# FUTURE DIRECTIONS FOR NUCLEAR PHYSICS

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*Abstract*

I will summarize opportunities for nuclear science, particularly those given as priority recommendations by the DOE/NSF Nuclear Science Advisory Committee in the 1996 document “Nuclear Science: A Long Range Plan”, and mention selected new initiatives abroad.

## 1 INTRODUCTION

The United States DOE/NSF Nuclear Science Advisory Committee (NSAC) provides advice to the agencies on nuclear science priorities. At approximately six-year intervals, NSAC is charged by the agencies to conduct a new study of scientific opportunities and priorities in U.S. nuclear physics research and to recommend a long rage plan which then becomes the guiding framework for a coordinated advancement of the nation’s basic nuclear physics research program.

In October 1994, NSAC was charged to conduct a new study and formulate a new long range plan (LRP) for nuclear science with realistically achievable goals within budgetary guidelines provided by DOE and NSF. Summarized below are important elements of the planning process, key science opportunities, and NSAC’s main recommendations.

## 2 THE PLANNING PROCESS

The NSAC long range planning process is done in close cooperation with Division of Nuclear Physics (DNP) of the American Physical Society, both in setting up the LRP Working Group and in seeking broad community input via a series of topical town meetings.

These town meetings were organized around six main topics:

- Nuclear Structure, Low Energy Nuclear Reactions, and Radioactive Beams;
- Electromagnetic Physics; Intermediate and High Energy Heavy-Ion Reactions;
- Theory;
- Electroweak Interactions, Astrophysics and Non-Accelerator Experiments;
- Intermediate-Energy and High-Energy Hadron Beams.

Each town meeting was planned by a steering group of widely recognized leaders in the field, who were also responsible for documenting the main findings and recommendations of the town meeting in a white paper.

Subsequent to obtaining this broad community input, in March 1995, the entire LRP Working Group (consisting of 64 scientists) convened for a week of presentations and deliberations at Caltech. The main recommendations for the new LRP were formulated at this meeting. In April 1995, these recommendations, together with an outline of the LRP document, were presented to the nuclear science community at the DNP spring meeting of the American Physical Society, and an interim report containing the main LRP recommendations was transmitted to the agencies.

The final LRP document, “Nuclear Science: A Long Range Plan”, was published in February 1996 and widely distributed to the DNP membership, the U.S. Congress and other interested parties. Apart from discussing major research opportunities for nuclear science and the facilities and resources needed to do this research, the LRP document also addresses important issues concerning education, international collaboration, and interdisciplinary and societal applications.

## 3 NUCLEAR SCIENCE THRUSTS

Nuclear Science is a multi-faceted field of research primarily aimed at understanding how the elementary building blocks of matter interact to form complex mesoscopic systems, nuclei, or macroscopic systems, (neutron) stars, which form the underpinning of the material world as we know it. While much has been learned about nuclei close to the valley of stability and their properties at modest excitation energies, little is known about nuclei very far from the valley of stability or about nuclear matter at sub and supra-normal densities and high temperatures where phase transitions from liquid to gas to quark-gluon-plasma are predicted to take place. Understanding the origin of the elements, i.e. the detailed paths of nucleosynthesis in the cosmos, requires knowledge of the properties of many isotopes with unusual neutron and proton numbers. Detailed investigation of these “exotic” nuclei is becoming possible with newly emerging radioactive beam facilities and innovative experimental techniques. Also little is known about how the quark-structure of nucleons influences the detailed properties of nuclei. These broad (as well as many detailed) questions present major challenges to the field of nuclear science.

Modern nuclear science can be cast into four scientific thrust areas which are described in Chapters I - IV of the LRP document. These four chapters, together with some of the identified research topics, are:

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*1. Nuclear Structure and Dynamics: Exploring the Limits*

- Properties of nuclei far from stability:
  - Limits of nuclear stability.
  - Extended distributions of nearly pure neutron matter.
  - Disappearance of shell structure.
  - Neutron-proton pairing: new form of p-n superfluidity for N=Z nuclei.
  - Proton emitters: tractable examples of three-dimensional quantum tunneling.

- New Aspects of Nuclear Rotation and Vibration:
  - New regions of superdeformation; hyperdeformation?
  - Identical bands in neighboring nuclei.
  - Multi-phonon excitations.
  - New symmetries.
  - Transition from order to chaos.

*2. To the Quark Structure of Matter*

- Quark-Gluon Structure of Hadrons.
  - Origin of the nucleon spin.
  - The role of sea-quarks.
  - Structure of the excited states of the nucleon.
  - Glueballs.

- Hadronic Interactions.
  - Breakdown of meson exchange picture.
  - $\Lambda$–N, $\Delta$–$\Delta$ interaction, hypernuclei.
  - Meson-meson interaction ($\pi^{+}-\pi^{-}$ “atoms”).
  - In-medium modifications.
  - Quark-gluon content of nuclei.
  - Vector meson production, color transparency.

*3. The Phases of Nuclear Matter*

- Liquid-Gas Phase Transition.
  - Multi-fragment disintegration of hot and expanded nuclei.
  - Equation of state and its isospin dependence.
- Quark-Gluon Plasma.
  - Chiral symmetry restoration.
  - Flavor equilibrium and strangeness production.
  - Color deconfinement and J/$\Psi$ suppression.

*4. Fundamental Symmetries and Nuclear Astrophysics*

- Nuclear Astrophysics with Beams of Rare Isotopes.
  - Experimental benchmark tests for theories of nucleosynthesis.
  - Supernovae physics: spin strength of unstable nuclei.
  - Primordial nucleosynthesis of light elements in Big Bang.
- Solar neutrino puzzle, neutrino oscillations.
- Tests of symmetries in weak interactions.

## 4 MAIN LRP RECOMMENDATIONS

In view of these major scientific thrusts, the 1996 LRP made the following priority recommendations:

*1. The highest priority for U.S. nuclear science is vigorous pursuit of the scientific opportunities provided by the nation’s recent investments in forefront instrumentation and facilities. Scientific, technological and educational returns commensurate with these investments will require resources consistent with those in the charge requesting this Long Range Plan.*

*2. RHIC remains our highest construction priority. Its timely completion and operation are of utmost importance for discovery of the quark-gluon plasma and for study of this new form of matter.*

Recommendations for new initiatives are:

*3. The scientific opportunities made available by world-class radioactive beams are extremely compelling and merit very high priority. The U.S. is well-positioned for a leadership role in this important area; accordingly*

- *We strongly recommend the immediate upgrade of the MSU facility to provide intense beams of radioactive nuclei via fragmentation.*

- *We strongly recommend development of a cost-effective plan for a next generation ISOL-type facility and its construction when RHIC construction is substantially complete.*

*4. Multi-GeV proton beams are an essential tool for forefront studies aimed at elucidating the quark structure of nucleons and nuclei.*

- *We strongly recommend funding for the Light-Ion Spin Synchrotron (LISS) as a major NSF research equipment initiative. This facility will build on Indiana University’s leadership in stored, cooled, polarized proton beam technology to enable innovative experiments addressing the short-range behavior of nuclear forces.*

- *The RHIC/AGS complex, in addition to its core heavy-ion program, will offer significant capabilities with hadron beams. In particular, the collisions of polarized proton beams in RHIC will enable unique studies of quark and gluon distributions inside the nucleon. These studies are important for understanding hadron structure and should be pursued.*

Other recommendations address the pressing need for new equipment and support for theory, international collaboration, education and outreach, and interdisciplinary research.

## 5 INTERNATIONAL CONTEXT

The unique opportunities offered by intense beams of rare isotopes ("radioactive beams") are recognized world-wide, and a number of projects are underway or in the advanced stages of planning to provide significant radioactive beam capabilities.

In addition to small-scale ISOL facilities at Louvain-La-Neuve and (more recently) Oak Ridge National Laboratory, a number of new ISOL facilities are under construction, including the SPIRAL project at GANIL ($E_{max}/A$ = 25 MeV, expected completion date: 1998), REX ISOLDE at CERN ($E_{max}/A$ = 2.2 MeV, expected completion date: 1999), and ISAC at TRIUMF ($E_{max}/A$ = 1.5 MeV, expected completion date: 2000).

A major new projectile fragmentation facility has been proposed by RIKEN and approval has been obtained for the first phase, consisting of a superconducting separate-sector cyclotron and a fragment separator. More recently, GSI has been discussing plans for a high-intensity heavy-ion facility for nuclear physics with radioactive beams which would also allow plasma-physics studies pertinent to the problem of inertial-confinement fusion driven by intense beams of heavy-ions.

ISOL-type radioactive beam capabilities are also being considered for the proposed Japanese Hadron Facility (JHF), using the 3 GeV, 200 μA beam from the booster synchrotron. The final beam energy and intensity of the JHF will be 50 GeV and 10 μA, respectively. If funded, the JHF would become the world's premier high-intensity, high-energy hadron facility; funding may be granted as early as 1998.

Well beyond the year 2000, new opportunities for research with ultra-relativistic heavy ion beams will become available at the Large Hadron Collider (LHC). In addition, there is interest in a new high-energy (E > 15 GeV) electron facility for nuclear physics research (possibly at DESY or at CEBAF), but no definitive proposals have been put forward.

## 6 PRESENT U.S. SITUATION

In the past year, the Department of Energy and the National Science Foundation have taken vigorous steps to implement the priority recommendations of the LRP. Positive developments for accelerator-based facilities include:

- Jefferson Lab now operates at the design energy of 4 GeV with experimental programs in all three experimental halls and plans to run experiments at 6 GeV in 1998.
- RHIC construction is proceeding well, and commissioning is expected in 1999.
- With significant funding contributions from Japan, the spin physics program at RHIC will be implemented and incorporated into the base program.
- The NSCL Coupled Cyclotron upgrade has been approved by the National Science Board in 1996, and construction funds have been provided by the NSF in FY97.
- Planning for a full-powered ISOL-type facility is moving ahead vigorously with workshops laying the foundation for a Conceptual Design Report scheduled for the second half of 1997.

In spite of these very positive developments, there is reason for concern. Congress's attempt of balancing the budget by reducing discretionary spending while protecting entitlements has lead to significant reductions in basic research funding. Adjusted for inflation, funding for basic nuclear physics research has decreased 31% for NSF and 5.3% for DOE between 1989 and 1997. Already in 1997, budgets for nuclear physics fall short of the minimum financial resources needed to properly implement the LRP. Nuclear Physics Funding by DOE is $315.9M for FY97, i.e. $9.1M short of the minimum estimate of the LRP. Funding by NSF is $39.81M for FY97, i.e. $5.2M below the minimum estimate of the LRP.

Careful long-term planning and consistent major investments in the past have provided forefront facilities such as the Jefferson Lab and RHIC, as well as a few unique smaller scale research facilities and programs at major universities. Together, these investments form the basis of the U.S. nuclear physics program. Even though the importance of nuclear science and its contributions to the country's technological infrastructure are widely recognized by Congress and the Executive Branch, our scientific and technological leadership in this critical field is now seriously threatened by decreases in funding. Fortunately, the science community is becoming increasingly effective in articulating the importance of basic research to Congress and positive statements by congressional leaders on the importance of science for the nation's well-being are becoming more frequent.