Neutrons for Science and Industry - Uppsala Neutron Beam Activities

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Abstract. A wide programme on neutron-induced data for various applications is running at the 20–180 MeV neutron beam facility at the The Svedberg Laboratory, Uppsala. The main research areas are nuclear data for accelerator-driven transmutation of nuclear waste, single-event effects, and dose effects in fast-neutron cancer therapy and aviation environments. In addition, experiments on fundamental nuclear physics are undertaken. Moreover, commercial device testing motivated by single-event effects is a growing activity.

INTRODUCTION

Recently, a large number of applications involving high-energy (> 20 MeV) neutrons have become important. Accelerator-driven systems (ADS) for transmutation of spent nuclear fuel and nuclear weapons materials, fast-neutron cancer therapy, dose effects to the crew onboard aircraft due to cosmic-ray neutrons, as well as electronics failures induced by atmospheric neutrons, have all gotten increasing attention.

This paper outlines experimental activities motivated by the issues above. Briefly, these can be divided into two main categories: measurements of nuclear data, and direct testing, the latter being rapidly growing.

THE NEUTRON BEAM FACILITY

The results presented here were all obtained at the old neutron beam facility at the The Svedberg Laboratory (TSL), Uppsala, Sweden [1, 2], originally designed for high-quality nuclear physics experiments. Recently, a new facility has been commissioned for joint use in nuclear-data measurements and electronics testing, and it is described in a separate contribution to this conference [3].

Neutron Production

At the old neutron facility (see Fig. 1), quasi-monoenergetic neutrons are produced by the reaction $^7\text{Li}(p,n)^7\text{Be}$ in a target of 99.98% $^7\text{Li}$. After the target, the proton beam is bent by two dipole magnets into an 8-m concrete tunnel, where it is focused and stopped in a well-shielded carbon beam dump. A narrow neutron beam is formed in the forward direction by a system of three collimators, with a total thickness of more than four metres.

The energy spectrum of the neutron beam is shown in Fig. 2. About half of all neutrons appear in the high-energy peak, while the rest are roughly equally distributed in energy, from the maximum energy and down to zero. The thermal contribution is small. The low-energy tail of the neutron beam can be reduced by time-of-flight measurements (see Fig. 2). With a proton beam of 5 µA onto a 4-mm lithium target, the total neutron yield in the full-energy peak at the experimental position, 8 m from the production target, is about $5 \cdot 10^8$ cm$^{-2}$s$^{-1}$. The energy resolution of the full-energy peak (1 – 2 MeV FWHM) depends on the choice of lithium target thickness.

FIGURE 1. The TSL neutron beam facility, from [2].


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FIGURE 2. The neutron-energy spectrum with and without time-of-flight rejection of low-energy neutrons, from [2].

FIGURE 3. The MEDLEY facility, showing the scattering chamber and the eight telescopes [4].

Beam intensity monitoring is provided by three techniques. The proton beam intensity is monitored at the beam dump after the neutron production area, providing a relative monitor. Two fission-based neutron monitors are used, a thin film breakdown counter system and an ionization chamber.

**Base Equipment**

Two major experimental setups are semi-permanently installed. One of these is the MEDLEY detector telescope array [4], housed in a scattering chamber and operated in vacuum (see Fig. 3). At the exit of this chamber, a 0.1-mm stainless steel foil terminates the vacuum system, and from here on the neutrons travel in air. Immediately after MEDLEY follows SCANDAL (SCAttered Nucleon Detection AssembLy), a setup designed for large-acceptance neutron and proton detection (see Fig. 4).

The MEDLEY detector array consists of eight particle telescopes, placed at 20-160 degrees with 20 degrees separation. Each telescope is a \( \Delta E - \Delta E - E \) detector combination, with sufficient dynamic range to distinguish all light ions from a few MeV up to maximum energy, i.e., about 100 MeV. The \( \Delta E \) detection is accomplished by fully depleted silicon surface barrier detectors, and CsI(Tl) crystals are used as \( E \) detectors. For some experiments, active collimators are used. These are plastic scintillators with a hole defining the solid angle. All the equipment is housed in a 100-cm-diameter scattering chamber, so that the charged particles can be transported in a vacuum.

Recently, the facility has been used also for fission studies. In that case, the silicon detectors are used for fission-fragment detection.

The SCANDAL (SCAttered Nucleon Detection AssemBlY) setup [2] (see Fig. 4) has been designed for elastic neutron-scattering studies. It consists of two identical systems, placed to cover 10–50\( ^\circ \) and 30–70\( ^\circ \), respectively. The energy of the scattered neutron is determined by measuring the energy of proton recoils from a plastic scintillator, and the angle is determined by tracking the recoil proton. In a typical neutron-scattering experiment, each arm consists of a 2-mm-thick veto scintillator for fast charged-particle rejection, a 10-mm-thick neutron-to-proton converter scintillator, a 2-mm-thick plastic scintillator for triggering, two drift chambers for proton tracking, a 2-mm-thick \( \Delta E \) plastic scintillator that is also part of the trigger, and an array of CsI detectors for energy determination of recoil protons produced in the converter by \( np \) scattering. The trigger is provided by a coincidence of the two trigger scintillators, vetoed by the front scintillator. SCANDAL can also be used as a proton or deuteron detector. In those cases, the veto and converter scintillators are removed.
RESEARCH PROGRAMME

Fundamental Physics

Recently, the \( np \) scattering cross section at intermediate energies has been under intense debate (for a review, see [5]). The \( np \) scattering cross section is of utmost importance for applications because it is used for normalization of nuclear data measurements. It is also of great fundamental importance, because \( np \) scattering data are being used for determination of the pion-nucleon coupling constant, i.e., the absolute strength of the strong interaction in the nuclear sector. This coupling constant is of great relevance not only to basic nuclear physics, but also on a cosmological scale.

Previously, a series of backward-angle \( np \) scattering experiments have been undertaken [6, 7, 8, 9]. Recently, these measurements have been complemented by a measurement at forward angles at 96 MeV [10, 11]. In addition, a novel method to study backward-angle \( np \) scattering by tagging techniques has recently been developed at IUCF, and it is described in another contribution to this conference [12].

A number of experimental observations seem to indicate that three-body forces exist in atomic nuclei. Recent calculations [14] have indicated that measurements of the differential cross section for elastic \( nd \) scattering in the 60–200 MeV range should be useful in searches for three-nucleon (3N) force effects. The neutron-deuteron (\( nd \)) elastic scattering differential cross section has been measured at 95 MeV incident neutron energy. Models based on inclusion of 3N forces describe \( nd \) data in the angular region of the cross-section minimum very well, while models without 3N forces cannot account for the data [15, 16] (see Fig. 6).

Elastic Neutron Scattering

Elastic neutron scattering is of utmost importance for a vast number of applications. Besides its fundamental importance as a laboratory for tests of isospin dependence in the nucleon-nucleon, and nucleon-nucleus, interaction, knowledge of the optical potentials derived from elastic scattering come into play in virtually every application where a detailed understanding of nuclear processes is important. Elastic-neutron scattering is important also for fast-neutron cancer therapy, because the nuclear recoils account for 10%–15% of the dose. Up to now, data on \(^{12}\text{C}\) and \(^{208}\text{Pb}\) at 96 MeV have been published [17, 18] (see Fig. 7), and five other nuclei are under analysis. For a detailed description of the elastic-neutron scattering project, we refer to the contribution to this conference by Hildebrand et al. [19].

A facility for studies of inelastic-neutron scattering has recently been commissioned, and first data taking will soon commence [22].

Light-Ion Production

Light-ion production is of major importance for assessment of the biological effects due to intermediate-energy neutrons (for a review, see, e.g., [23]). About half the dose in fast-neutron cancer therapy comes from \( np \) scattering, 10%–15% from elastic-neutron scattering, and the remaining 35%–40% from neutron-induced emission of charged particles, such as protons, deuterons, tritons, \(^{3}\text{He}\), and \( \alpha \)-particles. Double-differential cross sections for all these reactions in tissue-relevant nuclei are presently being studied with the MEDLEY setup [24].
FIGURE 6. Ratio of the nd and the np cross sections at 95 MeV, as a function of the laboratory angle of the recoiling proton or deuteron [16]. The solid (dotted) line is a cross-section calculation, based on the CD-Bonn nucleon-nucleon potential, without (with) three-nucleon effects included.

FIGURE 7. Angular distributions of elastic-neutron scattering from $^{12}$C (open circles) and $^{208}$Pb (solid circles) at 96 MeV incident energy [18]. The $^{12}$C data and calculations have been multiplied by 0.01. The solid lines represent best fits to the present data, using a parameterization by Koning and Delaroche [20], while the dotted lines are cross sections given by the evaluated nuclear data file ENDF-6 [21].

FIGURE 8. Double-differential cross sections for neutron-induced proton, deuteron, and triton production in iron, lead, and uranium at 96 MeV [25].

Although intended for medical purposes, the requirements from these led to a multipurpose detector design, which has turned out to be useful for many different applications. One of these is hydrogen and helium production in an ADS, exemplified with measurements on iron, lead, and uranium [25] (see Fig. 8). For electronics upsets, silicon has been studied [26] (see Fig. 9), which is described elsewhere at this conference [27].

Fast-Neutron Fission

Although the main fission effects in an ADS arise from neutrons at lower energies, the high-energy neutron fission gives significant contributions to the power released. Very little data exist on high-energy fission, but the situation is undergoing rapid improvement. This can be exemplified by the ongoing work at the TSL neutron beam,
manifested in a number of contributions to this conference [28, 29, 30, 31, 32]. A new facility for studies also of angular distributions is under commissioning [33].

**Neutron-Induced Electronics Failures**

Recently, the importance of cosmic-radiation effects in aircraft electronics has been highlighted. (For reviews on this issue, see, e.g., [34] and references therein. Nuclear data aspects are outlined in [35].) When an electronic memory circuit is exposed to particle radiation, the latter can cause a flip of the memory content in a bit, which is called a single-event upset (SEU). This induces no hardware damage to the circuit, but evidently, unwanted re-programming of aircraft computer software can have fatal consequences.

At flight altitudes, as well as at sea level, the cosmic-ray flux is dominated by neutrons and muons. The latter do not interact strongly with nuclei, and therefore neutrons are most important for SEU.

Since neutrons have no charge, they can only interact via violent nuclear reactions, in which charged particles are created that occasionally induce an SEU. Thus, knowledge of the nuclear interaction of neutrons with silicon is needed to obtain a full understanding of the SEU problem. Firm experimental information about neutron-induced cross sections is very scarce. Thus, one has had to rely heavily on calculations based on nuclear models that have a poor and essentially unknown precision. Measurements of neutron-induced charged particle-production cross sections are therefore of utmost importance for a full understanding of the SEU problem in aviation electronics.

If the neutron-induced charged-particle production cross sections were known, and thus the energy deposition on a microscopic level, it might be possible to calculate the SEU rate with reasonable precision also for any future components. Up to now, direct in-beam component testing has been carried out to characterize the effect, especially its neutron-energy dependence [36, 37].

These studies have been further developed by measurements of cross sections for light-ion production (see above), and experiments at the CELSIUS storage ring on production of heavier ions [38].

**OUTLOOK**

The rapid growth in demand for neutrons has motivated the construction of a new 20 – 180 MeV neutron beam facility at TSL (see Fig. 10). The most important features of the new facility are increased intensity by reduction of the distance from neutron production to experiments, availability of much larger beam diameters, increased versatility concerning various beam parameters such as the shape, and reserved space for a future pulse-sweeping
system.

For nuclear data research, the increased intensity will facilitate a large experimental program at 180 MeV, hitherto excluded by count-rate limitations. For testing of electronics, the increased intensity in combination with a larger beam diameter, which facilitates testing of a large number of components simultaneously, will provide a total failure rate of about a factor 300 larger than for the present facility. This means that the new TSL neutron-beam facility can outperform any existing facility in the world.

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