

PHYSICS THROUGH THE 1990s

Nuclear Physics



53-83
N964
cop. 2

PHYSICS THROUGH THE 1990s

Nuclear Physics

Nuclear Physics Panel

Physics Survey Committee

Board on Physics and Astronomy

**Commission on Physical Sciences,
Mathematics, and Resources**

National Research Council

NATIONAL ACADEMY PRESS 2101 Constitution Avenue, NW Washington, DC 20418

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

The Board on Physics and Astronomy is pleased to acknowledge generous support for the Physics Survey from the Department of Energy, the National Science Foundation, the Department of Defense, the National Aeronautics and Space Administration, the Department of Commerce, the American Physical Society, Coherent (Laser Products Division), General Electric Company, General Motors Foundation, and International Business Machines Corporation.

Library of Congress Cataloging in Publication Data

Main entry under title:

Nuclear physics.

(Physics through the 1990s)

Bibliography: p.

Includes index.

1. Nuclear physics. 2. Nuclear physics—Research—United States. 3. National Research Council (U.S.). Nuclear Physics Panel. I. National Research Council (U.S.). Nuclear Physics Panel. II. Series.

QC776.P59 1985 . 539.7 85-10584

ISBN 0-309-03547-3

Printed in the United States of America

PANEL ON NUCLEAR PHYSICS

***JOSEPH CERNY, University of California, Berkeley, and Lawrence
Berkeley Laboratory, *Chairman***

PAUL T. DEBEVEC, University of Illinois, Urbana

ROBERT A. EISENSTEIN, Carnegie-Mellon University

NOÉMIE BENCZER KOLLER, Rutgers University

STEVEN E. KOONIN, California Institute of Technology

***PETER D. MACD. PARKER, Yale University**

R. G. HAMISH ROBERTSON, Los Alamos National Laboratory

STEVEN E. VIGOR, Indiana University

JOHN D. WALECKA, Stanford University

***Member of Physics Survey Committee.**

PHYSICS SURVEY COMMITTEE

WILLIAM F. BRINKMAN, Sandia National Laboratories, *Chairman*
JOSEPH CERNY, University of California, Berkeley, and Lawrence
Berkeley Laboratory

RONALD C. DAVIDSON, Massachusetts Institute of Technology

JOHN M. DAWSON, University of California, Los Angeles

MILDRED S. DRESSELHAUS, Massachusetts Institute of Technology

VAL L. FITCH, Princeton University

PAUL A. FLEURY, AT&T Bell Laboratories

WILLIAM A. FOWLER, W. K. Kellogg Radiation Laboratory

THEODOR W. HÄNSCH, Stanford University

VINCENT JACCARINO, University of California, Santa Barbara

DANIEL KLEPPNER, Massachusetts Institute of Technology

ALEXEI A. MARADUDIN, University of California, Irvine

PETER D. MACD. PARKER, Yale University

MARTIN L. PERL, Stanford University

WATT W. WEBB, Cornell University

DAVID T. WILKINSON, Princeton University

DONALD C. SHAPERO, *Staff Director*

ROBERT L. RIEMER, *Staff Officer*

CHARLES K. REED, *Consultant*

BOARD ON PHYSICS AND ASTRONOMY

HANS FRAUENFELDER, University of Illinois, *Chairman*
FELIX H. BOEHM, California Institute of Technology
RICHARD G. BREWER, IBM San Jose Research Laboratory
DEAN E. EASTMAN, IBM T.J. Watson Research Center
JAMES E. GUNN, Princeton University
LEO P. KADANOFF, The University of Chicago
W. CARL LINEBERGER, University of Colorado
NORMAN F. RAMSEY, Harvard University
MORTON S. ROBERTS, National Radio Astronomy Observatory
MARSHALL N. ROSENBLUTH, University of Texas at Austin
WILLIAM P. SLICHTER, AT&T Bell Laboratories
SAM B. TREIMAN, Princeton University

DONALD C. SHAPERO, *Staff Director*
ROBERT L. RIEMER, *Staff Officer*
HELENE PATTERSON, *Staff Assistant*
SUSAN WYATT, *Staff Assistant*

**COMMISSION ON PHYSICAL SCIENCES,
MATHEMATICS, AND RESOURCES**

HERBERT FRIEDMAN, National Research Council, *Chairman*
THOMAS D. BARROW, Standard Oil Company (Retired)
ELKAN R. BLOUT, Harvard Medical School
WILLIAM BROWDER, Princeton University
BERNARD F. BURKE, California Institute of Technology
GEORGE F. CARRIER, Harvard University
CHARLES L. DRAKE, Dartmouth College
MILDRED S. DRESSELHAUS, Massachusetts Institute of Technology
JOSEPH L. FISHER, Office of the Governor, Commonwealth of
Virginia
JAMES C. FLETCHER, University of Pittsburgh
WILLIAM A. FOWLER, California Institute of Technology
GERHART FRIEDLANDER, Brookhaven National Laboratory
EDWARD D. GOLDBERG, Scripps Institution of Oceanography
MARY L. GOOD, Signal Research Center
J. ROSS MACDONALD, University of North Carolina
THOMAS F. MALONE, Saint Joseph College
CHARLES J. MANKIN, Oklahoma Geological Survey
PERRY L. MCCARTY, Stanford University
WILLIAM D. PHILLIPS, Mallinckrodt, Inc.
ROBERT E. SIEVERS, University of Colorado
JOHN D. SPENGLER, Harvard School of Public Health
GEORGE W. WETHERILL, Carnegie Institution of Washington

RAPHAEL G. KASPER, *Executive Director*
LAWRENCE E. MCCRAY, *Associate Executive Director*

Preface

This volume is the report of the Panel on Nuclear Physics of the Physics Survey Committee, established by the National Research Council in 1983. The report presents many of the major advances in nuclear physics during the past decade, sketches the impacts of nuclear physics on other sciences and on society, and describes the current frontiers of the field. It concludes with a chapter on the recommended priorities for this discipline.

The Panel on Nuclear Physics developed this report through its meetings in May 1983 and January 1984 and through extensive correspondence. We also joined with the Nuclear Science Advisory Committee (NSAC) of the Department of Energy and the National Science Foundation during its week-long Workshop in July 1983, when the major draft of its 1983 Long Range Plan was formulated. Appendix B lists those who attended the Workshop, which included broad participation beyond the members of NSAC or our Panel.

Most of the comments from 11 reviewers (see Appendix B), chosen to provide a representative viewpoint from the nuclear-science community, were incorporated into the manuscript, which was submitted to the National Research Council in May 1984 for further review. Additional comments were subsequently incorporated, and the final manuscript was submitted in August 1984.

Clearly, a comprehensive coverage of the field of nuclear physics would be impossible in a report of this size. Of necessity, only an

overview of selected topics can be given, and the Panel has attempted to maintain a reasonable balance throughout. Although no explicit reference to nuclear chemistry per se is made in this report, we wish to note that nuclear chemists and nuclear physicists are working toward the same goal of understanding the nucleus. They thus have many interests in common and share the same experimental facilities.

The Panel wishes to thank the reviewers as well as the members of the Physics Survey Committee, the Board on Physics and Astronomy of the National Research Council, and a number of other individuals for their help in this task. We wish particularly to thank Fred Raab for his outstanding and invaluable assistance in the technical rewriting and editing of this report.

Contents

	EXECUTIVE SUMMARY	1
1	INTRODUCTION TO NUCLEAR PHYSICS	9
	The Atomic Nucleus, 10	
	The Nuclear Many-Body Problem, 12	
	The Fundamental Forces, 13	
	The Elementary Particles, 16	
	Leptons, 17	
	Quarks, 18	
	Elementary Vector Bosons, 21	
	Conservation Laws and Symmetries, 24	
	Accelerators and Detectors, 28	
	Projectiles and Targets, 28	
	Energies, 30	
	Nuclear Interactions, 32	
	Particle Detectors, 32	
I	MAJOR ADVANCES IN NUCLEAR PHYSICS	
2	NUCLEAR STRUCTURE AND DYNAMICS	37
	Elementary Modes of Excitation, 39	

	Giant Electric Resonances, 40	
	Giant Spin Vibrations, 44	
	Deltas in Nuclei, 45	
	Electron-Scattering Results, 46	
	The Interacting Boson Model, 50	
	Macroscopic Nuclear Dynamics, 52	
	Resonances in Heavy-Ion Systems, 54	
	Deep-Inelastic Collisions, 57	
	The Nuclear Many-Body Problem, 59	
	The Three-Nucleon Nucleus and Infinite Nuclear Matter, 60	
	Properties of Finite Nuclei, 61	
	The Effective NN Interaction at Intermediate Energies, 63	
	Expanding the Traditional Many-Body Theory, 64	
3	FUNDAMENTAL FORCES IN THE NUCLEUS	67
	Nonnucleonic Constituents of Nuclei, 68	
	Probing Quark Structure with Leptons, 70	
	The Physics of Hypernuclei, 73	
	Quantum Chromodynamics at Low Energies, 75	
	The Nucleus as a Laboratory for Fundamental Symmetries, 77	
	Right-Handed Bosons in Beta Decay, 79	
	The Mass of the Neutrino, 80	
	Neutrino Oscillations, 81	
	Double Beta Decay, 83	
	Parity Violation in Nuclei, 85	
4	NUCLEI UNDER EXTREME CONDITIONS . . .	87
	Nuclei at High Temperature and Density, 88	
	High Nuclear Temperatures, 89	
	High Nuclear Densities, 91	
	Nuclear-Matter Equation of State, 92	
	The Heaviest Elements, 94	
	New Transfermium Elements, 94	
	The Search for Superheavy Elements, 96	
	Highly Unstable Nuclei, 97	

- Exotic Radioactivities, 97
 Long Isotopic Sequences, 101
 Nuclei with Extremely High Spin, 102

II IMPACTS OF NUCLEAR PHYSICS

- 5 NUCLEAR ASTROPHYSICS 107
 Nuclei Under Extreme Astrophysical Conditions, 108
 Nucleosynthesis of Light Elements, 108
 Supernova Explosions and Neutron-Star
 Formation, 111
 Weak-Interaction Processes in Supernovas, 113
 Nuclear Reactions in Stars, 114
 The Solar-Neutrino Problem, 115
 Stellar Evolution, 118
- 6 SCIENTIFIC AND SOCIETAL BENEFITS 120
 Condensed-Matter Physics, 121
 Atomic Physics, 124
 Geology and Cosmology, 125
 Nuclear and Radiation Medicine, 127
 Materials Modification and Analysis, 130
 Energy Technology, 131
 The Fine Arts, 134

III CURRENT FRONTIERS OF NUCLEAR PHYSICS

- 7 APPROACHING THE QUARK-GLUON PLASMA 137
 States of Nuclear Matter, 138
 Achieving Quark Deconfinement, 141
 Detecting the Quark-Gluon Plasma, 143
 Additional Relativistic Heavy-Ion Physics, 146
- 8 CHANGING DESCRIPTIONS OF NUCLEAR
 MATTER 150
 Quarks in Nuclei, 151

Mesons and Baryon Resonances in Nuclei, 154
Nuclear Properties Under Extreme Conditions, 156

9 THE ELECTROWEAK SYNTHESIS AND BEYOND 160

The Standard Model, 160
Physics with Neutrino Beams, 162
Testing the Grand Unified Theories, 163
 Time-Reversal-Invariance Violation, 164
 The Electric Dipole Moment of the Neutron, 164
 Rare Muon and Kaon Decays, 165

10 RECOMMENDED PRIORITIES FOR NUCLEAR PHYSICS 169

Accelerators in Nuclear Physics, 170
 Existing Facilities, 171
 The Planned Continuous Electron Beam Accelerator Facility, 172
The Next Major Initiative: The Relativistic Nuclear Collider, 173
 Recommendations from the NSAC 1983 Long Range Plan, 175
 Complementary Aspects of CEBAF and the RNC, 176
Further Recommendations, 178
 Additional Facility Opportunities, 178
 Nuclear Instrumentation, 180
 Nuclear Theory, 181
 Accelerator Research and Development, 181
 Training New Scientists, 183
 Enriched Stable Isotopes, 184
 Nuclear Data Compilation, 185

APPENDIXES

A NATIONAL AND DEDICATED UNIVERSITY ACCELERATOR FACILITIES 189

B ADVISORS AND REVIEWERS 196

BIBLIOGRAPHY	201
GLOSSARY	203
INDEX	215

Executive Summary

NUCLEAR PHYSICS TODAY

Nuclear physics deals with the properties of atomic nuclei, their structure and interactions, and the laws governing the forces between their constituents. The interactions in nuclei have their roots in the interactions of elementary particles, the quarks and gluons that together constitute nuclear matter. But additional dynamical forces, long known to exist in nuclei, cannot be understood with elementary particles alone, just as new cooperative interactions, not recognizable in nuclei or atoms, are known to exist in macroscopic materials.

The basic questions facing nuclear physics today span a broad range, including strong and electroweak interactions, and cover the properties of the physical world from the microscopic scale of nuclear forces to the large-scale structure of the universe. Nuclear physics deals with many-body aspects of the strong interaction. It also deals with tests of fundamental theories and symmetries. Furthermore, nuclear physics plays an important role in the fields of astrophysics and cosmology.

Our understanding of nuclear structure and nuclear dynamics continues to evolve. New simple modes of excitation have emerged, new symmetries are appearing, and some completely new phenomena are being discovered.

In the 1970s, for example, several new modes of vibration of nuclei were discovered, using the technique of inelastic scattering of charged particles from target nuclei. One of these vibrations, the giant mono-

pole, is particularly significant because of its direct relation to the heretofore unmeasured compressibility of nuclear matter. In similar studies using pions as projectiles, important information on the relative roles of protons and neutrons in nuclear vibrations has been gained, as well as that of nucleon excited states called deltas.

The use of high-energy electron scattering from nuclei has revealed unprecedented levels of detail of nuclear structure, in terms not only of the nucleons but also of the mesons present in nuclei and, to a rudimentary degree, of the quarks that compose all of these particles. Such studies represent one of the major frontiers of nuclear physics today.

At the opposite extreme of projectile size, heavy ions have come into increasingly widespread use, particularly as versatile probes of nuclear dynamics. Their massive impact on target nuclei can cause a great variety of excitations and reactions, analyses of which are invaluable for understanding different kinds of motions of the nucleons within a nucleus. Heavy-ion collisions have also been indispensable for producing many exotic nuclear species, including four new chemical elements (numbers 106 through 109) during the past decade.

It is noteworthy that almost all nuclear-physics research to date has been possible only within the very limited domain of nuclei under conditions of low nuclear temperature and normal nuclear density. The vastly greater domain of high-temperature, high-density nuclear physics has just recently begun to be explored, using heavy-ion projectiles at relativistic energies. This too is currently a major frontier of the field.

Inevitably, fundamental new problems arise to challenge our understanding of nuclear physics. For example, although we now know how to explain certain nuclear phenomena in terms of the presence, within nuclei, of mesons in addition to protons and neutrons, we are not yet able to solve the corresponding equations of quantum chromodynamics (the quantum field theory that is believed to govern the manner in which these particles interact) to describe the effects in question.

Current efforts to solve this problem are particularly important because they hold the promise of new insights into one of the fundamental forces of nature, the so-called strong force. Indeed, the nucleus in general represents a uniquely endowed laboratory for investigating the relationships among the fundamental forces as well as the symmetry principles underlying all physical phenomena. Its key role in shaping our view of the cosmos is evident in the field of nuclear astrophysics, which provides information vital to our understanding of the origin and evolution of stars and of the universe itself. On the Earth, meanwhile, nuclear medicine (including the development and use of specifically tailored radioisotopes and accelerator beams for

both diagnostic and therapeutic procedures), nuclear power (both fission and fusion), materials modification and analysis (for example, ion implantation and the fabrication of semiconductor microcircuits), radioactive tracers (used in a number of research areas ranging from geophysics to medical physics), as well as many routine industrial applications (including, for example, well-logging in test bores using miniaturized nuclear accelerators, food preservation by irradiation, and die hardening by ion implantation to reduce wear), and even the analysis of art objects are just a few examples of how the fruits of nuclear-physics research have found a multitude of useful and sometimes surprising applications in other basic sciences and in modern technologies, many of which have direct and significant impacts on society at large.

Much of this research is done with particle accelerators of various kinds. Some studies require large teams of investigators and high-energy accelerators, typically operated by national laboratories, while other, lower-energy studies continue to be performed at colleges and universities—typically by a professor and a few graduate students—using smaller accelerators or laboratory-scale equipment. Both produce fundamental advances in nuclear physics.

This very wide range of facilities and manpower requirements is among the unusual characteristics of nuclear physics. Maintaining the proper balance between the research programs of large and small groups is essential for overall progress in the field. Equally important is the balance between experimental and theoretical research, as well as the availability of state-of-the-art instrumentation and computers for the respective programs.

The major advances of the past decade of nuclear-physics research and the exciting prospects for its future—as well as some of the myriad ways in which nuclear physics has an impact on the other sciences and on society at large—constitute the subject of this nuclear-physics survey.

RECOMMENDATIONS FOR THE FUTURE OF NUCLEAR PHYSICS

In formulating the recommendations for the future of nuclear physics, as presented below, the Panel on Nuclear Physics has profited from extensive interactions between its members and the participants in the 1983 Long Range Planning Workshop of the Nuclear Science Advisory Committee (NSAC) of the U.S. Department of Energy and the National Science Foundation.