FPPNB-2000

Fundamental Physics with Pulsed Neutron Beams

Research Triangle Park, North Carolina, USA 1–3 June 2000

EDITORS

Christopher R. Gould
North Carolina State University, USA

Geoffrey L. Greene
Los Alamos National Laboratory, USA

Frank Plasil
Oak Ridge National Laboratory, USA

William M. Snow
Indiana University, USA

World Scientific
Singapore • New Jersey • London • Hong Kong

Published by

World Scientific Publishing Co. Pte. Ltd.
P O Box 128, Farrer Road, Singapore 912805
USA office: Suite 1B, 1060 Main Street, River Edge, NJ 07661
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

FUNDAMENTAL PHYSICS WITH PULSED NEUTRON BEAMS (FPPNB-2000)

ISBN 981-02-4667-6

Printed in Singapore.

WORKSHOP SUMMARY: FUNDAMENTAL NEUTRON PHYSICS IN THE UNITED STATES: AN OPPORTUNITY IN NUCLEAR, PARTICLE, AND ASTROPHYSICS FOR THE NEXT DECADE

GEOFFREY GREENE, *Los Alamos National Laboratory**
W. MICHAEL SNOW, *Indiana University*
CHRISTOPHER GOULD, *North Carolina State University and TUNL*
FRANK PLASIL, *Oak Ridge National Laboratory*

Conclusions based on the talks and discussions at the FPPNB2000 workshop are described. Low-energy neutrons are of great interest as experimental probes for the study of important questions in nuclear physics, particle physics, and astrophysics. Many precision experiments of the past were limited by systematic uncertainties. Compared to reactor sources, pulsed spallation neutron sources offer significant advantages in improving signal-to-noise ratios and in characterizing energy-dependent systematic uncertainties. The proposed Spallation Neutron Source at Oak Ridge National Laboratory will provide the highest peak flux neutron source in the world and offers the United States scientific community an unmatched opportunity in nuclear, particle, and astrophysics for the next decade.

Low-energy neutrons from reactor and spallation neutron sources have been employed in a wide variety of investigations that shed light on important issues in nuclear, particle, and astrophysics; in the elucidation of quantum mechanics; in the determination of fundamental constants; and in the study of fundamental symmetry violation (Appendix A, Glossary). In many cases, these experiments provide important information that is not otherwise available from accelerator-based nuclear physics facilities or high energy accelerators. An energetic research community in the United States is engaged in "fundamental" neutron physics. With exciting recent results, the possibility of new and upgraded sources, and a number of new experimental ideas, there is an important opportunity for outstanding science in the next decade.

"Fundamental" neutron physics experiments are usually intensity limited. Researchers require the highest flux neutron sources available, which are either high-flux reactors (continuous sources) or spallation neutron sources (pulsed sources). The primary mission of these major facilities is neutron scattering for materials science research. Notwithstanding this condensed matter focus, essentially all neutron scattering facilities have accepted the value of an on-site fundamental physics program and have typically allocated 5 to 10% of their capabilities (i.e., beam lines) toward nuclear and particle physics research activities.

Each experiment in a fundamental neutron physics program uses neutrons in a specific energy regime and a given experiment may or may not be well matched to the characteristics of a particular source. Experiments are distinguished by type of neutron beam that the facility must provide. See Appendix A, *Glossary*, for definitions of ultracold, cold, thermal, and epithermal neutrons, which will be used throughout the report. The neutron beams produced by high-flux reactors and spallation neutron sources differ significantly in their time structure. Particular experiments may be better suited to one source or the other.

Fundamental neutron physics has attracted an energetic community of academic and national laboratory researchers and includes a number of talented younger scientists. A special symposium at the October 1999 Division of Nuclear Physics meeting discussed nine different projects at the National Institute of Standards and Technology (NIST) and at the Los Alamos Neutron Science Center (LANSCE), involving ninety-seven participants from twenty-three different institutions. Activities in the fundamental neutron physics field have not been limited by a lack of interesting projects or a want of enthusiastic researchers but rather by a dearth of neutrons.

The broad range of scientific issues addressed by current experiments in fundamental neutron physics can be roughly placed into five categories as follows:

(1) the nature of time reversal non-invariance and the origin of the cosmological baryon asymmetry,

(2) the nature of the electroweak theory and the origin of parity violation,

(3) the nature and detailed description of the weak interaction between quarks,

(4) the origin of the heavy elements, and other issues in stellar astrophysics,

(5) the detailed investigation of quantum mechanics and precision measurements with neutron interferometry.

The first category, which lies at the heart of modern cosmology and particle physics, includes the search for the neutron electric dipole moment and the search for T-odd correlation coefficients in neutron beta decay ("D-coefficient" and "R-coefficient"). Among the important issues that are addressed by neutron experiments include whether or not the baryon asymmetry of the universe is directly related to fundamental T-violation and whether or not the magnitude of T-violation is consistent with the predictions of the Standard Model.

The second category involves the accurate determination of the parameters that describe neutron beta decay (lifetime and correlation coefficients). Comparison of these results can be used to see whether or not the weak interaction in the charged-current sector is completely left-handed (as it is in the Standard Model) or has right-handed components. These precision measurements can also provide important information regarding the completeness of the three family picture of the Standard

Model through a test of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Neutron beta decay also provides the time scale for Big Bang nucleosynthesis and remains the largest uncertainty in cosmological models that predict the ^{4}He abundance.

Category three involves the study of the weak interaction between quarks in the strangeness-conserving sector. This study is very difficult because of overwhelming direct effects of the strong interaction. As a result, the effective weak couplings in the usual meson-exchange model of the process are poorly known. In fact, different experiments yield contradictory results. Sensitive experiments using polarized cold neutrons to determine parity violation (an unambiguous tag for the weak interaction) in the n-p, n-D, and n-^{4}He systems provide an opportunity to measure NN weak interactions in simple systems that are not complicated by unknown nuclear structure effects. Knowledge of these interactions is required to understand parity violating phenomena in nuclei, such as the recently discovered nuclear anapole moment, and can be used to gain information on quantum chromodynamics (QCD) in the strongly interacting limit.

Category four examines stellar astrophysics and the origin of the heavy elements. Light element nucleosynthesis occurred during the first few minutes of the big bang; however, all isotopes with an atomic mass number greater than seven are created only in stellar processes. Typically, these stellar processes ("r, s, p, etc.") involve competition between neutron capture, which moves isotopes to increasing atomic mass number and beta decay, which increases atomic number. The relative abundances are particularly sensitive to the neutron capture cross sections of radioactive nuclei with lifetimes comparable to s-process time scales (months to years). Intense neutron sources in the few keV energy regime (corresponding to stellar temperatures) provide the only experimental method of obtaining this information.

Neutron interferometry (category five), perhaps the most ideal realization of Schrodinger wave optics, has been employed to elucidate a number of phenomena in non-relativistic quantum mechanics. In addition, neutron interferometry is currently being used to perform precise scattering length measurements, which will eventually improve our knowledge of the electromagnetic structure of the neutron and address the question of nuclear three-body forces. Many important experiments have been suggested, but as the technique is extremely count-rate limited, only a subset of these have been performed. An intense pulsed source offers the possibility of extending these efforts into the study of time-dependent phenomena, opening up a range of new investigations.

Activities in fundamental nuclear physics are focused at a few high-flux facilities in Europe and the United States. The premier facility is the Institut Laue Langevin (ILL) in France, whose reactor is the highest flux continuous neutron source in the world. The ILL has maintained a vigorous program of fundamental neutron physics since the early 1970s and has, in the past, been quite open to foreign scientists. Researchers from the United States have been heavily involved in activities at the ILL since its inception and, indeed, have provided significant leadership in many major experiments. Now, however, there is considerable political pressure on ILL management to require some financial contribution to operations for United States experiments and future access to the ILL for United States researchers should not be taken for granted. The NIST Cold Neutron Research Reactor (with about one-third the power of the ILL) maintains three beam lines for fundamental neutron physics and is the current center of this activity in the United States. The LANSCE Manuel Lujan Jr. Neutron Scattering Center at Los Alamos National Laboratory is the highest peak flux neutron source in the world and supports a variety of nuclear physics activities. An aggressive program of cold and ultracold neutron experiments is in the planning stage at LANSCE.

It is very important to realize that the optimal neutron source for a given experiment will depend upon the details of that experiment. Essentially all the experiments in this program are significantly limited by both statistics and systematic effects. Achieving the highest statistical accuracy requires the highest flux source (i.e., reactors). However, the time structure of a less intense pulsed spallation source affords opportunities to examine systematic effects, which can outweigh the reduction in statistical sensitivity.

At least ten United States led fundamental neutron experiments have reached a sufficient level of maturity to be taken seriously in planning for the next decade. These range from activities that have completed a first-phase measurement to speculative projects that will require extensive research and development before emerging as full-fledged proposals. A thoughtful national program in this area must be based upon a careful review of the scientific merits of each project, a determination of the most appropriate neutron source and, of course, an assessment of the available resources. These resources include not only financial support but also the availability of neutron beams.

With the solidification of the Spallation Neutron Source (SNS) project and the interest by the National Science Foundation in a second, cold neutron, target station, the United States will have an extraordinary opportunity to develop leadership in fundamental neutron physics. United States researchers are now playing important roles in the development of superthermal ultracold neutron sources and in the elaboration of new ideas and techniques to exploit spallation neutron sources for fundamental physics experiments. The purpose of the workshop was to identify whether or not any of these experiments would best be pursued at the SNS.

The conclusion was that a large fraction (perhaps one half) of the experiments discussed would indeed benefit from a spallation neutron source with the intensity and proposed moderator characteristics of the SNS. These experiments include, but are not necessarily limited to, the following categories (*brief comments on the advantages of a pulsed neutron source are included*):

(1) Experiments to measure the weak NN interaction, for example, gamma asymmetry in np and possibly nD capture, neutron spin rotation

measurements in np and possibly nD and n-^{4}He (*A spallation neutron provides time-of-flight information which allows important checks of possible systematic effects*);

(2) In-beam neutron decay experiments that require absolute neutron polarization measurements (A and B coefficients) (*A spallation source provides neutron time-of-flight information which allows polarized ^{3}He neutron polarizers to be exploited in a powerful way*);

(3) Neutron cross section measurements in the keV range on radioactive samples for nuclear astrophysics (*Only spallation sources produce neutrons in this energy regime. Neutron time of flight allows for the resolution nuclear resonances. The increased intensity of the SNS allows the study of interesting radioactive isotopes that are only available as very small samples*).

(4) Measurements with ultracold neutrons (such as neutron beta-decay measurements and the neutron electric dipole moment), which operate in a short-fill, long-counting mode. (*A high peak intensity pulsed source allows for greatly increased higher signal-to-noise ratios and improved understanding of the remaining backgrounds.*)

Although some of these experiments may be done at NIST or LANSCE before the SNS is operational, higher precision than is currently possible at these sources will be required to pursue the physics. In these cases, collaborators will be able to take an already-tested apparatus to the SNS. With many of the "bugs" already worked out of these experiments, the SNS should start to produce important physics results when the facility is turned on.

Besides the availability of neutron sources and beam lines, theoretical support is another important issue that must be addressed for the overall future health of a fundamental neutron physics program. For example, the physics impact of electron scattering experiments at Thomas Jefferson National Accelerator Facility (TJNAF) is obviously strongly influenced by the interchange between TJNAF-supported theorists and experimenters. A mechanism of adequate support for relevant theoretical work in fundamental neutron physics research must be developed.

There is also a question as to whether or not other facilities in the world could compete with the SNS. Both the European Spallation Source and the National Laboratory for High Energy Physics (Japan)/Japan Atomic Energy Research Institute projects, which are both pulsed neutron sources, are still at the proposal development stage and have not yet been approved. A new cold neutron beam line for fundamental neutron physics has just been established at the ILL: this beam would be the most intense in the world and would certainly be the most appropriate beam for certain experiments, although as mentioned above its availability to United

States researchers is uncertain. Another fundamental neutron physics beam line should be established at the new German research reactor in Munich: this facility is primarily intended to serve German researchers. A cold neutron beam line and an ultracold neutron facility based on a solid D_2 moderator are under development at the SINQ continuous spallation neutron source at the Paul Scherrer Institute. Time-reversal violation in neutron beta decay and the neutron electric dipole moment are the first planned experiments at this facility.

The main conclusion of the FPPNB 2000 workshop is as follows: ***In the scientific areas in which fundamental neutron physics measurements have an impact, many important experiments will best be carried out at the SNS.***