclear Structure and Reactions

- 288 stable isotopes
- 3000 isotopes known
- >6000 isotopes predicted

- Proton drip line reached up to Z=83
- Neutron drip line reached up to Z=8
- Current upper limit Z=118, A=294

Oxygen: beyond the limits of nuclear stability

- 16O (Z=8, N=8) stable
- New magic numbers at N=14, 16 (22O, 24O)
- 25O, 26O: neutron unbound

- 26O->24O by splitting out two neutrons

  New form of radioactivity (two-neutron)

- Benchmark for ab initio models

  Two and three-nucleon forces

Nuclear structure and reactions

- ab initio calculations (light nuclei)
- Nuclear Density Functional Theory (heavy complex nuclei)
- Microscopic reaction theory needed

- Data at the extremes of neutron-to-proton asymmetry and angular momentum needed

- Proton-neutron pairing
- Alpha clustering at the nuclear surface

Unification of nuclear structure and reactions

- Already happening in light nuclei

- Key reactions involving composite projectiles

- d + 7Li -> 8Li + p

- n + 6Li -> 4He + 3H
  (important in fusion research)

- 4He + 3He -> 7Be + γ
  (relevant for the standard solar model)

Neutron stars

- Neutron stars: more massive than the sun,

  20 km across

- Tremendous gravitational forces squeeze matter in the core to supranuclear density

- Neutron star: 18 orders larger than 208Pb,

  55 orders more massive than 208Pb,

  but same constituents, same strong interactions, same relation between pressure and density

Nuclear pasta

- Outer layers of neutron star cool rapidly (within a few years' time)

- Crust outer region: lower density, conventional atomic nuclei

- Denser regions of the crust:

  Platelike nuclei (lasagna)

  Rodlike nuclei (spaghetti)

  More complex shapes (nuclear pasta)

4. Nuclear Astrophysics

- Origin of the elements
- The life of stars
- The death of stars
- The matter of neutron stars

The Carbon-to-Oxygen ratio in our Universe

Important for:

- Development of the chemical building blocks of life
- Sequence of late stellar evolution phases for the massive stars that give rise to core collapse supernovae

Need:

- Reaction rates of carbon induced reactions
- Cosmic-ray-background-free environment (deep underground)

The origin of heavy elements

Origin of neutron-rich elements heavier than iron

- s-process (slow neutron capture)
- r-process (rapid neutron capture)

  (high temperature, high density, violent events

- Half of the nuclei with mass>100 originate in the r-process

- Where does the r-process happen?

  Large aperture observatories

  (Hubble telescope, Magellan observatory)

Advanced LIGO and nuclear physics

- Detection of gravitational radiation from the violent merging of neutron stars in binary systems

- Advanced Laser Interferomenter Gravitational-Wave Observatory (LIGO)

- Nature and behavior of ultradense neutron matter
- Conditions in the merger environment

Facilities for Nuclear Structure and Astrophysics

- Argonne Tandem Linac Accelerator System (ATLAS)
  Lemont, Chicago, Illinois
  Argonne National Laboratory (ANL)

- National Superconducting Cyclotron Laboratory (NSCL)
  East Lansing, Michigan
  Michigan State University (MSU)

- Facility for Rare Isotope Beams (FRIB) 2020-2022

- 88-inch Cyclotron
  Berkeley Hills, Berkeley, California
  Lawrence Berkeley National Laboratory (LBNL)

- Association for Research at University Nuclear Accelerators (ARUNA)
  12 institutions
  John D. Fox Accelerator Laboratoty, Florida State University

U.S. participation abroad – Europe

- ISOLDE, CERN radioactive beam facility
  Isotope separation on-line (ISOL) method
  Upgrade to HIE-ISOLDE (higher energy reaccelerated beams)

- SPIRAL, GANIL, Caen (France)
  Grand Accelerateur National d'Ions Lourds
  Upgrade to SPIRAL2 (reaccelerated RIBs)
  ISOL method

- SPES, NLN-INFN, Legnaro (Italy) under construction
  Selective Production of Exotic Species
  ISOL target

- NuSTAR, FAIR, Darmstadt (Germany) under construction
  FAIR: Facility for Antiproton and Ion Research
  Upgrade of existing in-flight program
  Highest energies

U.S. participation abroad

- Asia, in-flight facilities
- Rare Isotope Beam Facility (RIBF), Japan
  RIKEN (Institute of Physical and Chemical Research), Wako, Saitama
- RAON (=joyful, happy) Heavy Ion Accelerator, Korea
  Rare Isotope Science Project (RISP)
  Institute for Basic Science (IBS), Daejeon, Korea
- High Intensity Heavy Ion Accelerator Facility (HIAF), China
  Heavy Ion Research Facility (HIRF), Lanzhou
  Chinese Academy of Sciences (CAS)
- Canada, ISOL facility
  Isotope Separator and Accelerator (ISAC),
  TRIUMF (National Laboratory for Particle and Nuclear Physics), Vancouver
  Advanced Rare Isotope Laboratory (ARIEL) under construction

5. Fundamental Symmetries and Neutrinos

- What are the absolute masses of neutrinos, and how have they shaped the evolution of the universe?
- Are neutrinos their own antiparticles?
- Why is there more matter than antimatter in the present universe?
- What are the unseen forces that disappeared from view as the universe expanded and cooled?

The quest to observe rare nuclear decays

- Standard beta decay: e, v
- Double beta decay: e, e, v, v
- Neutrinoless double beta decay: e, e (v)   0vββ

Consequences:

- Neutrinos are their own antiparticles (Majorana particles)
- The total number of leptons in the universe is not a conserved quantity
- Leptogenesis explanations of the mystery of matter-antimatter imbalance in the universe

Matter over antimatter

- Why is there more matter than antimatter in the present universe?
- The fireball generated during the Big Bang was democratic
- Andrei Sakharov (Nobel prize): Forces in the early universe must have violated certain fundamental symmetries in ways not seen in the Standard Model
- Experimental search for permanent electric dipole moment of neutrons, protons, electrons, and atoms
- Leads to violation of time-reversal symmetry

Facilities for Fundamental Symmetries and Neutrino Physics

- Sanford Underground Research Facility (SURF)
  Lead, South Dakota
  Former Homestake gold mine

- Fundamental Neutron Physics Beamline (FnPB)
  Spallation Neutron Source (SNS)
  Oak Ridge National Lab (ORNL)
  Oak Ridge, Knoxville, Tennessee

- UltraCold Neutron (UCL) facility
  Los Alamos National Lab (LANL)
  Los Alamos, New Mexico

- Fermilab Muon Campus
  Fermi National Accelerator Laboratory
  Batavia, Chicago, Illinois

U.S. participation abroad

- KArlsruhe TRItium Neutrino (KATRIN) experiment, Germany
- Cryogenic Underground Observatory for Rare Events (CUORE), Gran Sasso, Italy
- KaMLAND-Zen experiment, Japan
- SNO+ experiment, SNOLAB, Sudbury, Canada
- Paul Scherrer Institute (PSI), Villigen, Switzerland
- TRIUMF ISAC RIB facility, Canada

6. Theoretical Nuclear Physics

- New investments in computational nuclear theory
- FRIB Theory Alliance
  Facility for Rare Isotope Beams
- Topical Collaborations

  Theory of Reactions for Unstable Isotopes (TORUS)

  Neutrinos and Nucleosynthesis in Hot and Dense Matter (NuN)

  Jet and Electromagnetic Tomography (JET)

7. Facilities and Tools

already presented

8. Workforce, Education, and Outreach

- Undergraduate Research Experience

- National Nuclear Physics Summer School (NNPSS)

  - International Balkan School

- Nuclear Science Outreach to Students and the Public

  - Πάνος Τριγάζης
  - Δήμος Δάφνης, αποπυρηνικοποιημένη περιοχή

9. Broader Impacts – Medicine

- Use of isotopes

  18F in PET imaging, Clinical diagnosis of cancers

  99Mo, source of 99mTc diagnostic isotope

  82Rb monitors lung and heart function

- Alpha emitters for cancer therapy

  223Ra metastatic prostatic cancers in bones

  225Ac metastasized breast cancers

- Proton radiation therapy

  Pediatric cancers, brain tumors, tumors near the spine (high precision)

  7 centers in 2007, 18 centers in 2014 + 17 under construction

Broader impacts – other

- National security
  Cargo inspections, port security screenings
  Integrity of nuclear arsenal, nuclear weapons testing

- Radioisotope dating
  Accelerator Mass Spectrometry (AMS)
  14C, 10Be, 26Al, 129I
  40Ar/39Ar dating rocks and minerals

- Elemental analysis
  PIXE (particle-induced X-ray emission)
  PIGE (particle-induced gamma-ray emission)
  RBS (Rutherford Back Scattering)
  NAA (Neutron Activation Analysis)
  XRF (X-Ray Fluorescence)
  Nondestructive studies in art and archaeology

Broader impacts – other

- Energy

  99 reactors, 20% of electricity demand (2013)

  5 new plants under construction

  12 new plants under active review by the NRC

  (Nuclear Regulatory Commission)

- Accelarator applications

  Purposeful modification of materials

  Semiconductor industry

  Infuse materials with dopants

  Destroying food- and water-borne pathogens

10. Budgets

- Department of Energy
  Office of Science
  Office of Nuclear Physics

- National Science Foundation
  Mathematical and Physical Sciences Directorate
  Physics Division

- Funding scenarios
  Modest growth
  Constant effort

1. Summary and Recommendations

Overarching science questions

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?

Recommendation I

- Completion of CEBAF 12 GeV upgade
- Completion of FRIB (Facility for Rare Isotope Beams)
- Targeted program of fundamental symmetries and neutrino research
- Upgrade RHIC facility
- Use of the two low-energy national user facilities (ATLAS and NSCL) by universities

Recommendations II, III, IV

- Development of U.S.-led ton-scale neutrinoless double beta decay experiment
- Construction of high-energy high-luminosity polarized Electron Ion Collider (EIC) following the completion of FRIB
- Increased investment in small-scale and mid-scale projects that enable forefront research at universities and laboratories

Initiatives

- New investments in computational nuclear theory
- Establishment of national FRIB theory alliance
- Expansion of the successful Topical Collaborations (TC) initiative to a steady-state level of five TC, selected by peer review

Workforce, education, and outreach

- Research Experiences for Undergraduates (NSF-supported)
- Advanced summer schools for graduate students and postdocs, like the National Nuclear Physics Summer School
- Creation of prestigious fellowship program designed to enhance the visibility of outstanding postdoctoral researchers

Μιλήτου άλωσις, 494 π.Χ.

- 490 π.Χ. Θεμιστοκλής, ναυπήγηση στόλου
- Άρνηση ολιγαρχικών (Ίππαρχος, Μεγακλής), συντηρητικών (Αριστείδης)
- Φρύνιχος <<Μιλήτου Άλωσις>>

…εξημίωσαν Φρύνιχον χιλίαις δραχμαίς ως αναμνήσαντα οικεία κακά…