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Annual Report 2002/2003

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August 2003

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Summary

The project NATT, Neutron data for Accelerator-driven Transmutation Technology, is performed within the nuclear reactions group of the Department for neutron research, Uppsala university. The activities of the group is directed towards experimental studies of nuclear reaction probabilities of importance for various applications, like transmutation of nuclear waste, biomedical effects and electronics reliability. The experimental work is primarily undertaken at the The Svedberg Laboratory (TSL) in Uppsala, where the group has previously developed two world-unique instruments, MEDLEY and SCANDAL.

Highlights from the past year:

- Analysis and documentation has been finalized of previously performed measurements of elastic neutron scattering from carbon and lead at 96 MeV. The precision in the results surpasses all previous data by at least an order of magnitude. These measurements represent the highest energy in neutron scattering where the ground state has been resolved. The results show that all previous theory work has underestimated the probability for neutron scattering at the present energy by 0–30 %.
- A new method for measurements of absolute probabilities for neutron-induced nuclear reactions with experimental techniques only has been developed. Previously, only two such methods have been known.
- One student has reached his PhD exam. Two PhD students have been accepted.
- TSL has decided to build a new neutron beam facility with significantly improved performance for these – and similar – activities.
- A new instrument for measurements of inelastic neutron scattering has been built, tested and found to meet the specifications. This work has been performed in collaboration with two French research groups from Caen and Nantes. The instrument is intented to be used for a series of experiments during the coming years.
- Previous work by the group on nuclear data for assessment of electronics reliability has lead to a new industry standard in the USA.

Sammanfattning

Projektet NATT, Neutrondata för Acceleratordriven Transmutationsteknik, bedrivs inom kärnreaktionsgruppen vid insitutionen för neutronforskning, Uppsala universitet. Gruppens verksamhet är inriktad mot experimentella studier av kärnfysikaliska reaktionssannolikheter för olika tillämpningsområden, som transmutation av kärnavfall, biomedicinska effekter och tillförlitlighet hos elektronik. Den experimentella verksamheten bedrivs huvudsakligen vid The Svedberglaboratoriet (TSL) i Uppsala, där gruppen tidigare utvecklat två världsunika instrument, MEDLEY och SCANDAL.

Höjdpunkter från det gångna verksamhetsåret:

- Analys och dokumentation har färdigställts av tidigare utförda mätningar av elastisk neutronspridning mot kol och bly vid 96 MeV. Precisionen i resultaten överträffar tidigare data med åtminstone en storleksordning. Dessa mätningar representerar den högsta energi i neutronspridning där grundtillståndet kan separeras från exciterade tillstånd. Resultaten visar att samtliga tidigare teorimodeller underskattat sannolikheten för elastisk neutronspridning vid denna energi med 0–30 %.
- En ny metod för att mäta absoluta sannolikheter för neutroninducerade kärnreaktioner med enbart experimentella tekniker har utarbetats. Tidigare är endast två sådana metoder kända.
- En doktorand har disputerat för doktorsexamen. Två nya doktorander har antagits.
- Beslut har fattats vid TSL om att bygga en ny, radikalt förbättrad neutronfacilitet för – bland annat – denna typ av verksamhet.
- Ett nytt experimentinstrument för mätning av inelastisk neutronspridning har byggts, testats och befunnits uppfylla specifikationerna. Detta arbete gjordes i samarbete med två franska forskargrupper från Caen och Nantes. Instrumentet avses att användas för en serie experiment under de kommande åren.
- Gruppens tidigare arbeten inom kärndata för bedömning av tillförlitlighet hos elektronik har lett till en ny industristandard i USA.

Contents

1 Background

1.1 The NATT project

The present project, Neutron data for Accelerator-driven Transmutation Technology (NATT), supported as a research task agreement by Statens Kärnkraftinspektion (SKI), Svensk Kärnbränslehantering AB (SKB), Ringhalsverket AB and Totalförsvarets forskningsinstitut (FOI), started 2002-07-01. The primary objective from the supporting organizations is to promote research and research education of relevance for development of the national competence within nuclear energy.

The aim of the project is in short to:

- promote development of the competence within nuclear physics and nuclear technology by supporting licenciate and PhD students,
- advance the international research front regarding fundamental nuclear data within the presently highlighted research area accelerator-driven transmutation,
- strengthen the Swedish influence within the mentioned research area by expanding the international contact network,
- provide a platform for Swedish participation in relevant EU projects,
- monitor the international development for the supporting organizations,
- constitute a basis for Swedish participation in the nuclear data activities at IAEA and OECD/NEA.

The project is operated by the Department of Neutron Research (INF) at Uppsala University, and is utilizing the unique neutron beam facility at the national The Svedberg Laboratory (TSL) at Uppsala University.

In this document, we give a status report after the first year (2002-07-01–2003-06-30) of the project.

1.2 The former KAT project

Project NATT was preceded by the project KAT (Kärndata för Acceleratorbaserad Transmutation, i.e. nuclear data for accelerator-driven transmutation). The contract on financial support to the KAT project was for four calendar years, during the period 1998-07-01–2002-06-30. Two students were supposed to be educated to PhD exam within the project. Because PhD students cannot be accepted at Uppsala university until full funding has been guaranteed, they were accepted September 1, 1998 (Joakim Klug) and March 1, 1999 (Cecilia Johansson). In addition, they have been involved on a minor fraction of their time in teaching and outreaching activities, paid from other sources.

Thereby, they still had some time left until dissertation for the PhD level at the time when the financial support was terminated. Funding for the remaining time has, however, been reserved, i.e. the total funding is adequate for completing the task. These modifications of the agenda have been presented to and agreed upon by the reference group.

Joakim Klug defended his PhD thesis “Elastic neutron scattering at 96 MeV” at June 6, 2003. Opponent was Dr. Arjan Plompen, EU-JRC Institute for Reference Materials and Measurements, Geel, Belgium. Cecilia Johansson reached licentiate exam in 2002, and is now close to completing her thesis work.

2 Introduction

Transmutation techniques in accelerator-driven systems (ADS) involve high-energy neutrons, created in the proton-induced spallation of a heavy target nucleus. The existing nuclear data libraries developed for reactors of today go up to about 20 MeV, which covers all available energies for that application; but with a spallator coupled to a core, neutrons with energies up to 1–2 GeV will be present. Although a large majority of the neutrons will be below 20 MeV, the relatively small fraction at higher energies still has to be characterized. Above about 200 MeV, direct reaction models work reasonably well, while at lower energies nuclear distortion plays a non-trivial role. This makes the 20–200 MeV region most important for new experimental cross section data /Blomgren, 2002/.

Very little high-quality neutron-induced data exist in this energy domain. Only the total cross section /Finlay et al, 1993/ and the np scattering cross section have been investigated extensively. Besides this, there are data on neutron elastic scattering from UC Davis at 65 MeV on a few nuclei /Hjort et al, 1994/. Programmes to measure neutron elastic scattering have been proposed or begun at Los Alamos /Rapaport and Osborne/ and IUCF /Finlay, 1992/, with the former resulting in a thesis on data on a few nuclei.

The situation is similar for (n,xp) reactions, where programmes have been run at UC Davis /Ford et al, 1989/, Los Alamos /Rapaport and Sugarbaker, 1994/, TRIUMF /Alford and Spicer, 1998/ and TSL Uppsala /Olsson, 1995; Blomgren, 1997/, but with limited coverage in secondary particle energy and angle. Better coverage has been obtained by the Louvain-la-Neuve group up to 70 MeV /Slypen et al, 1994/.

Thus, there is an urgent need for neutron-induced cross section data in the region around 100 MeV, which is an area where very few facilities in the world can give contributions. By international collaboration within an EU supported Concerted Action, which has been followed by the full scale project HINDAS, the level of ambition for the present project has been increased, and the potential of the unique neutron beam facility at The Svedberg Laboratory in Uppsala can be fully exploited.

3 Experimental setup and techniques

3.1 The TSL neutron beam facility

At TSL, quasi-monoenergetic neutrons are produced by the reaction $^{7}Li(p,n)^{7}Be$ in a ^{7}Li target bombarded by 50-180 MeV protons from the cyclotron, as is illustrated in Figure 3-1. /Condé et al, 1990; Klug et al, 2002/. After the target, the proton beam is bent by two dipole magnets into an 8 m long concrete tunnel, where it is focused and stopped in a well-shielded Faraday cup, which is used to measure the proton beam current. 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 consists of a high-energy peak, having approximately the same energy as the incident proton beam, and a low-energy tail. 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 using time-of-flight (TOF) techniques over the long distance between the neutron source and the reaction target (about 8 m).

The relative neutron beam intensity is monitored by integrating the charge of the primary proton beam, as well as by using thin film breakdown counters, placed in the neutron beam, measuring the number of neutron-induced fissions in ^{238}U /Prokofiev et al, 1999/.

Two multi-purpose experimental setups are semi-permanently installed at the neutron beam line, namely MEDLEY and SCANDAL. These were described in detail in the annual report 1999/2000, and only a brief presentation is given here.

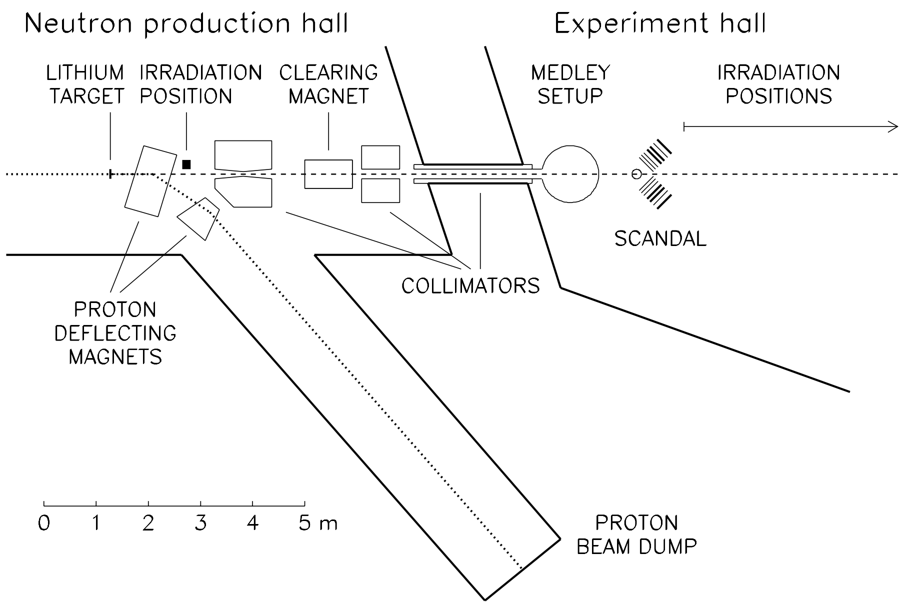

***Figure 3-1**. The TSL neutron beam facility.*

3.2 The MEDLEY setup

The MEDLEY detector array /Dangtip et al, 2000/, shown in Figure 3-2, is designed for measurements of neutron-induced light-ion production cross sections of relevance for applications within ADS and fast-neutron cancer therapy and related dosimetry. It consists of eight particle telescopes, installed at emission angles of 20–160 degrees with 20 degrees separation, in a 1 m diameter scattering chamber, positioned directly after the last neutron collimator. All the telescopes are fixed on a turnable plate at the bottom of the chamber, which can be rotated without breaking the vacuum.

Each telescope is a ΔE–ΔE–E detector combination, where the ΔE detectors are silicon surface barrier detectors with thicknesses of 50 or 60 µm and 400 or 500 µm, respectively, while the E detector is a 50 mm long inorganic CsI(Tl) crystal. ΔE-ΔE or ΔE-E techniques are used to identify light charged particles (p, d, t, 3He, α). The chosen design gives a sufficient dynamic range to distinguish all charged particles from a few MeV up to more than 100 MeV.

The solid angle of the telescopes is defined by active collimators, designed as thin hollow plastic scintillator detectors, mounted on small photomultiplier tubes. A signal from such a detector is used to veto the corresponding event, thereby ensuring that only particles that pass inside the collimator are registered.

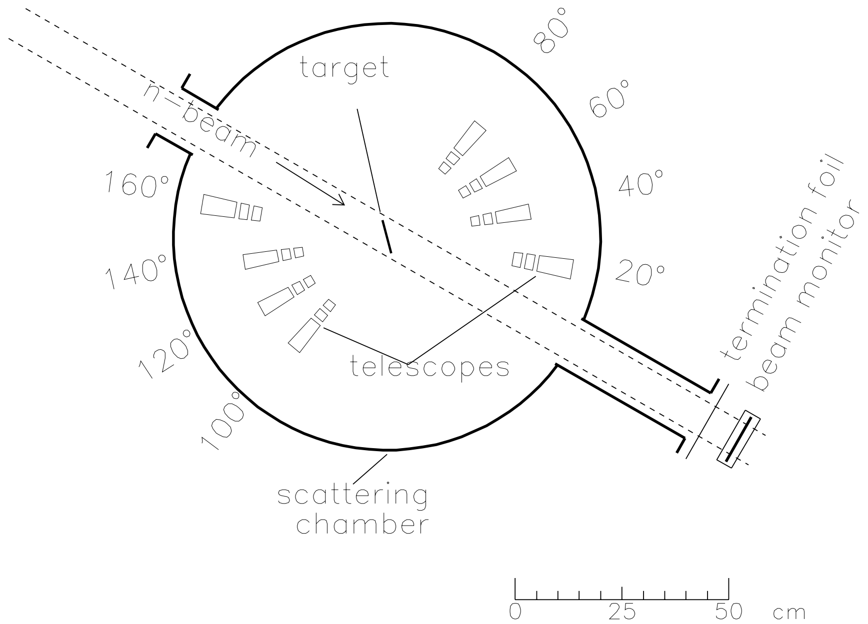

***Figure 3-2**. The MEDLEY setup.*

3.3 The SCANDAL setup

The SCANDAL setup /Klug et al, 2002/ is primarily intended for studies of elastic neutron scattering, i.e. (n,n) reactions. Neutron detection is accomplished via conversion to protons by the H(n,p) reaction. In addition, (n,xp) reactions in nuclei can be studied by direct detection of protons. This feature is also used for calibration, and the setup has therefore been designed for a quick and simple change from one mode to the other.

The device is illustrated in Figure 3-3. It consists of two identical systems, in most cases located on each side of the neutron beam. The design allows the neutron beam to pass through the drift chambers of the right-side setup, making low-background measurements close to zero degrees feasible.

In neutron detection mode, each arm consists of a 2 mm thick veto scintillator for fast charged-particle rejection, a neutron-to-proton converter which is a 10 mm thick plastic scintillator, a 2 mm thick plastic scintillator for triggering, two drift chambers for proton tracking, a 2 mm thick ΔE plastic scintillator, which is also part of the trigger, and an array of 12 large CsI detectors for energy determination. The trigger is provided by a coincidence of the two trigger scintillators, vetoed by the front scintillator. The compact geometry allows a large solid angle for protons emitted from the converter. Recoil protons are selected using the ΔE and E information from the plastic scintillators and the CsI detectors, respectively.

The energy resolution is about 3.7 MeV (FWHM), which is sufficient to resolve elastic and inelastic scattering in several nuclei. The angular resolution is calculated to be about 1.4 degrees (rms) when using a cylindrical scattering sample of 5 cm diameter.

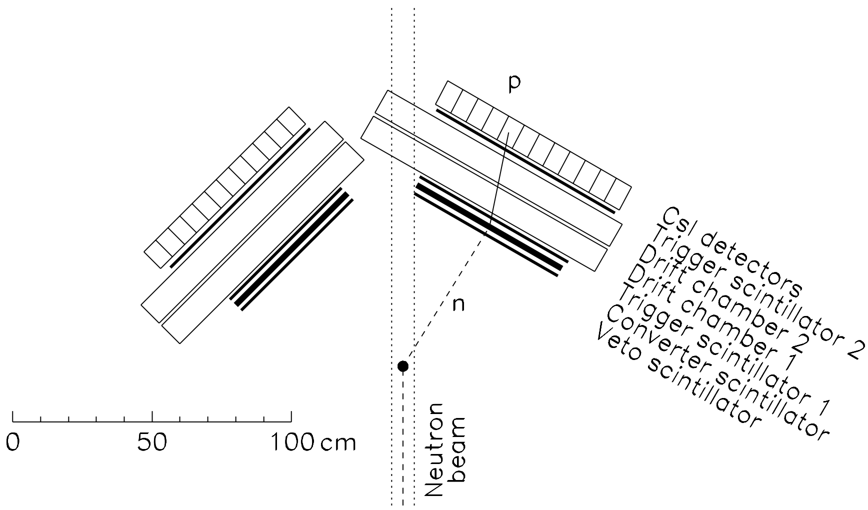

***Figure 3-3**. The SCANDAL setup.*

When SCANDAL is used for (n,xp) studies, the veto and converter scintillators are removed. A multitarget arrangement can be used to increase the target content without impairing the energy resolution, which is typically 3.0 MeV (FWHM). This multitarget box allows up to seven targets to be mounted simultaneously, interspaced with multi-wire

proportional counters (MWPC). In this way it is possible to determine in which target layer the reaction took place, and corrections for energy loss in the subsequent targets can be applied. In addition, different target materials can be studied simultaneously, thus facilitating absolute cross section normalization by filling a few of the multitarget slots with CH2 targets. The first two slots are normally kept empty, and used to identify charged particles contaminating the neutron beam.

3.4 New neutron beam facility at TSL

The rapidly increasing number of neutron beam users has motivated a new facility to be built. The overall design has been agreed upon, and at present details of the individual components are being designed. Practical work has begun during spring 2002, which includes re-building of beam line magnets, removal of obsolete heavy equipment and procurement of concrete for the new shielding walls. The experimental programme will face a down-period during autumn 2003 to allow for major installations.

4 Results

4.1 Elastic scattering

The analysis of the data on elastic scattering from ^{12}C and ^{208}Pb has now resulted in final data. A preliminary angular distribution of neutrons scattered from carbon and lead is shown in Figure 4-1. For a full account of these data, see appendix III and /Klug et al, 2003/.

The final resolution is about one order of magnitude better than for any previous experiment in this energy range. In fact, the present experiment represents the highest energy, 96 MeV, at which resolved elastic scattering has been accomplished. The previously highest energy is 65 MeV, so the movement of the limit is significant (50 %). The data show that all theory models existing before the experiment underpredict the data by 0–30 %, which obviously has some influence on the design of the neutronics of accelerator-driven systems. Last but not least, this experiment allowed a novel technique for purely experimental measurements of absolute neutron-induced cross sections to be developed. This is noteworthy, since only two such techniques have existed up to now.

A one-week experiment was performed in August 2002 with SCANDAL on neutron scattering from yttrium and deuterium. The yttrium data, aiming at an improved understanding of neutron interaction with transmutation-relevant elements (yttrium is a substitute for zirconium) is being analyzed by Angelica Hildebrand, while the deuterium data, aiming

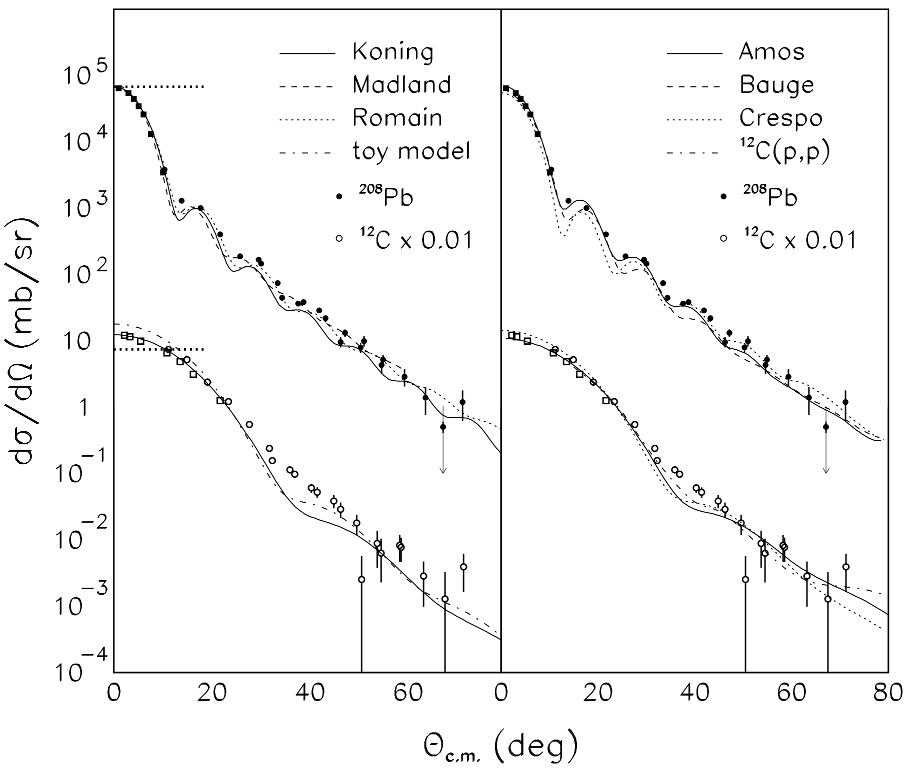

Figure 4-1*. The ^{12}C and ^{208}Pb elastic neutron scattering cross sections at 96 MeV. For details, see appendix III and /Klug et al, 2003/.*

at a general understanding of many-body effects in neutron scattering, is being analyzed by Philippe Mermod. Additional experiments on deuterium were performed in October 2002 as well as in February and March 2003. In the letter two runs, a Japanese research group participated, and in November 2002, four group members participated in an experiment in Osaka, Japan, on neutron-deuterium scattering.

4.2 (n,xlcp) reactions

In parallel with the other experiments mentioned above and below, data were taken with the MEDLEY setup on light-ion production reactions. During the last year, these measurements have been concentrated on providing improved statistics on already existing data sets.

4.3 (n,xn) reactions

We have a collaboration project with a group from Caen, france, on (n,xn) reactions. For these studies, a modified SCANDAL converter (CLODIA) has been designed and built in Caen. A series of test runs have lead to a final design, which was commissioned in beam in March 2003. Data are under analysis, aiming at a publication. A series of experiments is planned for the coming few years.

4.4 Tagged neutron-proton scattering

Neutron-proton scattering is the reference cross section for fast-neutron reactions, i.e. it is the standard which all other cross sections are measured relative to. Experimental studies of this cross section have been undertaken at TSL as part of the present project, and they will form a major part of the thesis by Cecilia Johansson. We have also been involved in a similar experiment at Indiana University Cyclotron Facility (IUCF), Bloomington, Indiana, USA. A large paper on the technical aspects of the project has been accepted for publication by Nuclear Instruments and Methods A (appendix V), and the results have been presented at an international conference (appendix VI).

4.5 Fission

We are working on the development of a setup for fission studies, based on MEDLEY in a revised geometric configuration. In November 2002, this facility was tested and in April 2003, data for publication were taken on fission cross sections and fragment angular distributions. One interesting feature of the new setup is that it allows a prices determination of the absolute cross section by measuring np scattering simultaneously. This is important, since only one previous experiment on high-energy fission has been performed with a reasonably good control of the absolute scale.

5 International activities

5.1 Collaboration

INF participates in the EU project HINDAS (High- and Intermediate Energy Nuclear Data for Accelerator-Driven Systems), which involves 16 European institutions from Belgium, France, Germany, The Netherlands, Spain, Sweden and Switzerland. The experimental work is performed at six European laboratories (UCL in Louvain-la-Neuve, TSL in Uppsala, KVI in Groningen, PSI in Villigen, COSY at Jülich and GSI in Darmstadt). Work on the theoretical interpretation of the experimental results is also included. The project, which started 2000-09-01 and runs over three years, is coordinated by Professor Jean-Pierre Meulders, Louvain-la-Neuve, Belgium.

HINDAS has a total budget of 2.1 MEUR, whereof 210 kEUR falls on the Uppsala partner, while the collaborators that use the TSL neutron facility have received in total about 500 kEUR. Most of the money is intended for PhD students or postdocs. This means an increasing engagement for the Uppsala group and TSL, but also more focus on the activities here.

To our judgement, HINDAS has been well organized and focused. It involves a major part of the competence and equipment available in Europe, and will also contribute to the development of nuclear data activities in Europe, by bringing new scientists into this area. At present, there are discussions about possible nuclear data activities in the upcoming 6^{th} framework program.

5.2 Meetings and conferences

Nils Olsson has taken on duty as Swedish representative in the OECD/NEA Nuclear Science Committee (NSC) and its Executive Group. Notes from the meetings are enclosed in appendix VII–VIII.

6 Administrative matters

6.1 Staff and students

During the project year, Jan Blomgren has been project leader. Stephan Pomp has worked full time within the project with research and student supervision. During the year, he got a new position as assistant professor (forskarassistent), starting July 1, 2002. Nils Olsson, former project leader and now research director at FOI, is active within the project on a part-time basis (20 %). Michael Österlund, associate professor (högskolelektor) at Jönköping university, has been active as part-time supervisor. Starting July 1, 2003, he will be permanent staff member of the group (universitetslektor). Leif Nilsson, retired professor, has been employed by the group on 10 % time for student supervision. Finally, Valentin Corcalciuc, professor in Bucharest, Romania and Louvain-la-Neuve, Belgium, has filled a vacancy during a parental leave by Stephan Pomp.

Two PhD students are directly connected to and financed by the present project, Angelica Hildebrand and Philippe Mermod, which both are connected to the research school AIM (Advanced Instrumentation and Measurements). The KAT PhD students, Cecilia Johansson and Joakim Klug, are discussed separately. Two other students, Bel Bergenwall who is financed by AIM, and Udomrat Tippawan with a scholarship from Thailand, have tasks strongly related to the present project, and especially to the line of development emerging from the collaboration with the French groups within HINDAS.

During the year, an agreement has been reached between INF and Kärnkraftsäkerhet och Utbildning AB (KSU), which is an education company owned and operated by the nuclear power industry. INF will provide courses aiming at improved understanding of the physics of nuclear power for a six-year period, 2003–2009. INF has recruited two associate professors (universitetslektorer) for this project, one of them being Michael Österlund mentioned above.

Members of our group participate in several courses on nuclear physics as well as on energy technology. Some of these include problems related to transmutation. Also a number of outreach talks, seminars, articles and interviews related to this project have been given.

6.2 Reference group

Reference group meetings, with participation by Per-Eric Ahlström (SKB), Benny Sundström (SKI), Thomas Lefvert (Vattenfall AB), Fredrik Winge (BKAB) and Anders Ringbom (FOA), were held in Uppsala 2002-10-31 and 2003-05-16. Katarina Wilhelmsen Rolander has recently replaced Anders Ringbom as FOI contact person. Scientific and administrative reports on the progress of the project were given at these meetings.

In addition to the meetings, the progress of the work has continously been communicated to the reference group members by short, written, quarterly reports.

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Appendix I

Radiation Protection Dosimetry
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BEYOND KERMA — NEUTRON DATA FOR BIOMEDICAL APPLICATIONS

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INVITED PAPER

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Abstract — Presently, many new applications of fast neutrons are emerging or under development, like dose effects due to cosmic-ray neutrons for airplane crew, fast-neutron cancer therapy, studies of electronics failures induced by cosmic-ray neutrons, and accelerator-driven incineration of nuclear waste and energy production technologies. All these areas would benefit from improved neutron dosimetry. In this paper, the present rapid progress on measurements of double-differential neutron-induced nuclear reaction data are described. With such data at hand, the full response of, in principle, any system, including human tissue, can be calculated in detail. This could potentially revolutionise our understanding of biological effects in tissue due to fast neutrons.

INTRODUCTION

Recently, a large number of applications involving high-energy (>20 MeV) neutrons have become important. It has been established during recent years that air flight personnel receive among the largest radiation doses in civil work, due to cosmic-ray neutrons[1,2] Cancer treatment with fast neutrons is performed routinely at several facilities around the world, and today it represents the largest therapy modality besides the conventional treatments with photons and electrons. For a review of this field, see, for example, Reference 3.

When a body is irradiated with charged particles, like electrons, protons or ions, the dose, i.e., the energy released per unit volume, is deposited directly by ionisation along the particle track. When uncharged particles are used, like photons or neutrons, an additional step is needed, i.e., the conversion of the kinetic energy of the incident uncharged particle to charged particles within the volume. This takes place by the interaction of the uncharged particles with the atoms or atomic nuclei in the tissue, resulting in charged particles being released. After having been released, these secondary charged particles deposit energy along their tracks, resulting in tissue damage.

When comparing photons and neutrons as primary particles, there is one striking difference. Photon interactions result almost exclusively in release of electrons, while neutrons induce emission of several different types of charged particles, such as protons, deuterons, alpha particles and heavier ions. This means that a fundamental understanding of the effects in tissue due to neutrons require knowledge of processes at two stages. First, the probability for neutrons to create charged particles must be known, and this information has to be detailed, i.e., the particle type, its energy and direction has to be known. Second, the biological effect of this secondary particle at its energy must be known.

It is well known that the effect of a certain dose, i.e., a given deposited energy, can be very different for different types of particles in a biological system. As an example, the cell survival rate for 1 Gy of electrons or 1 Gy of alpha particles, both at 5 MeV, differs by an order of magnitude. This is caused by the very different ionisation densities, which affect the cell damage, and the possibilities for the cell to repair the damage. Thereby, the same dose given in, e.g., electron and neutron therapy can result in rather different biological effects.

Today, the biological effects of the various charged particles released after neutron interaction in the most common atomic nuclei in tissue are relatively well known. Thus, the second stage above is under reasonable control. What is not equally well known is the first stage, i.e., the microscopic cross sections for creation of charged particles.

Because of the complexity and poor knowledge of the interaction processes between neutrons and nuclei, the existing dosimetry methods and treatment techniques are to a large extent based on integral quantities and experience, rather than on knowledge of detailed fundamental physics. Due to the recent development of neutron beams with good intensity and energy resolution, it is today possible to study all the fundamental processes involved in detail, and thus dramatically

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improve both the dose determination in neutron fields and the radiation quality planning in connection with tumour therapy.

The purpose of this paper is to describe the currently rapid progress on measurements of double-differential neutron-induced nuclear reaction data. Such experimental data are most useful to guide the theoretical models that are used to produce cross section databases. With such databases of high quality at hand, the full response of, in principle, any system, including human tissue, can be calculated in detail. This could in the future allow a fully reductionistic approach to the entire problem of understanding the biological effects due to neutron radiation.

In the relevant energy range (up to about 70 MeV for therapy and even higher for aviation doses), it is unfortunately difficult to describe nuclear processes theoretically in a simple way. Compound nuclear processes, direct processes and intermediate or pre-compound processes are all important and nuclear reaction models must take into account all these processes and, where appropriate, the competition between them. As a result, predictions based on theory are sometimes uncertain to 50% or more. Such uncertainties are far larger than acceptable in, e.g., a treatment situation.

This situation is different in photon and electron interaction with tissue, which is governed by the well-known electromagnetic interaction, in which theory predictions of cross sections can be made with an accuracy of far better than 1%, i.e., other uncertainties dominate. If cross sections cannot be computed, they have to be measured, but the database for neutrons is meagre in this energy region.

In the case of photon and electron interaction, the cross sections vary rather smoothly with energy and atomic number, making interpolations fairly reliable when data are unavailable. This is not the case for neutron-induced reactions. Cross sections can vary dramatically for different isotopes of the same element in a seemingly random fashion in the relevant energy range.

This situation implies that all relevant cross sections on all relevant nuclei have to be measured in reasonably narrow incident energy steps. Fortunately, the number of important nuclei in tissue is small and the nuclear reactions which give significant contributions are also relatively few, as will be further discussed below.

Most of the evaluated databases were compiled to be used in the development of nuclear fission and fusion energy sources and do therefore have a 20 MeV upper energy limit. The lack of extensive databases at higher energies makes it difficult to estimate correctly the dose given by neutrons using computational methods. A substantial improvement in the knowledge of fundamental nuclear data is therefore needed for a better understanding of the processes occurring on a cellular level.

High-energy neutrons are also of primary importance in other applications. Recently, the importance of cosmic radiation effects on aircraft electronics has been highlighted. (For reviews, see, e.g., References 4–6 and references therein). 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.

A potentially large future area of applications of high-energy neutrons is transmutation of nuclear waste*. There is intense international research on accelerator-driven neutron spallation sources coupled to reactor cores for incineration of spent nuclear fuel. If this technique becomes a reality, it will require thorough investigations of the dose effects due to the very energetic neutrons (up to 1–2 GeV) involved in the concept.

All the areas above are of interest from a dosimetry point of view. For the applications involving tissue, it is evident that techniques for dose determinations are of great importance. Concerning electronics effects on board aircraft, there is a need for light and inexpensive neutron intensity monitors, similar to the dosemeters used for estimation of health effects.

In this paper, techniques for development of dosimetry for high-energy neutrons are discussed. Some concepts used when linking fundamental physics and macroscopic tissue effects are outlined, and which data are of importance is discussed. Techniques to produce neutron beams are presented, and a survey of such facilities is given. As an example, the Uppsala neutron beam facility, together with an experimental set-up for double-differential cross section measurements, are also described in some detail.

LINKS BETWEEN FUNDAMENTAL PHYSICS AND TISSUE EFFECTS

Kerma

Like X and gamma rays, neutrons exert their biological effect through secondary charged particles, but whereas photons interact with atomic electrons, neutrons interact with nuclei and the secondary particles are nuclear particles such as protons, deuterons, alpha-particles and heavier nuclear recoils. Evidently, a neutron transfers its energy to tissue in two stages. The first stage involves the interaction of a neutron with a nucleus, which can result in a wide range of secondary charged particles. The second stage involves the transfer of energy from secondary charged particles to tissue through excitation and ionisation. The quantity kerma, an acronym for Kinetic Energy Released in MAtter, is used to describe the initial interaction, i.e., the first stage. It corresponds to the kinetic energy released by

*For an introduction to this topic see, for example, www.neutron.kth.se and links from this site.

the primary neutrons per unit mass in the form of secondary charged particles. Furthermore, the kerma coefficient is the kerma per unit neutron fluence*[7].

Dose is defined as energy absorbed per unit mass from the secondary charged particles, i.e., the second stage. Thus, the concepts of kerma and dose are not identical, because the secondary particles have a certain range and deposit their energy predominantly downstream of their point of origin. The secondary charged particles are preferentially emitted in the forward direction, which means that the dose is low at the surface and rises with depth towards the range of the charged particles. Kerma, on the other hand, does not rise but falls slowly with depth as the incident beam is attenuated[8]. In photon dosimetry, kerma is a more directly useful quantity than for neutrons[9], since the difference between kerma and dose is smaller in this case.

It is important to emphasise that in neutron dosimetry, the kerma coefficient is only a measure of how much energy per unit fluence is given to light charged particles and residual nuclei in a certain volume, regardless of the nature of and energy spectrum of the secondary particles. Since the biological response varies dramatically with ionisation capability, i.e., the particle type and energy, the same kerma or dose does not necessarily correspond to the same damage (see below).

There are two ways kerma coefficients are determined: from direct calorimetric measurement of kerma, and from calculation of kerma coefficients from basic nuclear cross sections. Direct measurement of kerma coefficients can be difficult and values are available only for a few elements and neutron energies. Moreover, such measurements require total particle equilibrium in the studied volume. This is not always the case in practice, which necessitates significant corrections. Calculation of kerma from basic nuclear data requires information on all significant reaction channels, including angular and/or energy distributions of secondary reaction particles, which have to be explicitly represented. Such information is taken from nuclear data libraries, which normally are obtained by evaluation of experimental microscopic cross sections and nuclear model predictions.

The relation between the microscopic nuclear cross sections and the kerma coefficient, k_Φ, is

$$k_\Phi(E_n) = N\,\Sigma_i \int E \int (d^2\sigma_i(E_n)/d\Omega dE)\, d\Omega dE$$

where N is the number of nuclei per unit mass, the index i represents the charged-particle type, e.g., proton, deuteron, triton, ^{3}He, etc., E is the energy of the secondary charged particle and $d^2\sigma_i(E_n)/d\Omega dE$ is the double differential cross section at neutron energy E_n.

*A definition can be found in ICRU 60, *Fundamental Quantities and Units for Ionizing Radiation* (1998).

Radiation quality

Different types of ionising radiation cause different tissue damage, in spite of the same energy being deposited. This is primarily due to the fact that the cell damage proceeds via two mechanisms, namely creation of free radicals and DNA strand breaks.

In the first mechanism, molecules in the cell are being ionised and become chemically much more reactive, which affects the cell chemistry and metabolism. This requires very little energy transfer, of the order of a few eV, and whether the creation of these reactive chemical elements is well localised or more diffuse does not make a very large difference. Instead, the total number of created reactive elements is most important, and thus the total deposited energy per unit mass gives a reasonable estimation of the cell damage. Thus, which type of particle causes the ionisation is not very crucial.

In the second mechanism, the ionising radiation breaks the DNA molecule and thereby disturbs the cell reproduction. This damage is much more efficient if both strands are struck close to each other. If just one strand is broken, the remaining one can often be used in the repair process. Thus, this mechanism is more efficient for radiation with large ionisation per unit length, i.e., well localised radiation. This argument points towards relatively heavy ions, like alpha particles, which have a much larger ionisation per unit length than, e.g., electrons.

Ionisation per unit length is often expressed in terms of linear energy transfer (LET), commonly quantified in keV μm^{-1}. The 'biological effectiveness' is related to LET, but not linearly. The lowest LET radiation is due to photons and electrons. The biological effect increases with increasing LET, until a maximum is reached at about 200 keV μm^{-1}. Going to even higher LET makes the effectiveness go down again, simply because a cell cannot be killed more than once, no matter how much localised dose is given.

Since high-energy neutrons produce a multitude of secondary particles, from high-energy protons, with relatively low LET, to low-energy alpha particles and heavier recoils, which have very high LET, the damage caused by such neutrons is a complicated function of the delivered energy, or kerma.

Beyond kerma

As mentioned above, the kerma coefficient is the average energy transferred from neutrons to charged particles (including recoils) per unit mass of material per unit neutron fluence. It is widely used for dosimetry in neutron therapy and radiation protection. Where applicable, mostly in the low-energy region, kerma coefficients can be directly measured. This is the reason why the kerma concept is being used; it allows a determination of the dose even if microscopic cross sections are unavailable. Alternatively, one can calculate kerma coefficients from microscopic nuclear data. A comparison of the calculated and the measured kerma coefficients provide a valuable integral test of the microscopic cross section data.

However, what is of more interest, especially in a treatment-planning situation, is the absorbed dose in the treatment volume, including all aspects playing a role, e.g., ionisation density and oxygen abundance. Although kerma coefficients could be used for a rough estimate of the biological effect, there is no simple relation between kerma and cell damage.

In addition, such a calculation is not performed from first principles. The whole kerma concept could actually be omitted by calculating the biological effect in a specific volume directly by, e.g., a Monte Carlo radiation transport code. Such an approach can be described in a simple manner as follows. For each neutron, the type of nucleus with which the neutron is about to interact, is chosen based on the total cross sections. Particle emission (e.g., alpha, gamma, neutron, proton or a heavy particle) is sampled based on the total particle production cross sections. Given the particle type, the emission angle and energy of the particle is chosen on the basis of double-differential data. Finally, the secondary particle is followed until its energy is lower than a predefined threshold, or it escapes the volume of interest, or initiates a new nuclear reaction. When this transport phase is completed, the energy, which the various particles deposit in the volume of interest, is converted to absorbed dose. In this last step, it would be possible also to take the biological effects of the various particles involved into account. The accuracy of the calculated dose evidently depends on the quality of the atomic and nuclear data used for the sampling, and also on the quality of the transport scheme, the statistical accuracy of the requested calculation and the description of the external radiation source. An example of such an approach is the all-particle transport Monte Carlo code PEREGRINE[10], developed at Lawrence Livermore National Laboratory, and used for radiotherapy dose calculations.

Such a method is not only useful for dose estimates in tissue, but also in, e.g., detectors. Actually, such techniques have been used in detector simulations for a long time, especially in nuclear and particle physics, and some of the modern all-particle transport Monte Carlo codes now being developed for dose calculations are partly built on detector simulation codes. With relevant data at hand, the performance of dosemeters can be calculated, which could be of great benefit to the development of new dosimetry techniques.

Finally, it should be pointed out that double-differential cross sections contain much more information than kerma. Kerma can be obtained by integrating double-differential cross sections over all ejectile energies and angles, but in this process, valuable information is lost. For instance, it is possible that two reactions give the same kerma, but significantly different tissue damage, because different particles are released, or energy or angular distributions can be different. On the other hand, knowledge of kerma does not allow double-differential cross sections to be determined. With the rapid development of computing power and numeric methods, we expect full Monte Carlo modelling of radiation effects to become the standard tool in the future, and that estimations based on kerma might gradually become less important.

It is likely, however, that there will still be a need for relatively simple dose determinations in some practical applications. In such cases, an ionisation chamber measurement and a fluence-to-kerma conversion coefficient has a great practical advantage. Nevertheless, if this conversion factor could also be computed from microscopic cross sections, the whole procedure would gain confidence.

WHICH DATA ARE IMPORTANT?

About half the dose in human tissue due to neutrons of several tens of MeV comes from proton recoils in neutron–proton (np) scattering, 10–15% from nuclear recoils due to elastic neutron scattering and the remaining 35–40% from neutron-induced emission of light ions, i.e., protons, deuterons, tritons, ^{3}He and alpha particles. With double-differential cross sections for all these reactions in tissue-relevant nuclei, i.e., carbon, nitrogen, oxygen and calcium at hand, the dose distribution could be calculated in detail.

A coordinated research programme (CRP), organised by the IAEA, expressed that, with the exception of hydrogen, sufficiently accurate data for use in fast neutron therapy do not yet exist to allow neutron therapy to reach its full potential[11,12]. High priority was given by the CRP to new measurements of double-differential charged-particle production cross sections and kerma coefficients for the most important elements in tissue, i.e., carbon, oxygen, nitrogen and calcium. Similar needs have repeatedly been emphasised[13,14]. Such data are important to validate evaluations, in which complete sets of data are obtained by combining experimental and theoretical information. The most recent evaluation[7,15] can be considered as state-of-the-art in this context.

If it is clear which data are of most importance when determining the dose in human tissue, it is less obvious which cross sections to determine for improving dosimetry. Many different nuclear reactions are employed in dosemeters. This also involves reactions not taking place in tissue. An example is fission in bismuth, which has some nice features for dosimetry of high-energy neutrons. The cross section is very small all the way up to about 50 MeV, so it is very useful for dosimetry of high-energy neutrons in a low-energy neutron background. Fission is a good nuclear reaction for simple and portable equipment, because it releases extremely large energy per reaction, making the detection of it relatively unambiguous. With the presently rapidly increasing interest in dose effects in human tissue due to high-energy neutrons, we would like to advocate a coordinated research programme spanning the border between dosimetry and nuclear physics, to establish a priority list over which nuclear cross sections to measure for development of fast-neutron dosimetry.

NEUTRON BEAMS FOR DATA MEASUREMENTS

Before going to more detailed discussions, a general distinction between neutron sources for research and treatment should be made. In, e.g., cancer therapy, high intensity is of primary importance while energy resolution is not crucial. In dosimetry research, often the requirements are the opposite; typically, much fewer neutrons are needed for a cross section measurement or dosemeter calibration than for treatment, but the performance demands on the beam, like energy resolution, time structure, etc., are much more stringent. In this section, we discuss research facilities only.

Basic principles of high-energy neutron production

At energies below about 20 MeV, truly monoenergetic neutron beams can be produced. There are a few light-ion reactions, like $D(d,n)^3He$ and $T(d,n)^4He$, which have positive Q-values and sizeable cross sections. The most widely used reaction is $T(d,n)^4He$, where deuterons of only a few hundred keV can produce 14 MeV neutrons.

Such a beam is strictly monoenergetic up to an incident deuteron energy of about 2 MeV. Above this energy, there is a possibility that the deuteron breaks up into a proton and a neutron. In reality, this is not a major obstacle below about 30 MeV neutron energy, because the $T(d,n)^4He$ cross section is so large that the break-up neutrons form only a small low-energy tail. At even higher energies though, the $T(d,n)^4He$ cross section is smaller, making the total yield too low for most measurements.

The break-up effect is there in all nuclei, and in almost all nuclei neutrons are bound by about 8 MeV. The largest neutron separation energy is about 20 MeV. The consequence of this is that truly mono-energetic beams are impossible to produce above that energy. What are available at higher energies are quasi-monoenergetic beams, i.e., beams where a single energy dominates, but a low-energy tail always accompanies it.

If we go to energies of 50 MeV and above, three production reactions give reasonably monoenergetic beams. These are the D(p,n), $^6Li(p,n)$ and $^7Li(p,n)$ reactions. The first has a large cross section, but it has the drawback that the energy resolution of the full-energy neutrons cannot be better than 3 MeV due to the Fermi motion of the neutron inside the deuteron. If a sharper energy definition is required, one of the two reactions using lithium isotopes has to be selected. Their overall merits are about equally good, but there is a major practical difference: ^6Li is used in hydrogen bombs and is therefore difficult to obtain, while ^7Li is easily provided. Not surprisingly, $^7Li(p,n)$ is the most common production reaction for monoenergetic neutron beams. At 100 MeV, about 50% of the neutrons fall within 1 MeV at maximum energy, while the remaining half are distributed about equally from maximum energy down to zero. This is the closest to monoenergetic conditions nature provides.

There is also a completely different approach to the whole production. Instead of trying to get the neutrons as well gathered in energy as possible, all energies are produced simultaneously. A high-energy proton beam hits a thick (most often stopping) target and many neutrons of all energies are produced, with typically a $1/E_n$ spectrum. If the incident proton beam is bunched and the experiment target is placed at a large distance from the neutron production target, time-of-flight methods can be used to determine the energy of the incident neutron on an event-by-event basis.

The advantage of such so-called white beams is the total intensity, which is larger than for monoenergetic beams, but instead the intensity per energy interval is much lower at high energies. Summing data over limited energy intervals can partly compensate for this, but still the intensity per such interval is lower. As a consequence, white beams are restricted to experiments at low energies, where the intensities are large, or to high-energy reactions with large cross sections. Another feature is that white sources require event-by-event measurements. Experiments of effects with an energy dependence where the individual events cannot be distinguished, like for some dosimetry techniques, cannot be performed at white beams. For experiments fulfilling the requirements above, white sources can, however, provide large quantities of very valuable information. This is especially true when the excitation function, i.e., the energy dependence of a cross section, is of particular interest.

A notorious problem in all activities involving neutrons is to determine the beam intensity. A charged particle interacts with the electrons of the atom. Thereby it is possible to build systems where every particle gives a signal when passing through a detector, and hence it is a relatively simple task to determine the beam intensity by just counting pulses. Another option is to stop particles via their energy loss — which is also an effect of interaction with the atomic electrons — and finally measure the collected charge. This is performed in every Faraday cup at every laboratory.

Neutrons interact by the strong interaction only, and they are uncharged. This means that there is no way one can build a device that produces a signal for each particle that passes, and one cannot stop neutrons in a controlled way. Detection of neutrons always has to proceed via a nuclear reaction, releasing charged particles, which subsequently can be detected. The problem is that there is no way to determine a nuclear cross section from theory only with a reasonable precision. This means we end up in circular reasoning.

Let us assume that we want to use neutron–proton scattering for neutron detection. Counting the protons emanating from a hydrogenous material is a simple task, but we need to know the cross section to derive the number of incoming neutrons. To measure that cross section, however, we need to know the number of incident neutrons. There are ways to get out of this vicious circle, but they all require painstaking efforts. Thus, the quality of a neutron beam facility should not only be judged on its intensity and energy spectrum, but also on the precision in monitoring the intensity.

High-energy neutron production facilities

Neutron beam facilities above 50 MeV have traditionally been of two types; white sources and quasi-monoenergetic ones (see above). White spallation sources have been used at Los Alamos[16] and the Paul Scherrer Institute[17], and a new source has recently been installed at CERN[18]. Typically, the energy-integrated flux is significantly larger than for monoenergetic sources, at the expense that the flux per energy unit is much smaller. A consequence of this is that white sources primarily have been used for measurements of relatively large cross sections.

Monoenergetic sources are in most cases employing the ^{7}Li(p,n) reaction. Such installations have been operated at UC Davis[19], TSL Uppsala[20,21], IUCF[22], TRIUMF[23], NAC/iThemba[24], UCL Louvain-la-Neuve[25], TIARA[26] and RIKEN[27].

Recently, a novel technique has been developed at IUCF to produce tagged neutrons at the cooler ring[28]. This technique can be used to provide neutron beams with very well defined energy and intensity, but with very poor intensity. A programme is under way to measure neutron–proton scattering, for which the intensity is sufficient, while it is inadequate for other cross sections of biomedical relevance.

The Uppsala monoenergetic neutron beam facility

The installation at the The Svedberg Laboratory, Uppsala, Sweden, can serve as an example of a monoenergetic neutron beam facility[21]. An overview is presented in Figure 1. Protons from the cyclotron impinge on a neutron production target from the left. After the target, the proton beam is bent into a beam dump tunnel. A narrow neutron beam is defined by a system of three collimators. The major experimental devices, MEDLEY for charged-particle production measurements[29] and SCANDAL for elastic scattering studies[21], are installed in a separate experiment hall after the collimators. Several metres of beam length are also available for various irradiation experiments.

Lithium targets of 100–800 mg cm^{-2} in thickness (2–15 mm), enriched to 99.98% in ^{7}Li, are mounted in a remotely controlled water-cooled stainless-steel rig with four target holders. One of the target positions contains a fluorescent screen viewed by a TV camera, which is used for beam alignment and focussing.

The ^{7}Li(p,n) reaction produces a neutron spectrum consisting of a full-energy peak and a continuum of neutrons at lower energies, roughly evenly distributed in energy. The full-energy peak is due to excitation of the ground state and first excited state (E_x = 0.43 MeV) in ^{7}Be. The energy of it is slightly lower than the initial proton energy ($Q = -1.6$ MeV), and the width is prim-

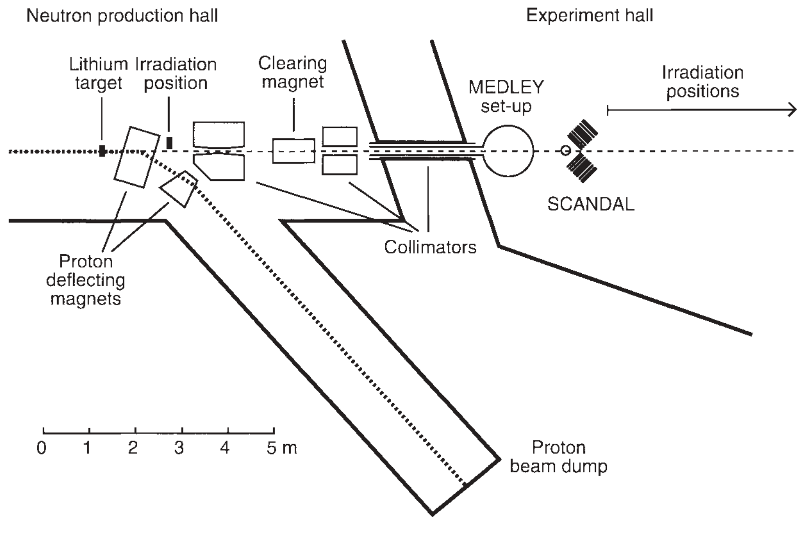

Figure 1. Overview of the Uppsala neutron beam facility. The neutron production, shielding and collimation are shown, as well as the permanent experimental setups MEDLEY[29] and SCANDAL[21].

arily given by the thickness of the lithium target. A measurement of the highest-energy part of the neutron energy spectrum is presented in Figure 2. In that case, the width of the peak is dominated by the limited resolution of the detection device; the intrinsic peak width is about 1 MeV.

After passage of the lithium target, the proton beam is deflected by two magnets and bent into an 8 m long tunnel, where it is focussed onto a water-cooled graphite beam dump. The integrated current from this Faraday cup is used for proton beam monitoring, since the relation between the proton beam current at the lithium target position and at the Faraday cup stays constant during a run, and the ratio can be determined with sufficient accuracy. Thus, this proton beam current monitoring is also used as a relative monitoring of the neutron beam.

The neutron beam produced in the forward direction is geometrically defined by a system of three collimators. The first one consists of a 1.1 m long iron cylinder of revolver type with four axial holes of different diameter. The collimators are doubly conical in shape, with a central waist defining the solid angle. In most experiments, a solid angle of 60 μsr is selected, which corresponds to a beam spot diameter of about 8 cm at the position of the MEDLEY set-up. The second collimator is 0.8 m thick and consists of iron and paraffin slabs, while the third one, about 2 m thick, is made of iron only. Neither of these two collimators shapes the neutron beam, but serve as scrapers of the beam halo from the first collimator.

Proton beam currents are typically around 5 μA, which result in neutron intensities of the order of 10^6 per second, integrated over the beam spot. For activation measurements, an irradiation position closer to the target, before the collimators, can be used (see Figure 1).

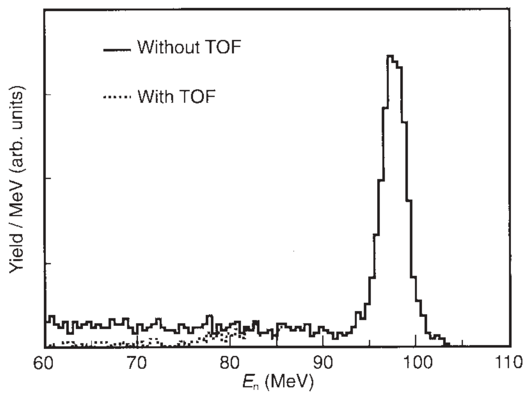

Figure 2. Reconstructed energy spectra of incoming neutrons, using an np proton recoil spectrum in the angular range 0°–5° measured with the LISA magnetic spectrometer[20]. The solid line shows the spectrum without time-of-flight conditions, and the dotted line is a spectrum obtained with such a cut.

In this position, which is just outside the 0° beam line, the intensity is about a factor of 50 higher.

All the neutron production and collimation takes place in vacuum. The first major installation in the experimental hall, MEDLEY, is part of the vacuum system, which is terminated by a 0.1 mm stainless-steel foil at the exit of the MEDLEY scattering chamber.

A prominent feature of the neutron production facility is the very good shielding between the dumping and the experimental area, which gives low experimental background. The long distance between the neutron production and the experiment area allows rejection of low-energy neutrons by time-of-flight techniques, which is illustrated by the dotted line in Figure 2.

Relative monitoring is provided by the proton beam Faraday cup (see above). In addition, absolute monitoring of the neutron fluence is obtained from a fission detector, based on thin-film breakdown counters (TFBCs), mounted immediately after the vacuum termination foil at the exit of the MEDLEY scattering chamber.

MEDLEY — a multi-purpose cross section facility

The MEDLEY detector set-up[29], shown in Figure 3, has been constructed to measure double-differential light-ion production cross sections for neutron energies

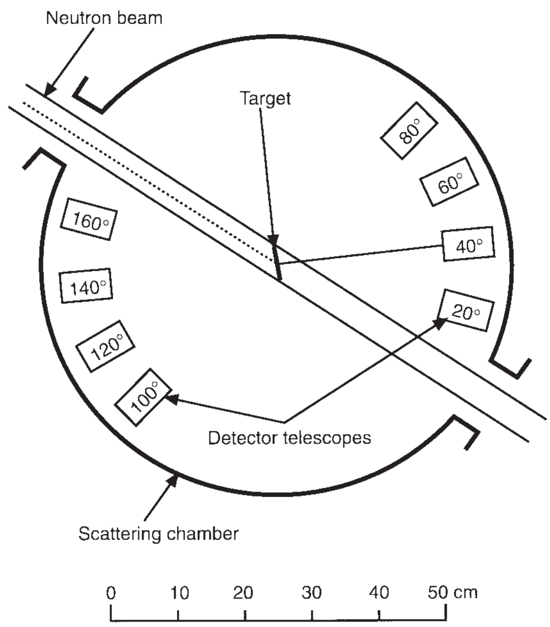

Figure 3. The MEDLEY facility, showing the scattering chamber and the eight three-detector telescopes, mounted at angles from 20° to 160°. The target under study is mounted in the centre of the chamber. The fission TFBC detector, used to monitor the neutron beam, is positioned just outside the vacuum terminating foil.

in the 20–150 MeV range. It consists of a 100 cm diameter evacuated chamber, containing eight three-element particle telescopes. The telescopes are mounted to cover scattering angles from 20 to 160° in 20° intervals. Each telescope consists of two ΔE detectors and one thick E detector, which give good separation between the different particle types over a large dynamic range.

The target under study, being typically a disc of 20–25 mm diameter with a thickness of 0.1–0.5 mm, is mounted in one of three frames using thin threads. These aluminium frames are positioned in the centre of the scattering chamber. They are large enough not to be hit by the beam, and can be switched into or out of the beam without breaking the vacuum.

The 450 mm^2 ΔE detectors are fully depleted standard ORTEC silicon surface barrier detectors. The thickness of the front ΔE detector is 50–60 μm, while the second one is 400–500 μm. CsI(Tl) crystals, 3 cm thick, directly coupled to photodiodes, are used as E detectors. To obtain a well-defined acceptance, collimators are placed in front of the telescopes. To avoid the problem of scattering in thick, stopping collimators, we have chosen to employ thin, active collimators, where the signal from a hit is used to veto the related event. The plastic scintillator collimators have a 19 mm diameter hole at the centre and a thickness of 1 mm.

For each detector, output signals are generated for energy (E) and timing (T). The E branch is amplified and shaped, and an ADC registers the pulse height. For the T branch, only signals from the silicon detectors of each telescope are fed to timing discriminators. This information is used to define an event, but also to determine the neutron TOF with respect to a reference, given by the cyclotron RF. The raw data are stored on tape on an event-by-event basis.

After several steps of analysis, the data are finally sorted into different histograms according to the angle and type of particle. These histograms thus represent both the energy and angular distributions of the different ejectile particles, i.e., the double-differential cross sections. The absolute scale is obtained by comparison with similar data acquired with a hydrogenous target, using the well-known np scattering cross section as a reference. Examples of such double-differential cross sections for proton production in carbon are shown in Figure 4. The strong angular dependence of the shape of the energy spectra can particularly be noted.

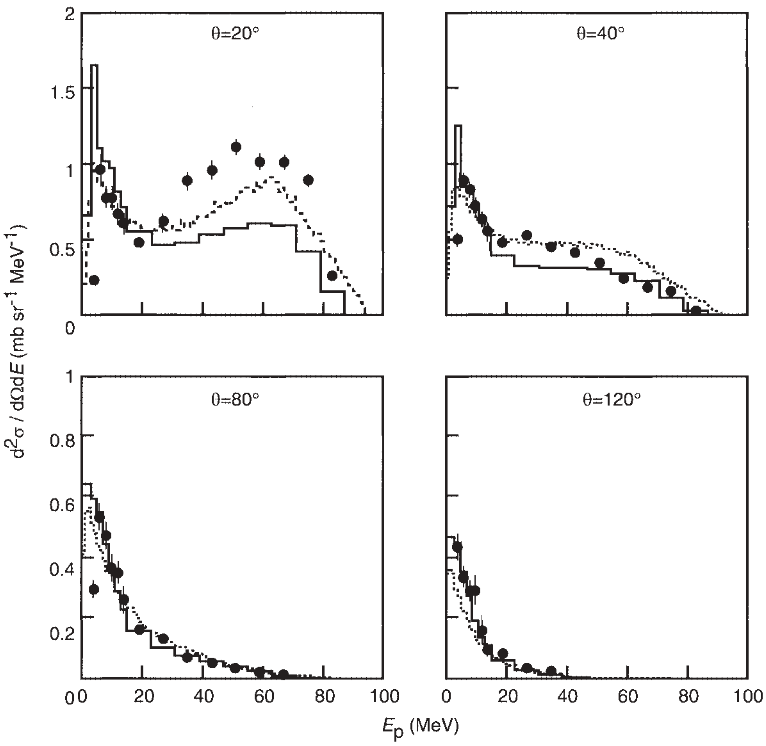

Figure 4. Double-differential cross sections at θ = 20°, 40°, 80° and 120° for the ^{12}C(n,xp) reaction at 95 MeV[47]. Solid histograms represent evaluated data[15], and dotted curves are from a pre-equilibrium calculation of the ^{12}C(p,xp) reaction[51].

THE NUCLEAR DATA SITUATION ABOVE 20 MeV

As was mentioned above, the relevant nuclear data for assessing the dose due to fast neutrons are np scattering, elastic scattering from nuclei, and light-ion production reactions.

Of these, the np scattering data are of the highest quality. This reaction has been thoroughly investigated from thermal energies and up to about 1 GeV incident neutron energy. The global database comprises several thousand data points, and typically the experimental uncertainties are in the 5% range. Recently, there has been an intense debate about the np scattering cross section at backward angles, where different data sets deviate by 10% or even more (see Reference 30 for a review). These discrepancies, however, affect only a rather limited angular range, and for the present applications, this is of little importance, because the solid angle subtended is small, which results in very small contributions to the total uncertainty in dose determinations.

Compilations of most of the data published can be found in databases accessible via www[31,32], where also theory analyses of the data can be obtained. Most measurements on np scattering have concentrated on detecting the recoil proton, simply because this is much less difficult experimentally. Presently, experiments are under way to study the remaining part of the angular distribution by neutron detection, which should result in a complete data set[33].

The data situation on elastic scattering from nuclei is satisfactory up to about 30 MeV. Above this energy, there are published measurements from UC Davis on a few nuclei, including carbon, at 65 MeV[34]. Presently, a project on elastic scattering at 100 MeV, using the SCANDAL facility, is in progress at TSL in Uppsala[21], where carbon data are under analysis[35].

Studies of light-ion production above 20 MeV have been undertaken at UC Davis, UCL Louvain-la-Neuve and Tohoku University. The UC Davis set-up[36] was used to measure all light ions emitted from carbon[37], as well as nitrogen and oxygen[38] at 27.4, 39.7 and 60.7

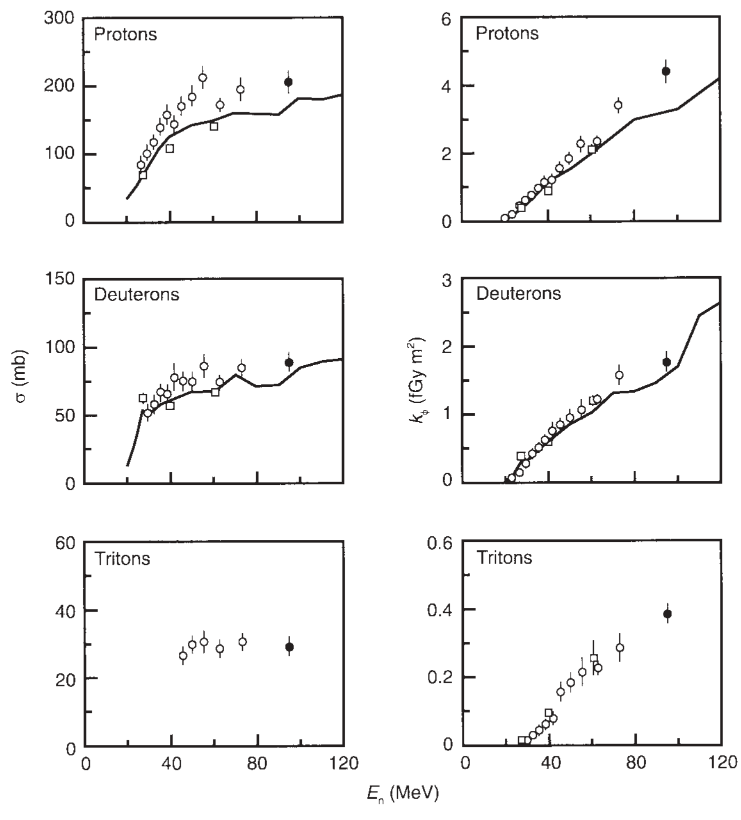

Figure 5. Left panel: Integrated cross sections for production of protons, deuterons and tritons in carbon versus incident neutron energy. The filled circles are from Uppsala[47], open circles are from Louvain-la-Neuve[49] and open squares from UC Davis[37]. Solid curves represent evaluated data[15]. Right panel: Partial kerma coefficients for production of protons, deuterons and tritons in carbon versus incident neutron energy for the same data and evaluation.

MeV. In the case of carbon, data are extensive in the forward direction, but scarcer at backward angles, whilst the nitrogen and oxygen data extend only out to 65°. At UCL Louvain-la-Neuve, measurements of the same light ions have been performed between 30 and 75 MeV for carbon[39–42], and between 25 and 65 MeV for oxygen[43–45]. The UC Davis and UCL Louvain-la-Neuve data display considerable discrepancies, especially for oxygen in the low-energy domain. Proton and deuteron data from Tohoku have been published for carbon at 64.5 and 75 MeV[46]. These data, however, have a very high low-energy limit because the experiment was carried out in air.

Recently, a programme to measure similar data at 100 MeV, using MEDLEY, has been initiated at The Svedberg Laboratory, Uppsala[29]. Up to now, data on carbon at 96 MeV in the 20°–160° angular range have been obtained[47], and additional measurements on carbon and oxygen are under analysis[48]. It is found that the proton spectra have a higher cross section in the mid- to high-energy range at forward angles compared to a recent state-of-the-art evaluation[15], as is shown in Figure 4. This feature is probably caused by a stronger component of direct reaction mechanisms, e.g., quasi-elastic scattering, and leads, because of the energy weighting, to a partial kerma coefficient that is 35% higher (see Figure 5). Since protons give a large contribution to the total kerma, the obtained value for carbon is about 25% higher than that given in the evaluation, as is illustrated in Figure 6. It is notable that the new data at 96 MeV support a trend observed for similar data up to 73 MeV[49], both concerning cross sections and kerma coefficients (see Figures 5 and 6). It is also striking that the kerma coefficients based on microscopic cross sections (filled symbols in Figure 6) seem to be systematically higher than those determined using other techniques (open symbols).

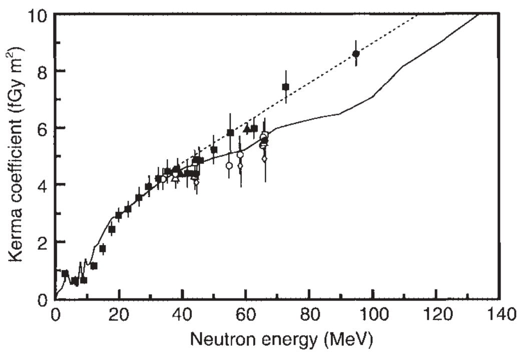

Figure 6. Total kerma coefficients for the ^{12}C + n reaction versus incident neutron energy. The solid circle at 96 MeV is from Uppsala[47]. The other data are taken from the literature[15]. The dashed line is an eye-guide to the data from microscopic measurements in the region 40–100 MeV.

New data at an even higher energy, e.g., 150 MeV, is of high priority to understand better the evolution of various reaction mechanisms with neutron energy, and ultimately to resolve the problems of increasing discrepancy between data and theory with increasing energy. Such a measurement is being planned at TSL in Uppsala.

Proton, deuteron and triton production on carbon has been measured in the 300–580 MeV range at angles from 51° to 165° using the white neutron source at PSI[50]. At these high energies, the cross sections can be reasonably well described by relatively simple scaling relations. This is an interesting observation, and it makes sense from basic nuclear physics arguments. At higher energies (above 200 MeV or so), the reaction mechanisms gradually become simpler, because fewer nucleons are involved. This means that information from free scattering can be used for reasonably precise predictions, while at lower energies (20–200 MeV), the effects of the nuclear medium are large, which makes the theory much more complicated. Although these energies are higher than common treatment energies, they are of interest for dose delivery due to cosmic-ray neutrons. In addition, they can be of use to guide theory, also for lower energies. Effects, which are clearly seen at 300 MeV, might have their onset at much lower energy without being clearly visible.

SUMMARY AND CONCLUSIONS

Many new applications of fast neutrons require improved understanding of the fundamental processes involved for their further development. With the presently rapid progress in high-quality measurements of neutron-induced nuclear cross sections, as well as in numeric computation and modelling, it is possible that Monte Carlo methods might become a standard tool within a foreseeable future for detailed calculations of the full response, in principle, of any system, including human tissue or detector media.

This could allow a fully microscopic approach to assessment of biological effects in tissue due to neutrons, and this could potentially revolutionise our understanding of these effects. A prerequisite for this development is, however, a continuing rapid growth of the experimental database on double-differential cross sections for light-ion production in relevant nuclei.

ACKNOWLEDGEMENTS

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Relations Between Basic Nuclear Data and Single-Event Upsets Phenomena

Jan Blomgren, Bo Granbom, Thomas Granlund, and Nils Olsson

Abstract

This article approaches single-event upset (SEU) problems from the standpoint of experimental nuclear physics, with a focus on certain neutron experiments and neutron data essential for SEU studies. A review is given of some research programs, both basic and applied, that are strongly motivated by SEU applications. Some specific examples are presented from the The (short for Theodor) Svedberg Laboratory (TSL) in Uppsala, Sweden: First, using the quasi-monoenergetic neutron beam, SEU cross sections (of chips) are measured over the neutron energy range of 20–150 MeV. Data from the same technology generation, in general, can be fitted into a simple curve. Second, the particle origins of SEUs are discussed from the framework of neutron–nucleus spallation reactions.

Keywords: *microelectronics, nuclear data, single-event upsets.*

Introduction

Radiation effects induced by terrestrial cosmic rays in microelectronics—on aircraft as well as at sea level—have attracted much attention in the last two decades. When a memory circuit is exposed to cosmic rays, the memory state of a cell can be flipped, from a 1 to a 0 or vice versa, resulting in an error in a bit. This phenomenon is called a single-event upset (SEU), or soft error. This is a random error, which is irreproducible, but does not induce any hardware damage in the circuit. But as one bit of data is corrupted, it raises serious reliability and performance issues in many applications in which data integrity is of critical importance. First predicted in the late 1970s, SEUs were experimentally confirmed in mainframe computers at IBM and extensively studied by the researchers there during the 1980s and 1990s.[1] Similar software errors were rediscovered by accident in a portable personal computer used in an airplane a few years ago. The PC SEU effects were later verified under controlled conditions, in flight measurements[2,3] and in laboratory tests.[4–6]

A single-event upset, at the most fundamental level, is caused by a single particle hitting a device. This is in contrast to the permanent damage in electronics caused by an integrated radiation dose, which is usually delivered by a high particle flux.

At flight altitudes, as well as at sea level, the cosmic rays are dominated by neutrons and muons. Neutrons interact with device materials through the strong nuclear force, whereas muons interact with these materials through the much weaker electromagnetic force. As far as SEUs are concerned, neutrons are the most important part of the terrestrial cosmic rays. This has been pointed out in the article by Tang and Rodbell in this issue of *MRS Bulletin*, and also in References 7–10. The status of our current knowledge of terrestrial neutron flux on the ground and in the atmosphere is reviewed by Goldhagen in this issue.

Since neutrons do not carry electric charge, they do not ionize the device they hit. However, when a high-energy cosmic neutron collides with a nucleus in the device material (e.g., Si, O, N), a spallation reaction is initiated. A sequence of complex nuclear processes takes place, which is best described in terms of two stages: intranuclear cascade processes, followed by statistical decay processes called a compound nucleus reaction. The net result is the breakup of the target nucleus and the production of light secondary particles—neutrons, protons (^{1}H), deuterons (^{2}H), tritons (^{3}H) consisting of one proton and two neutrons, ^{3}He, ^{4}He (alpha particles), Li, Be, and pions—and a heavy recoil nucleus like Mg, O, or C.[8,11] If this happens in a sensitive volume, for example, near a *p-n* junction, the charged secondary particles can induce a spurious electrical pulse that leads to an SEU. Hence a profound understanding of SEU issues requires knowledge of the neutron–nucleus reactions and of how the radiation-induced carriers in a device are transported and collected by a node (any fundamental electronic component in the device).

In this article, we approach SEU problems from the standpoint of experimental nuclear physics. We focus on certain neutron experiments and neutron data that are essential for SEU studies. We review some of the experimental activities at the The (short for Theodor) Svedberg Laboratory (TSL) in Uppsala, Sweden. These research programs, both basic and applied, have been strongly motivated by SEU studies. We discuss how these neutron experiments contribute to important new databases for future SEU studies.

Basic Nuclear Data and Experiments Important for Single-Event Upset Studies

Fundamental Nuclear Data

Data on energy and angular distributions of the secondary particles produced from neutron–nucleus collisions are essential input for analyses and calculations of SEU rates. These nuclear data are either measured from neutron-induced reactions or calculated from nuclear reaction models. Reference 12 is a 1997 review of the status of nuclear data on light elements, which are crucial for SEU research and other radiation-related applications. Two important points are noted. First, most of the available data have been single-particle inclusive spectra of light secondary particles (like protons and alpha particles) measured from proton-induced reactions. Single-particle inclusive spectra contain data from the single outgoing particle that is measured, plus data from undetected outgoing particles. Corresponding data from high-energy neutrons (in the range of 100 MeV or higher) are practically nonexistent. Second, there are few heavy-recoil data in the form of double differential cross sections. In the rest of the article, we discuss how some of the ongoing experimental programs at TSL are aimed at improving this situation.

Neutron-Induced SEU Cross Section

A direct way to characterize the SEU sensitivity of a device or circuit is to measure its neutron-induced SEU cross section as a function of neutron energy, using a quasi-monoenergetic neutron beam. Figure 1, taken from Reference 13, shows some typical SEU cross sections plotted against the incident neutron energy. The symbols are the measured experimental data for several memory chips: Matra-H, Cypress (cy7c199), Micron (MT5C2568), Toshiba (TC551001), and NEC (D431000), all manufactured with four-transistor complementary metal oxide semiconductor (CMOS) technology. The solid curve is constructed from SEU model calculations, to be discussed later. Here, the SEU cross section has a threshold of about 10 MeV. It rises almost linearly with increasing neutron energy up to about 100 MeV; it then reaches some saturation value and comes down slightly at higher neutron energies. Saturation occurs because at higher energy other competitive reactions can take place, and the interaction time for a given reaction is shorter, reducing its probability of occurring. It turns out that this shape of the SEU cross section is quite representative of CMOS devices, but the energy-threshold value and the saturation value of the cross section depend on details of the device structure. With technology moving to smaller dimensions, in general both the energy threshold and the saturation value of the cross section tend to go down.

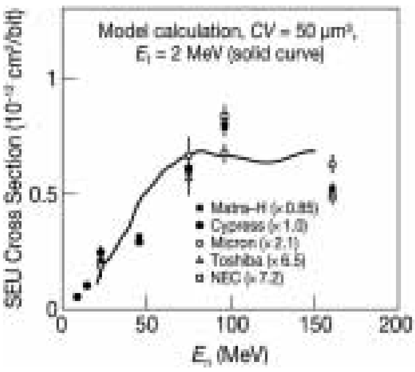

Figure 1. The single-event upset (SEU) cross section for several memory devices as a function of incident neutron energy. The symbols are measured experimental data for several memory chips. The solid curve is an SEU model calculation. CV *is the charge-collection efficiency (*C*) and volume (*V*) product,* E_t *is the threshold energy, and* E_n *is the incident neutron energy. See text for details.*

To compute the absolute SEU rate, or soft error rate (SER), due to the cosmic neutrons, one multiplies the (energy-dependent) SEU cross section with the neutron energy spectrum and integrates over the relevant energy range.

Artificial Neutron Fields

Two types of neutron sources are available for SEU studies: (1) quasi-monoenergetic neutron beams, and (2) white neutron sources. White neutron sources contain a wide range of energies in the spallation energy spectrum, similar to the range of optical energies that make up white light. Examples of the first category are the neutron facilities at TSL (with a maximum energy of 180 MeV), the Institut de Physique Nucléaire of the Université Catholique de Louvain in Belgium (with a maximum energy of 80 MeV), and Crocker Nuclear Physics Laboratory of the University of California, Davis (with a maximum energy of 67.5 MeV). The Weapons Neutron Research Facility (WNR) at the Los Alamos National Laboratory in New Mexico is a white source with a continuous neutron energy spectrum that extends from below 1 MeV up to 800 MeV.

Figure 2 is a schematic diagram of the neutron facility at TSL. Protons in the energy range of 20–180 MeV from a cyclotron impinge on a ^{7}Li target to produce neutrons. The transmitted proton beam is bent by magnets and dumped. The neutrons generated are collimated into a narrow beam at 0° by iron collimators. A 7-cm-diameter beam spot is obtained at a distance of 8 m from the production target. The experimental area is located in a separate room to avoid background from the production and beam dump. The quasi-monoenergetic neutrons produced have a full-energy peak at approximately the same energy as the protons, with a small and almost flat low-energy tail, as shown in Figure 3. The low-energy neutrons can be suppressed by time-of-flight (TOF) techniques (dotted histogram). A typical intensity in the full-energy peak is about 10^6 neutrons per second in the full beam. For a detailed description of the entire facility, see References 14 and 15.

A significant advantage of this kind of facility is that it can be used for fundamental nuclear research as well as engineering studies. While it is ideal for measurements of basic neutron cross sections, at the same time it can be used to measure neutron-induced SEU cross sections of devices and circuits without having to make major modifications to the experimental setups.

A white neutron beam consists of neutrons with a broad range of energies, which are produced simultaneously. A high-energy proton beam bombards a thick target (which often stops the beam), and produces a large number of neutrons of all energies, with typically a $1/E$ energy spectrum. This results in an intense neutron flux, which strongly resembles the atmospheric neutron spectrum. This feature makes a white neutron beam appealing for direct SEU tests of electronic products.

It is important to point out that what one extracts from quasi-monoenergetic neutron-beam measurements is the SEU cross section of a device, whereas the data from a white neutron source are the SER, or FIT (failure in time) rate (1 FIT = 1 failure/10^9 operating hours of a device or circuit). The relation between these two different quantities is analyzed in the article by Tang and Rodbell in this issue. Starting from the SEU cross section as a function of neutron energy, and using the cosmic neutron flux, one can compute the FIT rate for a given radiation background. However, a measurement of the FIT rate alone does not allow one to recover the detailed information of the SEU cross section. In order to analyze the important trends of the SEU sensitivity from one technology to the next, the energy-dependent SEU cross sections are crucial, and they are more fundamental than the FIT rates.

SEU-Related Research at The Svedberg Laboratory

Measurements of Neutron-Induced Cross Sections

The double differential cross section of a secondary particle in a reaction, which is a measure of the probability that the particle is produced within a certain energy and angular range, is a fundamental quantity. Cross sections of all charged secondaries provide crucial input for SEU analyses. Measured cross sections are also critical experimental checks on the validity and accuracy of nuclear-reaction models. In turn, nuclear-reaction models are required to generate cross sections in energy ranges over which no measurements are available.

An objective of some of the ongoing experiments at TSL is to generate high-quality production cross sections of the light ions ^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}Li, and ^{7}Li from high-energy neutron reactions, in order to provide new nuclear databases for the radiation physics and SEU communities. These measurements are performed using the MEDLEY setup,[16] which

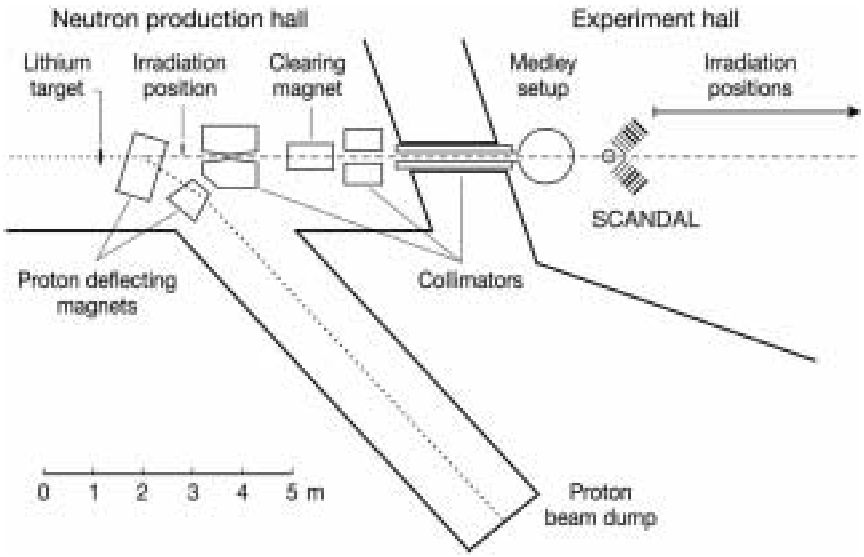

Figure 2. A schematic diagram of the neutron beam facility at The Svedberg Laboratory in Uppsala, Sweden. SCANDAL is the SCAttered Nucleon Detection AssembLy.

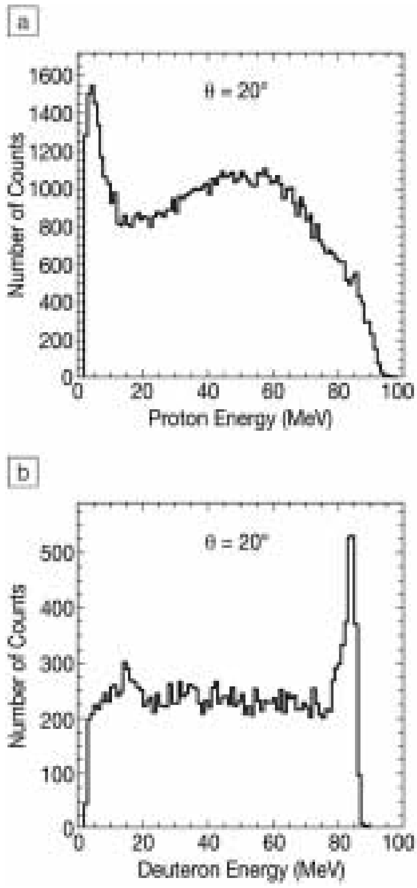

Figure 5. Double differential (a) proton and (b) deuteron spectra of secondary ions produced at 20° from neutron-induced reactions on silicon at 96 MeV.

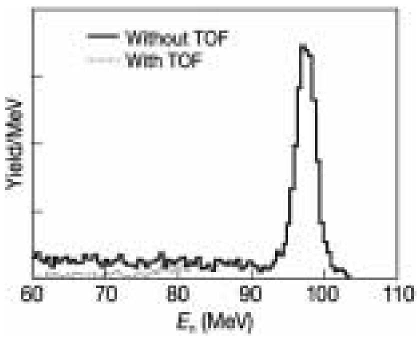

Figure 3. The neutron-energy spectrum with and without rejection of low-energy neutrons by the time-of-flight (TOF) techniques. See text for details.

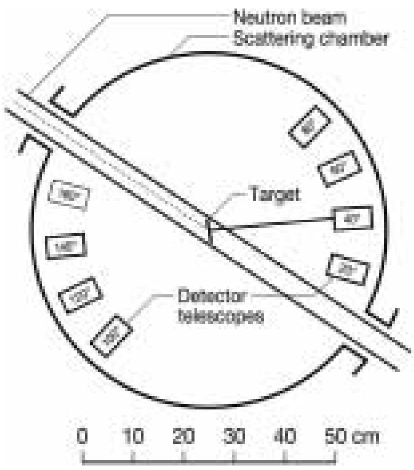

Figure 4. The MEDLEY setup, which consists of eight three-detector particle telescopes mounted in a scattering chamber.

consists of eight three-detector particle telescopes mounted in a scattering chamber, as shown in Figure 4. As an example, we show some results from recent measurements of light-ion production by 95-MeV neutrons on silicon.[17] Figures 5a and 5b show double differential cross sections of the secondary protons and deuterons produced at an angle of 20°.

Device Testing Activities

Microelectronic companies and university research groups have, over the past few years, used the neutron facility at TSL to perform SEU tests of devices and circuits. For example, Saab has been doing accelerated testing of memory chips and microprocessors since 1993. To address the reliability issues of electronic equipment on aircraft, BAE Systems and Saab Avionics have been working together to develop programs for SEU testing and simulation.

Up to the present time, extensive studies have been done on static random-access memories (SRAMs) and dynamic random-access memories (DRAMs). They show that memory devices, computer caches included, from various technologies, are susceptible to neutron radiation.

Cross-checking of SEU measurements using the quasi-monoenergetic neutron beam at TSL and the white neutron source at Los Alamos National Laboratory has been carried out. The SEU cross sections of the chips were measured at TSL over neutron energies of 20–180 MeV. The data were folded with the energy spectrum of the white neutron source. The integrated failure rates of the chips were then compared with FIT rates obtained from direct measurements at Los Alamos. The two sets of results were found to be in agreement, thus indicating the robustness and internal consistency of these two types of test procedures.

The energy-dependence of proton-induced SEU cross sections[18] has been found to be very similar to the neutron SEU data. High-energy protons, like neutrons, induce SEUs in electronic devices by means of spallation reactions. (The ionization energy of a high-energy proton, in general, is too small to cause an SEU.) At high energies, proton–nucleus and neutron–nucleus reactions produce very similar secondary-particle spectra. In the case of light targets like Si, this is true down to about 50 MeV. This is a major reason why the SEU cross sections from high-energy protons and neutrons are similar. At lower energies (e.g., below 50 MeV), differences between protons and neutrons are expected to show up due to the Coulomb interaction between the proton and the nucleus.

For future research, it would be of great interest to make systematic comparisons between proton- and neutron-induced SEU cross sections for devices from the same technology family. SEU data measured with proton beams are important for electronics used in space programs, because their radiation environment consists of mainly high-energy protons.

SEU Simulations

In addition to running regular tests and experiments, some chip manufacturers have made a considerable effort to develop SEU simulation codes for devices at design stages. These SEU simulations involve detailed analyses and use as input realistic nuclear data and process parameters that fully reflect the complexity of the technology under development. For example, IBM is the first company to develop a full three-dimensional SEU simulator, called soft error Monte Carlo modeling (SEMM) Program,[8,19] which utilizes realistic chip geometry, device physics, and a state-of-the-art nuclear spallation reaction model, NUSPA (for NUclear SPAllation),[8,11] that keeps track of all secondary fragments in detail. This IBM SEU model has been used extensively as a design tool for bipolar technologies in the 1980s, and for CMOS technologies from the 1990s up to the present time.

Technology designers who are not the original chip manufacturers and hence do not have a complete knowledge of all manufacturing processes of the devices have to resort to less sophisticated SEU simulation methodologies. Over the years, the so-called burst generation rate (BGR) method[20] has been a popular approach adopted by various groups. As an example, we present here some simulation results from a BGR-type model developed by Saab. The essential input to the Saab program include: (1) stopping power and range data from SRIM (stopping and range of ions in matter) calculations,[21] (2) neutron–silicon cross-section data calculated by the GNASH code of Los Alamos National Laboratory[22] (with the database covering a neutron-energy range from 20 MeV to 150 MeV; and all isotopes from $Z = 1$ to $Z = 14$); and (3) the linewidth (physical size of transistor gates) and sensitive thickness (depth of the source or drain node) of the devices in question. For 0.8-μm CMOS technology, typical values used are 2.5 μm for the sensitive thickness, yielding a sensitive volume of 80 μm^3, and a threshold of about 2 MeV for upsets. In the calculations, it is assumed that only particles heavier than boron contribute to the SEU cross section. The final results are scaled by a factor of 0.63, corresponding to a charge-collection efficiency (C) and volume (V) product of $CV = 50\ \mu m^3$. The simulations, shown as the solid curve in Figure 1, are compared with the memory chips measured at TSL.[13] It appears that the parameters (device size and charge-collection efficiency) used have approximately incorporated dynamic effects like funneling.[23] Despite the rough estimates, to within a factor of about two, there is an overall agreement between simulations and measurements. It is again emphasized that the neutron data are crucial input for the calculations.

Recoil Experiments: Highlights of New Developments

As SEUs have been recognized as an important area of applied research, the demands at TSL for SEU tests have been increasing in the past few years. This has prompted the design and commissioning of a new neutron-beam facility. The new facility is designed to deliver about 250× more neutrons per second integrated over the full beam area. It is expected to be in full operation and available to outside users in 2004.

The secondary charged particles from neutron–nucleus reactions cause SEUs. Heavy fragments in general are more effective than the light ones. Experimentally, however, the heavy fragments are much more difficult to measure than the light ones. Light particles—from protons to alpha particles or even Li ions—can be readily measured by the $\Delta E - E$ techniques, which involves measuring the energy loss in a detector the particles pass through versus the energy deposited when the particle is stopped by a second detector. For heavier charged particles, such as Be or C ions, this technique is difficult, because the particles cannot penetrate the first ΔE detector, which is necessary for proper particle identification. For ions heavier than C, there is an additional problem: there is a high probability that the heavy fragments are absorbed within the target.

Inverse kinematics is an ideal method to measure heavy recoils. The feasibility of this method was demonstrated in 1995 in the United States by a collaboration spearheaded by H. Tang at IBM and J. Romero at the University of California, Davis. Experiments[12] were run at the National Superconducting Cyclotron Laboratory of Michigan State University. Si beams at an energy of 80 MeV/nucleon collided with stationary CH_2 targets. (Normally, Si is the target in kinematics experiments; inversion of target and beam gives an "inverse kinematics" experiment.) The spectra of the secondary fragments (light and heavy) measured from these experiments were equivalent to the secondary spectra produced from a conventional experiment using an 80-MeV proton beam on a stationary Si target. The two sets of particle spectra derived from apparently different experimental setups are in fact connected by a coordinate transformation. At the present time, there are only a few laboratories worldwide that can exploit this elegant technique. GANIL (Grand Accelerateur National d'Ions Lourds) in Caen, France, is another facility that can run experiments using the inverse kinematics method.

The CELSIUS (Cooling with ELectrons and Storage of Ions from the Uppsala Synchrocyclotron) accelerator and storage ring at TSL is capable of making direct measurements of neutron-induced recoil data, and can accelerate Si ions up to an energy of 450 MeV/nucleon. By directing a silicon beam onto a "neutron" target, the heavy fragments leave the target with the beam velocity, and thus can be easily detected. Furthermore, due to the reaction kinematics, the fragments are focused in a forward cone, and thus all cross sections can be measured with a rather small forward detector. An excellent "neutron" target is a deuterium-gas cluster-jet target, which is available at CELSIUS. A recoiling spectator proton (one that does not participate in the reaction, but merely "watches" as the silicon nucleus collides with the neutron) from the deuterium target leaving the reaction point with low energy at an angle of about 90° can be detected by a silicon-strip detector proton tagger (developed by a group at TSL). The proton tagger measures the energy and direction of the proton to determine if it was a spectator proton, or actually a participant in the reaction. The forward-going heavy ions, from Li to Si, can be detected by a dedicated forward-detector system, covering angles from 0° to a maximum of a few degrees. Since the nuclear cross sections to be measured have a threshold, it turns out that the neutron-energy range from a few tens of MeV to a few hundred MeV is the most important region. This fits very well with the characteristics of CELSIUS. Thus, the combination of a circulating silicon beam in CELSIUS, a tagged neutron target, and a dedicated forward detector with angular granularity (position resolution) and particle-identification properties suitable for ions from lithium to silicon provides the best setup for double differential recoil measurements.

Recently, an international collaboration focused on recoil measurements was initiated at TSL. It is led by a group[24] at the V.G. Khlopin Radium Institute in St. Petersburg, Russia, funded by the International Science and Technology Center (ISTC) in Moscow. The aim of this collaboration is to deliver a large quantity of new and important nuclear cross-section data for the basic and applied research communities.

Summary

Single-event upsets have been identified in recent years as a critical reliability area for modern electronics. In this article, the SEU problem is approached from the standpoint of the underlying nuclear processes. For most applications, terrestrial cosmic-ray neutrons are found to be a major source of SEUs. Furthermore, neutron–nucleus spallation reactions play a key role; they produce charged secondary fragments that ionize the devices and cause SEUs. We have discussed some of the current projects at The Svedberg Laboratory in Uppsala, Sweden, that are strongly motivated by SEU considerations.

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RAPID COMMUNICATIONS

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Elastic neutron scattering at 96 MeV from ^{12}C and ^{208}Pb

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A facility for detection of scattered neutrons in the energy interval 50–130 MeV, scattered nucleon detection assembly, has recently been installed at the 20–180 MeV neutron beam line of The Svedberg Laboratory, Uppsala. First results on elastic neutron scattering from ^{12}C and ^{208}Pb at 96 MeV incident neutron energy are presented. This experiment represents the highest neutron energy where the ground state has been resolved from the first excited state in neutron scattering. The results are compared with modern optical model predictions.

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The interest in high-energy neutron data is rapidly growing, since a number of potential large-scale applications involving fast neutrons are under development, or at least have been identified. These applications primarily fall into three sectors: nuclear energy and waste, nuclear medicine, and effects on electronics.

For all these applications, an improved understanding of neutron interactions is needed for calculations of neutron transport and radiation effects. The nuclear data needed for this purpose come almost entirely from nuclear scattering and reaction model calculations, which all depend heavily on the optical model, which in turn is determined by elastic scattering and total cross section data.

The present work is part of the EU project HINDAS (high and intermediate energy nuclear data for accelerator-driven systems) [1], which has been designed to meet the demand for new nuclear data for feasibility assessments of accelerator-based transmutation techniques. It is, however, also relevant for various biomedical applications.

Neutron scattering data are also important for a fundamental understanding of the nucleon-nucleus interaction, in particular for determining the isovector term [2]. Coulomb repulsion of protons creates a neutron excess in all stable nuclei with $A > 40$. Incident protons and neutrons interact differently with this neutron excess. The crucial part in these investigations has been neutron-nucleus elastic scattering data to complement the already existing proton-nucleus data.

Above 50 MeV neutron energy, there has been only one measurement on neutron elastic scattering with an energy resolution adequate for resolving individual nuclear states, an experiment at UC Davis at 65 MeV on a few nuclei [3]. In addition, a few measurements in the $0°-20°$ range are available, all with energy resolution of 20 MeV or more. This is, however, not crucial at such small angles because elastic scattering dominates heavily, but at larger angles such a resolution would make data very difficult to interpret.

The neutron beam facility at The Svedberg Laboratory, Uppsala, Sweden, has recently been described in detail [4], and therefore only a brief description is given here. The 96 ± 0.5 MeV [1.2-MeV FWHM (full width at half maximum)] neutrons were produced by the $^7Li(p,n)$ reaction by bombarding a 427 mg/cm^2 disk of isotopically enriched (99.98%) ^7Li with protons from the cyclotron. The low-energy tail of the source neutron spectrum was suppressed by time-of-flight techniques. After the target, the proton beam was bent into a well-shielded beam dump. A system of three collimators defined a 9-cm-diameter neutron beam at the scattering target.

Scattered neutrons were detected by the scattered nucleon detection assembly (SCANDAL) setup [4]. It consists of two identical systems, placed to cover $10°-50°$ and $30°-70°$, respectively. The energy of the scattered neutron is determined by measuring the energy of proton recoils from a plas-

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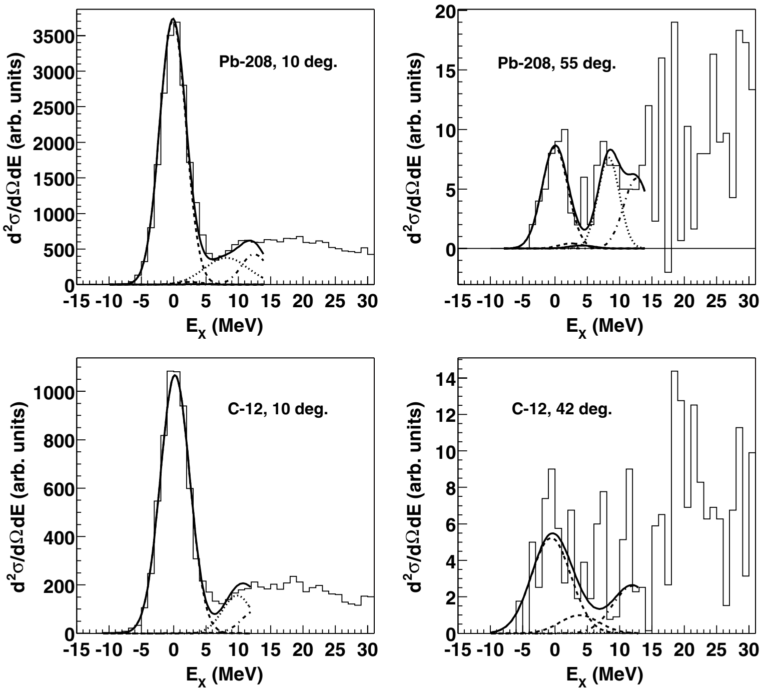

FIG. 1. Excitation energy spectra for elastic neutron scattering from ^{12}C and ^{208}Pb at 96 MeV incident neutron energy, together with Gaussians representing known excited states. See the text for details.

tic scintillator, and the angle is determined by tracking the recoil proton. In the present experiment, each arm consisted 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 ΔE plastic scintillator which was also part of the trigger, and an array of CsI detectors for energy determination of recoil protons produced in the converter by neutron-proton (n-p) scattering. The trigger was provided by a coincidence of the two trigger scintillators, vetoed by the front scintillator. The total excitation energy resolution varies with CsI crystal, but is on average 3.7-MeV FWHM. The angular resolution is in the $1.0°-1.3°$ (rms) range.

Two targets were used, a carbon cylinder, 5 cm high and 5 cm in diameter, with a mass of 178 g and a natural isotopic composition (98.9% ^{12}C), and a radiogenic lead cylinder (88% ^{208}Pb), 6.3 cm high and 2.9 cm in diameter, with a mass of 444 g.

Excitation energy spectra are presented in Fig. 1. In these spectra, Gaussians representing known states are indicated. For ^{12}C, the ground state (0^+) and the two collective states at 4.4 MeV (2^+) and 9.6 MeV (3^-) are shown. In the case of ^{208}Pb, the ground state (0^+) and the two collective states at 2.6 MeV (3^-) and 4.1 MeV (2^+) are shown, as well as a Gaussian at 8.3 MeV representing a cluster of weak states. For both nuclei, a Gaussian at 12.6 MeV represents the opening of conversions due to $^{12}C(n,p)$ reactions in the converter scintillator, i.e., an instrument background. As can be seen, in no case the population of excited states seriously affects the determination of the ground state cross section.

Angular distributions of elastic neutron scattering from ^{12}C and ^{208}Pb at 96 MeV incident neutron energy are presented in Fig. 2. The data are compared with phenomenological and microscopic optical model predictions in the upper and lower panels, respectively. The theoretical curves have all been folded with the experimental angular resolution to facilitate comparisons with data. The data by Salmon at 96 MeV [5] are also shown.

The angular distributions presented have been corrected for reaction losses and multiple scattering in the target. The contribution from isotopes other than ^{208}Pb in the lead data has been corrected for, using cross section ratios calculated with the global potential by Koning and Delaroche [6]. The absolute normalization of the data has been obtained from knowledge of the total elastic cross section, which has been determined from the difference between the total cross section σ_T [7] and the reaction cross section σ_R [8,9]. This $\sigma_T - \sigma_R$ method, which is expected to have an uncertainty of about 3%, has been used to normalize the ^{12}C data. The present $^{208}Pb(n,n)$ data have been normalized relative to the present $^{12}C(n,n)$ data, knowing the relative neutron fluences, target masses, etc. The total elastic cross section of ^{208}Pb has previously been determined with the $\sigma_T - \sigma_R$ method. The accuracy of the present normalization has been tested by comparing the total elastic cross section ratio ($^{208}Pb/^{12}C$) obtained with the $\sigma_T - \sigma_R$ method above, and with the ratio determination of the present experiment, the latter being insensitive to the absolute scale. These two values differ by about 3%, i.e., they are in agreement within the expected uncertainty. A second, independent, normalization method is under development, which is based on relative measurements versus the n-p scattering cross section [10].

The data are compared with model predictions in Fig. 2, where the upper and lower panels show phenomenological (I–III,VII) and microscopic (IV–VI) models, respectively. Model I refers to a recent phenomenological global optical

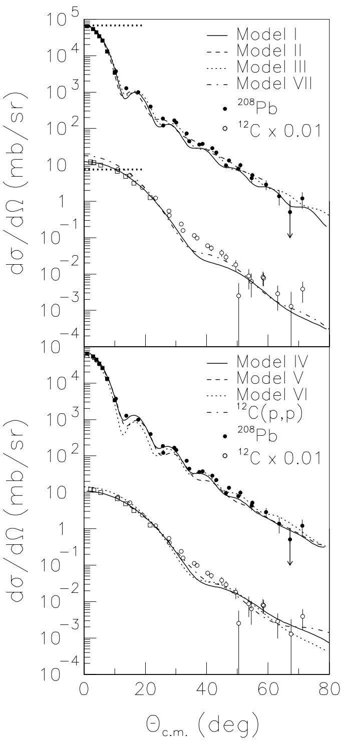

FIG. 2. Angular distributions of elastic neutron scattering from ^{12}C (open circles) and ^{208}Pb (solid) at 96 MeV incident neutron energy. The ^{12}C data and calculations have been multiplied by 0.01. The data by Salmon at 96 MeV [5] are shown as squares. Upper panel: predictions by phenomenological models (I–III,VII). The thick dotted horizontal lines show Wick's limit for the two nuclei. Lower panel: predictions by microscopic models (IV–VI), and data on elastic proton scattering from ^{12}C [23]. See the text for details.

model potential (OMP) [6], which is valid for incident nucleon energies between 1 keV and 200 MeV and masses from 24 to 209. It is based on a smooth functional form for the energy dependence of the potential depths, and on physically constrained geometry parameters. An extensive collection of experimental datasets for different types of observables was used to determine the parameters of this OMP.

We have performed a Dirac scattering calculation [11] (model II), which uses a global nucleon-nucleus intermediate energy Dirac phenomenological optical potential for ^{208}Pb [12]. The potential contains scalar and vector terms, based upon the Walecka model [13], and includes isospin dependence through a relativistic generalization [14] of the Lane model [15]. The isospin dependence was determined by simultaneous least-squares adjustment with respect to measured proton elastic scattering and neutron total cross section observables. Symmetrized Saxon-Woods form factors are used, and the potential contains a total of 20 parameters to describe nucleon scattering by ^{208}Pb in the energy range 95–300 MeV. An OMP calculation [16], based on a dispersive OMP approach treating nonlocality in a manner similar to that of Perey and Buck [17] for energy dependences, is presented as model III.

Model IV is a microscopic (g-folding) prescription for the optical potentials [18], where a complete $(0+2)\hbar\omega$ model of the structure of ^{12}C, and a Skyrme Hartree-Fock model for ^{208}Pb, have been used in the foldings. The predictions were obtained employing the effective (medium modified) nucleon-nucleon (NN) interaction based upon the Bonn-B interaction [19].

Model V is a Lane-consistent, semimicroscopic OMP [20], which is built by folding radial matter densities from a Hartree-Fock-Bogolyubov calculation (using the Gogny D1S effective interaction) with an OMP in nuclear matter that is based on an extension of that of Jeukenne, Lejeune, and Mahaux [21]. This extended OMP features strong renormalizations of its isovector components, and has recently been tested extensively against (p,p) and (n,n) data, as well as (p,n) IAS data [20].

Finally, the elastic observable was generated by a multiple-scattering expansion of the optical potential in terms of the free NN transition amplitude, calculated in the single-scattering $t\rho$ approximation [22] (model VI). In the description of the target nucleus, there is no distinction between protons and neutrons. For ^{12}C, the matter density distribution is deduced directly from the harmonic-oscillator shell model, with $b=1.55$ fm. In the case of ^{208}Pb, a two-parameter Fermi matter density distribution with halfway radius 6.62 fm and diffuseness 0.55 fm has been used.

When comparing these predictions with data, a few striking features are evident. First, all models are in reasonably good agreement with the ^{208}Pb data. It should be pointed out that none of the predictions contain parameters adjusted to the present experiment. In fact, they were all made before data were available. Even the absolute scale seems to be under good control, which is remarkable, given that neutron beam intensities are notoriously difficult to establish. The level of agreement between models and data has been inspected by computing the χ^2. For this exercise, only the uncertainties due to counting statistics have been used. Models III and IV have the lowest χ^2, with models I and V in a second group. It should be pointed out, however, that the results are not dramatically different for the various models. That models III and IV are in best agreement is not surprising, because they are single-nucleus models, while models with a larger range of validity give a less perfect description for a particular nucleus. Model II was determined by simultaneously fitting a large proton data set and a small neutron data set (mostly total cross sections). For such a procedure, the agreement is surprisingly good.

A normalization error can produce a major χ^2 contribution. Therefore, we have tested to renormalize all theories to produce a minimum χ^2. The absolute χ^2 values were reduced by this procedure, but the order between the models concerning the level of agreement was unchanged. What is notable is that models III and IV required very small renormalizations, 1–4 %, with models I and V in a second group with renormalizations of about 14%.

Second, all models fail to describe the ^{12}C data in the 30°–50° range. The models predict a saddle structure, which is not evident from the data. The reason for this mismatch might be that there are target correlations other than Pauli principle that are not included in the theoretical models.

It can be noted that proton scattering data on ^{12}C at 95 MeV [23], which should agree with our data if isospin were a good symmetry, are closer to our data than the theory models are. The disagreement between models and ^{12}C data should not be overemphasized though. Models which presume mean-field properties of nuclei to be dominant can have problems describing ^{12}C data, because surface effects are very important in ^{12}C.

The models above are all valid for spherical nuclei. It is known, however, that ^{12}C to a significant degree displays properties of a three-α cluster. Coexistence of such a structure with a spherical shape might result in a matter distribution with a more diffuse edge than anticipated by the spherical models, and thus the predicted structure could be washed out.

We have developed a toy model to investigate this hypothesis. The increased effective radius of the ^{12}C ground state due to three-α cluster effects has been studied theoretically for proton elastic scattering, however, at higher energies [24]. We have modified model I, using the parameters of Ref. [24], to calculate the elastic neutron scattering cross section (model VII). As can be seen in Fig. 2, this modification moves the prediction closer to the data in the 30°–50° range, but at the expense that the description gets worse at small angles. It should be pointed out, however, that this should only be seen as an indication of a possible cause of the effect, since the model is too simplified to allow quantitative conclusions.

A basic feature of the optical model is that it establishes a lower limit on the differential elastic scattering cross section at 0° if the total cross section is known, often referred to as Wick's limit. It has been observed in previous experiments at lower energies that for most nuclei, the 0° cross section falls very close to the Wick's limit, although there is no *a priori* reason why the cross section cannot exceed the limit significantly. An interesting observation is that the present ^{208}Pb data are in good agreement with the Wick's limit, while the ^{12}C 0° cross section lies about 70% above the limit. A similar behavior has previously been observed in neutron elastic scattering at 65 MeV [3], where the ^{12}C data overshoot the Wick's limit by about 30%, while the ^{208}Pb data agree with the limit. A follow-up experiment on the ^{12}C cross section at 0° is under analysis.

In short, first results on elastic neutron scattering from ^{12}C and ^{208}Pb at 96 MeV incident neutron energy have been presented, and compared with theory predictions. This experiment represents the highest neutron energy where the ground state has been resolved from the first excited state in neutron scattering. The measured cross sections span more than four orders of magnitude. Thereby, the experiment has met—and surpassed—the design specifications. The overall agreement with theory model predictions, both phenomenological and microscopic, is good. In particular, the agreement in absolute cross section scale is impressive. A detailed account of all aspects of the measurements, including more detailed comparisons with theoretical models, is under preparation [25].

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Studies of Inelastic Scattering of Fast Heavy Ions

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Abstract

In the present experiment 250A MeV ^{17}O ions were inelastically scattered from xenon and argon in the cluster-jet target of the CELSIUS storage ring. The magnetic lattice of the ring is such that the quadrant following the target can be used as a magnetic spectrometer with an acceptance cone of $\pm 0.6^\circ$, centred at 0°. A focal plane telescope, placed in the injection straight section, determined the excitation energy of the residual target nuclei. Data were taken for excitation energies between 15 and 35 MeV. The neutron decay was studied by the EDEN detector array positioned around the target, covering an angular range of 7–110°.

In order to investigate a previously observed forward peaked fast neutron component, significant improvements were made in measurements of neutron energy, angular resolution and coverage, as well as in the design of the focal plane telescope. Preliminary comparisons between data and statistical model calculations show an excess of fast neutrons. The forward peaking of the angular distribution for argon is, however, weaker than was indicated in a previous experiment on xenon.

1. Introduction

In the excitation energy spectrum of about 10 to 50 MeV in nuclei, giant resonances of various multipolarities are prominent features. They have been studied extensively during the last couple of decades. One of the methods used is inelastic scattering of heavy ions, typically in the few tens of MeV per nucleon region [1,2]. Heavy ions have also been used to study multi-phonon giant resonances [3], even at energies of several hundred MeV per nucleon [4].

Very few experiments have been performed at intermediate energies. One example is an experiment where 250A MeV ^{17}O ions were scattered from xenon [5]. Neutrons from the excited target nuclei were recorded in coincidence with the inelastically scattered projectiles. A forward-peaked distribution of the fast neutrons was observed.

In the present experiment, the above-mentioned study is extended using more sophisticated detection techniques both for the charged particles and the neutrons. In particular, a much wider neutron angular range is covered. As a complement to xenon, a lighter target was also studied. The choice of ^{40}Ar, being almost monoisotopic and having two neutrons outside the closed $N = 20$ shell, was made mainly to see whether knockout processes play an important role in the emission of fast neutrons. If the cross section for direct reactions would indeed be large, it could open interesting possibilities for the use of fast heavy ions as probes for the study of the tails of the neutron wave functions, i.e., the neutron skin.

2. Experimental arrangements

The set-up consisted of two detector systems (Fig. 1). One was placed at the focal plane of our spectrometer, where the position of the scattered ions was a measure of the relative energy loss, and thereby the excitation of the target nuclei. The decay, mainly by neutron emission, was studied using a detector array positioned around the cluster-jet target.

2.1. *The CELSIUS ring as a spectrometer*

The experiment was performed at the CELSIUS storage ring. This consists of four quadrants, each with ten dipole and two quadrupole magnets, connected by straight sections. The magnetic lattice is such that the quadrant following the cluster-jet target can be used as a magnetic spectrometer with an acceptance cone of $\pm 0.6^\circ$, centred at 0°. The fields of the two quadrupole magnets positioned between the target and the dipoles are adjusted so that particles scattered inelastically through small angles are focused, both horizontally and vertically, at a detector telescope at the injection straight section of CELSIUS, 22.76 m downstream from the target. This property of the ring has been described previously [6].

In this kind of experiments there is no possibility to detect projectile excitation. This reduces the resolution in excitation energy, and structures linked to bound excited states in the projectile rather than the target can appear in the spectrum. However, as only ions with magnetic rigidities close to that of the beam and, except for very light fragments, with equal or slightly lower charge-to-mass ratios reach the focal plane, one can reduce this problem by selecting a projectile with few states below the neutron emission threshold. Our choice was ^{17}O, which has three such states. Inelastic electron scattering data [7,8] show that only the highest state, at 3.84 MeV, is excited to any considerable extent, but it carries just a small fraction of the total (E3) strength.

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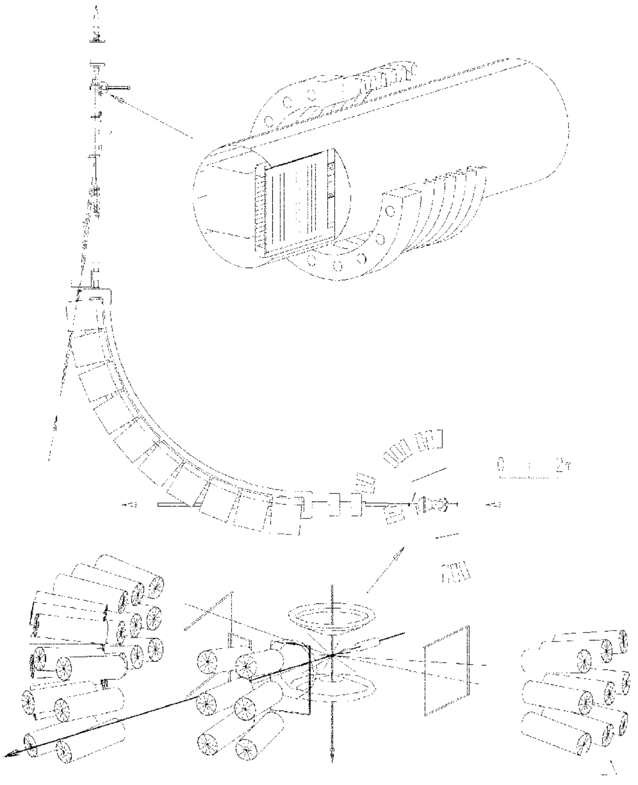

Fig. 1. Plan view of the experimental setup showing the fourth quadrant of the CELSIUS ring with inserts illustrating the focal plane telescope (above) and the neutron detector array around the cluster jet target (below).

2.2. *The focal plane telescope*

The telescope at the focal plane consisted of two single-sided position sensitive silicon strip detectors, the first having vertical and the second horizontal strips, followed by a plastic scintillator used mainly for timing. The detectors were in air, with the whole unit inserted into a stainless steel cylinder with a 0.5 mm thick, flat window (Fig. 1). The cylinder also housed the PM tube of the plastic scintillator, and the preamplifiers for the silicon detectors were placed at its open end. The whole assembly was shielded to reduce noise pickup.

The cylinder was mounted on bellows, and could be moved to the desired position within the beam pipe by the use of a stepping motor. The motor control was linked to the ring cycle, allowing the detectors to be moved into the measuring position after injection and acceleration, thereby avoiding unnecessary radiation damage.

With a 250A MeV ^{17}O beam, the horizontally sensitive silicon detector covered an interval of approximately 20 MeV in excitation energy.

The silicon detectors were 300 μm thick and had an active area of $40 \times 40\,\text{mm}^2$; one side being divided into strips of 1 mm. They were mounted in U-shaped frames, with the open side towards the beam. The detectors were read out by resistive charge division. The signals from each side of the chain were fed into charge-sensitive preamplifiers, followed by spectroscopy amplifiers. After gain matching, the total energy deposited in the detector is proportional to the sum of the two signals, and the position is given by their difference (normalised by the energy).

The advantage of this method compared with individual readout of each strip is simplicity, as it requires only four channels to obtain both horizontal and vertical information. The drawbacks, which include higher noise and lower maximum count rate, did not present a problem in our case. This can be seen in Fig. 2, where the signals from the two sides of the resistor chain in the second, vertically sensitive, detector are plotted versus each other, showing that the individual strips are clearly resolved.

In this figure, one can clearly see bands corresponding to constant pulse heights, i.e. different ions. It is interesting to note that while the ^{17}O band runs across all the strips, the others cover only a few. In the case of ^{17}O this is due to a beam halo, which is created in the interactions of the beam with the target and residual gas molecules. Ions created in nuclear reactions, on the other hand, usually do not have the correct rigidity to make a complete turn around the ring, and the corresponding bands therefore lack a halo. By selecting just the four strips actually covered by the beam, one can greatly improve the ratio of true versus halo events in the data set. One can also add a soft cut that removes ions other than ^{17}O. It should also be noted that Fig. 2 contains raw data, and gating on coincident neutrons strongly reduces the halo contribution.

The signal from the NE102A plastic scintillator was used for the trigger, and served as the start for the time-of-flight measurement of the coincident neutrons. The pulse height information was also used for particle identification, and in order to achieve a sufficient resolution we chose a thickness of 4 cm. When combined with the energy information from the horizontally sensitive silicon detector, the resulting $\Delta E_1 - \Delta E_2$ plot, displayed in Fig. 3, shows a clearly separated ^{17}O peak, as well as some lighter ions. The horizontal tails are mainly due to nuclear reactions in, or scattering out of, the plastic detector. To the upper right there are pile-up events and ^{18}O ions created in pickup reactions. One can also see a weak, but clear, continuous distribution of pulse heights from particles interacting after passing the dipoles, the upper part of which comes from those stopping in the plastic detector. The main source of these particles is the window of the focal-plane cylinder, and a cut on the ^{17}O peak removes them efficiently. Crossing this distribution is a vertical line of ^{17}O events

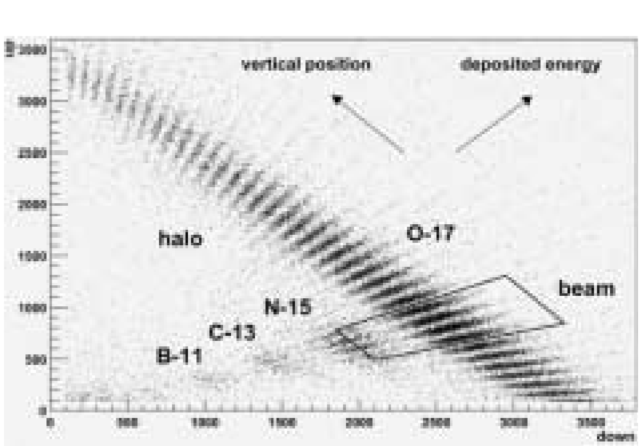

Fig. 2. Display of data from the vertically sensitive silicon-strip detector. The axes show the signals from the upper and lower sides of the detector. The separation of individual strips is illustrated as well as the distributions of scattered ions and halo particles.

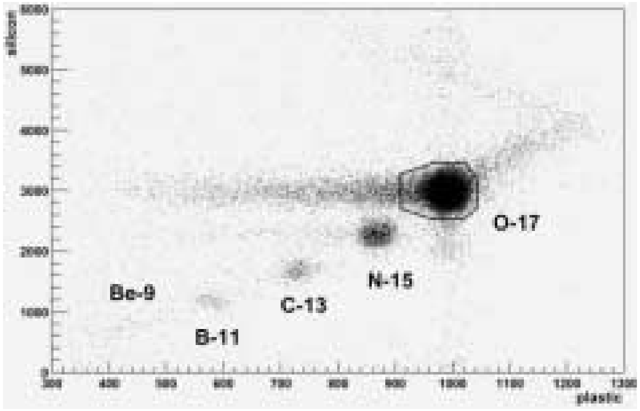

Fig. 3. Scatter plot of the (total) pulse height in the horizontally sensitive silicon-strip detector versus the pulse height in the plastic scintillator of the focal plane telescope. The ^{17}O peak is strongly saturated in order to show other details.

giving pile-up in the silicon detector, but not in the faster plastic.

2.3. *The neutron detectors*

To detect neutrons emitted from the excited target nuclei, the EDEN array was used. It consists of 40 NE213 organic liquid scintillator detectors, each with a thickness of 50 mm and a diameter of 200 mm. The stainless steel front cover of each cell is 0.2 mm thick and deforms as the liquid expands, allowing the detectors to operate at temperatures of up to 45° C. EDEN has been comprehensively described elsewhere [9].

The positions of the detectors around the cluster-jet target chamber are illustrated in Fig. 1. The flight path varied slightly between the detectors, but was around 2 m. The only notable exceptions were the two groups at the most forward angles. These were placed, in order of increasing angle, at 1.5 and 2.3 m, respectively. This represented a considerable improvement in resolution compared to the previous experiment, where three 51 mm and four 152 mm thick detectors were placed at distances between 0.6 m and 0.7 m from the target.

Figure 1 also indicates the thin plastic veto detectors, placed between the neutron detectors and the target, which were added to the EDEN system in this experiment for charged particle identification and rejection.

2.4. *Electronics and data acquisition*

The EDEN array is equipped with a full set of electronics [9] and uses a VME-based data acquisition system, which also reads out the electronics of the focal plane telescope and charged particle veto detectors. Both time and charge were recorded for the vetoes. This allowed us to detect the highest energy protons without lowering the discriminators into the noise.

The trigger condition was a coincidence of a signal in the plastic scintillator of the focal plane telescope and an OR of all the neutron detectors. Since the dead time of the system was low, there was no need to include the vetoes in the trigger.

An important feature of the NE213 scintillator material is that it is well suited for pulse shape discrimination of neutrons from gammas, since the former give pulses with a longer tail. In EDEN this is accomplished by splitting the linear signal into two, and then digitising both branches, one with a long (400 ns) and the other with a short (35 ns) gate.

3. Experimental procedure and results

3.1. *Beam and target*

A beam of $^{17}O^{5+}$ ions from the ECR source was accelerated in the cyclotron to 16.6A MeV. After stripping injection into CELSIUS, the $^{17}O^{8+}$ beam was first cooled and then accelerated to 250A MeV. After acceleration the RF cavity was turned off and the cooler turned on again. This compensated for increased momentum spread of the stored coasting beam due to the target and residual gas. The current after acceleration was typically 1 mA (electric), corresponding to 3×10^8 stored ions, falling to about 50% by the end of the 900 s cycle, of which 87% was used for data taking.

Two target gases were used during the experiment: natural xenon and argon, 99.6% of which is ^{40}Ar. Typical target thicknesses were 1.6 ng/cm^2 for xenon and 3.3 ng/cm^2 for argon.

3.2. *Excitation energy resolution*

The dominant contribution to the resolution in excitation energy is usually the horizontal size of the beam at the target, and its value depends on the precise alignment of the electron beam in the cooler with respect to the ion beam. Since even small drifts would considerably degrade the performance, online monitoring was essential. Two beam profile monitors were available. A magnesium-jet placed at the beginning of the injection straight section provided horizontal information. Continuous monitoring also came from the vertically sensitive silicon detector at the focal plane.

Calculations [6] have shown that the size of the beam at the target is smaller than at the focal plane by a factor of two in the vertical and three in the horizontal plane. The measurements in injection straight section indicate a horizontal beam size of around 1 mm FWHM at the target, contributing approximately by 1.5 MeV to the resolution in excitation energy. Other sources are projectile excitation and the strip width, as each strip covers about 0.5 MeV. Due to its very close proximity to the detector, the contribution from angular straggling in the window of the focal plane cylinder is negligible.

3.3. *Neutron spectra*

The spectra displayed in this section illustrate some of the results obtained so far. They are all from a detector located at a distance of 1.95 m and an angle of 79°. In addition to the cuts on ^{17}O in the focal plane telescope mentioned in Section 2.2, the vetoes have been used to reject charged particles, and pulse shape discrimination to select neutrons. The unusually good n-γ separation in this spectrum is not representative for all detectors, and is helped by a software threshold of 220 keV$_{ee}$, corresponding to 1.05 MeV neutrons. To avoid effects of cross-talk, i.e., neutrons scattered between the detectors, events in which more than one detector fired were rejected.

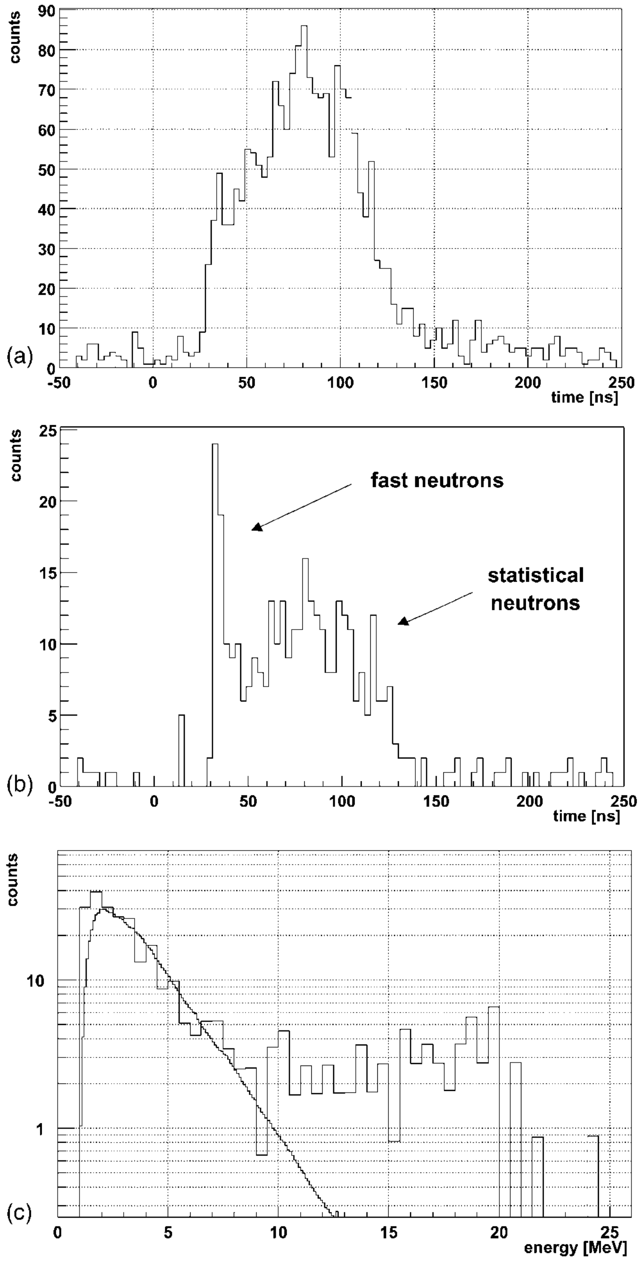

Fig. 4. (a) Neutron time-of-flight spectrum for ^{40}Ar for the entire measured excitation energy range of 15 to 35 MeV. (b) Neutron time-of-flight as in (a), but gated on events with an excitation energy between 25 and 30 MeV, which is well above the peak of the isovector dipole resonance. (c) Neutron energy spectrum corresponding to the time-of-flight spectrum in (b), with a superimposed CASCADE calculation.

Figure 4(a) shows a neutron time-of-flight spectrum for ^{40}Ar for the whole excitation energy range, i.e., 15 to 35 MeV. As expected this is dominated by statistical decay. Figure 4(b) shows a similar spectrum, but from a much narrower excitation energy range, between 25 and 30 MeV, which is well above the peak of the isovector dipole resonance. A strong component of fast neutrons is clearly evident. The structure of the peak can be seen better in the corresponding neutron energy spectrum, as shown in Fig. 4(c). A background corresponding to a constant level in the time-of-flight spectrum has been subtracted. Superimposed is a CASCADE [10] calculation of the statistical decay, which is in good agreement with the low-energy part. The calculation has been corrected for detector efficiency, and uses level densities in the residual nucleus based on Ref. [11].

4. Summary and conclusions

An experiment was performed where 250A MeV ^{17}O ions were scattered at very forward angles on xenon and argon targets. The goal was to investigate the fast neutron component found in earlier measurements on xenon [5] using new detectors that offered improved neutron energy resolution and angular granularity. The coverage was also extended to much smaller angles, from 57° down to 7°.

It is interesting to note that the new focal plane telescope, where the detectors were positioned outside the ultra high vacuum of the CELSIUS ring, not only was simpler to build and operate, but also offered improved performance.

The analysis so far has concentrated on the argon data, and has confirmed the presence of a fast neutron component there. Work is still in progress on reduction of the experimental uncertainties. It is already clear, however, that in the case of argon the angular distribution is not as forward-peaked as the previous xenon data seemed to indicate.

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Appendix V

Development of a Tagged Neutron Facility at Intermediate Energies

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Abstract

A unique experimental facility has been developed to measure absolute neutron scattering cross sections through the use of tagged intermediate-energy neutrons. The neutrons are produced via the reaction $p + d \rightarrow n + 2p$ with an electron-cooled circulating proton beam of 200 MeV bombarding energy incident on a deuterium gas jet target. The "tagging" of the neutrons is accomplished by detection of the associated recoil protons in an array of silicon microstrip detectors located in vacuum. The detection of two protons in coincidence signals the production of a neutron, while energy and position measurements on the recoil protons allow for reconstruction of the four-momentum of the neutron, and its impact position on a secondary target, on an event-by-event basis. Performance characteristics of this facility are presented, and its future application to an absolute measurement of the np elastic scattering cross section is described.

Key words: tagged neutron source, double-sided silicon strip detectors, neutron scattering
PACS: 25.40.Dn, 29.25.Dz, 29.40.Gx, 29.40.Wk

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1 Introduction

An important open question in the field of nucleon-nucleon scattering is the proper normalization for the *np* elastic scattering differential cross section. While total neutron cross sections have been measured precisely [1], many *np* differential cross section data have been reported as relative measurements only, and the normalization methods used to quote absolute cross sections in other cases are not entirely reliable or have large uncertainties. The primary difficulty in determining the normalization in these experiments stems from the problem of accurately determining the absolute neutron flux. Beyond the normalization question, there are inconsistencies in the *np* database at intermediate energies which a high-precision differential cross section measurement might also address. For example, there are existing datasets that differ in the shape of the angular distribution at backward angles [2,3], and those who perform analyses of NN data often use controversial criteria in selecting which data to include [4–6]. The experimental discrepancies in both normalization and shape of the differential cross section could in principle be resolved by a measurement of *np* elastic scattering using a "tagged" neutron beam. Such a measurement would also have considerable bearing on the controversy over the proper value for the pion-nucleon coupling constant [2,6,7], one of the basic parameters of nuclear physics.

This work describes the development and commissioning of a tagged neutron facility at the Indiana University Cyclotron Facility using the Cooler, the laboratory's electron-cooled light ion storage ring [8]. The term "tagged neutrons" indicates that the neutrons used as a beam for a scattering experiment each have their production marked by the detection of the other final-state particles emerging from the initiating reaction. The production of tagged neutrons in this manner presents the possibility of measuring absolute neutron cross sections with unprecedented precision via direct counting of the neutron flux through the scattering target. The key to this endeavor is to determine the path of each produced neutron with sufficient precision to discern reliably whether and where the neutron passes through a secondary scattering target. Previous attempts [9,10] to tag intermediate-energy neutrons for the purpose of calibrating neutron detector efficiencies have not focused on preparing a secondary beam useful for neutron scattering experiments.

2 Experimental Setup

2.1 Basic Concept

A storage ring with a cooled beam and internal target, such as the IUCF Cooler [8], possesses many of the attributes necessary for a tagged medium-energy neutron facility. First, a windowless gas target makes possible detection of low-energy recoil particles associated with the production of a neutron, while the storage ring environment provides reasonable luminosities even with such thin production targets. Electron cooling results in beams of well-defined energy with very narrow energy spread ($\Delta T_p \lesssim 20$ keV for $T_p = 200$ MeV), so that the energy of a neutron can be accurately determined from energy measurements of the low-energy recoil particles associated with its production. Furthermore, the small emittance of a cooled beam results in a tight constraint for both the lateral event origin (due to the small beam size) and initial momentum direction (due to the small divergence) of the neutron. As will be explained further below, both of these constraints facilitate kinematic reconstruction of an outgoing neutron with good resolution.

The production reaction chosen is $p + d \rightarrow n + 2p$ using a circulating proton beam of bombarding energy near 200 MeV incident on a deuterium gas jet target (GJT) [11]. This reaction is one which has been used to produce neutron beams for other experiments, such as in the Polarized Neutron Facility (PNF) at IUCF [12]. A favorable aspect of this production reaction is that the strength of the $^1S_0$ final state interaction for the two outgoing protons results in a neutron beam of relatively small intrinsic energy spread (∼10 MeV) at small angles [13]. To tag a neutron using this reaction, it is necessary to detect two protons of low energy (∼0.5–15 MeV) in coincidence in a detector array (the "tagger") located in vacuum. Energy and position measurements of the recoil protons allow reconstruction of the four-momentum of the neutron, making it possible to determine whether and where the neutron is incident on the secondary target. A side benefit to use of this system is that a tagged secondary proton beam can be defined and used simultaneously with the tagged neutrons, by detecting recoil deuterons in the tagger from elastic $p + d$ scattering events in the GJT. The simultaneous acquisition of secondary np and pp scattering events permits careful crosschecks to be performed on the target thickness and detector acceptances relevant to the secondary scattering.

Due to the three-body $n + 2p$ final state, even for neutrons of a fixed energy at a particular angle, the recoil protons emerge with a distribution spread both in energy and angle. Consequently, the tagging efficiency (the fraction of neutrons incident on the target that are tagged) attained depends on both the solid angle covered by the recoil detectors and the triggering efficiency for pairs of protons with small spatial separation. A tagging efficiency well below unity can be accommodated because we require a tag to be associated with all neutron scattering events analyzed, so that the untagged neutrons incident on target do not enter into the analysis. It is also important to exclude the substantial fraction of *tagged* neutrons that miss the secondary target, placing a premium on good energy and position resolution for the recoil protons. These two classes of uninteresting neutrons do not complicate absolute cross section measurements as long as the associated rates are not too high. That is to say, the rates in the forward detector array from the scattering of *untagged* neutrons must be small enough that accidental coincidences with tags not become a problem. Likewise, the rate of tagged neutrons that do not pass through the target must be small enough that it does not dominate the tagged neutron flux sample. In practice the tagged neutron beam is defined by the size and placement of the secondary scattering target. Likewise, the neutron energy distribution, as well as the upper limit on the tagged neutron yield (given by the actual neutron production cross section), is set by the range in outgoing neutron angle defined by the placement of the secondary target. Finally, the operating luminosity is limited by the rate of false neutron tags arising from accidental coincidences in the recoil detector.

One issue that must be dealt with is the extended nature of the gas jet target. Because only one (x, y) position measurement is made on each recoil proton (they are generally too low in energy to traverse two position-sensitive detectors), the event origin must be known to determine the angles at which the protons emerged, and, therefore, the outgoing angle of the neutron. The longitudinal coordinate (z) of the event vertex along the central beam axis is determined by comparing the magnitude of the outgoing neutron's momentum calculated using conservation of energy,

$$p_E c = \sqrt{(E_i - E_{p1} - E_{p2})^2 - m_n^2 c^4} \tag{1}$$

to that calculated using conservation of momentum:

$$\vec{p}_M(z) = \vec{p}_i - \vec{p}_{p1}(z) - \vec{p}_{p2}(z). \tag{2}$$

In Eqs. (1) and (2) E_i is the initial total relativistic energy of the system (beam proton plus target deuteron) and $\vec{p}_i$ is the incident proton momentum vector; $(E_{p1}/c, \vec{p}_{p1}(z))$ and $(E_{p2}/c, \vec{p}_{p2}(z))$ denote the four-momenta of the two detected recoil protons; and m_n is the neutron rest mass. Note that evaluation of Eq. (1) is independent of z, while the recoil proton three-momenta in Eq. (2) are not. By forming the quantity,

$$\Delta\, p(z) \equiv p_E - p_M(z), \tag{3}$$

Measurement of the Absolute Differential Cross Section for np Elastic Scattering Near 190 MeV

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The np scattering database at intermediate energies is marred by inconsistencies among cross section angular distributions measured by different groups[1], and by the absence of solid experimental absolute normalizations.[1,2] These problems have led, in the past, to controversy[1−4] over the selection criteria used for inclusion of data in partial wave analyses and over extracted values of the πNN coupling constant. We will report preliminary results of a new experiment carried out at the Indiana University Cooler ring, dedicated to a cross section measurement of high absolute precision.

The experiment utilized a tagged neutron beam produced by forward charge exchange of a 200 MeV electron-cooled, stored proton beam in a deuterium gas jet target. The thin target permitted detection of the two low-energy recoil protons in a double-sided silicon strip detector (DSSD) array, to provide event-by-event determination of the neutron energy (with a typical FWHM resolution $\sim$150 keV) and impact position (FWHM $\sim$few mm) on a secondary target $\sim$1 m downstream of the production target. Solid secondary targets of CH_2 and C, carefully matched in transverse dimensions and in the areal density of carbon nuclei, were interchanged often during the experiment to allow reliable subtraction of quasifree scattering background from the free-scattering signal. Protons from np scattering in the secondary target were detected in a forward array of plastic scintillators and multi-wire proportional chambers spanning a c.m. angle range from 90° to 180°. Tagged pp scattering was measured simultaneously with the same targets and detectors, tagging the secondary proton beam via DSSD detection of recoil deuterons from pd elastic scattering in the gas jet production target. The layout of the tagger and forward detection array is shown in Fig. 1.

The data sample acquired is sufficient to yield a statistical precision approaching $\pm$1% in most angle bins ($\approx$ 5° c.m. bin width), growing to a few % at $\theta_{c.m.} \geq 170°$. The systematic error goal for the measurement is $\pm$1% on the absolute cross section scale. Systematic error analyses and internal consistency checks on the measured cross sections will be presented. The results will be compared with those of other measurements at nearby energies and of partial wave analyses of the existing database.

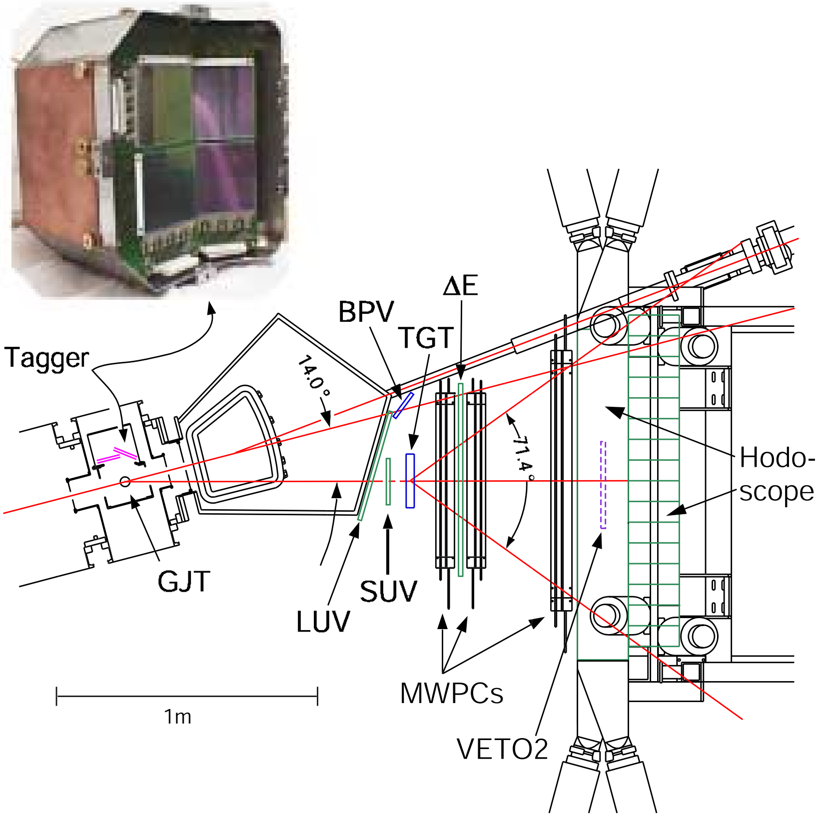

Figure 1: A top view of the experimental setup for the np scattering experiment, including the tagger (DSSD's in housing shown in inset photo), the 6° Cooler magnet and exit pipe for the stored primary protons, and the secondary target and forward detector array.

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Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development **25-Jun-2003**

English - Or. English

NUCLEAR ENERGY AGENCY
NUCLEAR SCIENCE COMMITTEE

NEA/SEN/NSC/EG(2003)4
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Executive Group

SUMMARY RECORD OF THE TWELFTH MEETING OF THE EXECUTIVE GROUP OF THE NUCLEAR SCIENCE COMMITTEE

4th June 2003 (a.m.)
Château de la Muette, Paris

JT00146664

English - Or. English

SUMMARY RECORD OF THE TWELFTH MEETING OF THE EXECUTIVE GROUP OF THE NUCLEAR SCIENCE COMMITTEE

4th June 2003

1. The Chair, P. D'Hondt, Belgium, opened the meeting and welcomed the delegates. Eleven delegates from Member countries and one delegate from the EC attended the meeting. T. Mori, Japan, participated for the first time. Apologies for absence had been received from H. Leeb, Austria, R. Mach, Czech Republic, E. Nonbøl, Denmark, W. Wiesenack, Norway and N. Olsson, Sweden.

2. The NEA Deputy Director, T. Dujardin, informed the Group that the Data Bank manpower situation was expected to remain at the present level throughout 2003 and 2004. The A5 post as head of the Data Bank had been announced in early autumn 2002, but the recruitment had been delayed due to an imposed freeze of vacant posts, as a result of the difficult budget discussions in OECD. The programmer C. Penon had been replaced by T. Ergun from Turkey and a post as assistant to the system manager had recently been announced. Two professional posts, both allocated to the nuclear data services, were expected to become vacant, one in autumn 2003 and the other in the first half of 2004.

Adoption of the Agenda

3. The proposed agenda for the twelfth meeting of the Executive Group was adopted without modification.

Approval of the Summary Record of the Eleventh Meeting of the Executive Group

4. The Summary Record of the eleventh meeting of the Executive Group was approved without modification.

Progress Report for 2002, Work in hand in 2003 and Programme of Work for 2004

5. C. Nordborg, NEA, introduced the document (NEA/SEN/NSC/EG(2003)2) containing the progress report for 2002, as well as the status of the biennial programme of work for 2003 and 2004. He informed the group that a few erroneous numbers had been found in the tables on page 19 and that a new version of the document would be issued shortly.

Computer program services

6. E. Sartori, NEA, presented an overview of the computer program services, including statistics on the acquisition and distribution of computer programs and integral data sets. Close to 4700 requests for computer codes and integral data sets had been recorded in 2002, which was the highest figure ever. The increase in the request for computer programs was especially noticeable, with a 35% increase compared to 2001. It was also noted that the computer documentation had now been transformed into computer-readable form, to enable all program packages to be distributed on CD-ROM. Five computer program training courses had been organised in 2002, mainly related to the Monte Carlo code MCNP, and another 6-7 courses were planned for 2003.

7. I. Kodeli, the IAEA representative at NEA, presented the computer program services to the non-OECD member countries. More than 900 packages, representing about 20 percent of the total Data Bank distribution, had been sent upon request to non-OECD countries in 2002. This increase was partly due to requests originating from the Workshop on Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety held in February and March 2002 at the International Centre for Theoretical Physics (ICTP).

8. One of the delegates noted that many program packages had been distributed to non-OECD countries that had not signed the non-proliferation treaty (NPT). He expressed his concern about this development and cautioned the Data Bank to strictly follow the distribution restrictions imposed on the individual computer programs by the originating country. T. Dujardin assured the Executive Group that the Data Bank was well aware of these restrictions and that they were meticulously followed by the computer program service team.

9. Y.-J Kim, Korea, considered that the Data Bank computer program training courses were very useful and he asked if such courses could be arranged also in the Asian region. E. Sartori answered that some courses were being arranged by RIST in Japan and that the Data Bank would consider organising courses, in for example Korea, if a minimum number of participants could be guaranteed. The cost for organising a course depended mainly on charges related to infrastructure and on remuneration of teachers. A typical participation fee for courses organised in Europe was about 2 000 – 2 300 Euros.

Nuclear Data Services

10. The nuclear data services were presented by M. Kellett, NEA. The number of compiled data for the databases containing bibliographic data (CINDA) and experimental data (EXFOR) had been in line with the previsions. It had recently been agreed with the IAEA that the NEA Data Bank would in the future assure the annual printing and distribution of the CINDA book. Concerning the nuclear data services, it was noted that the accesses to the on-line services had drastically increased following the decision last year to remove the password restrictions. A total of about 14 500 accesses to the databases had been registered in 2002.

11. The Data Bank had also developed a database system for the High Priority Request List for Nuclear Data, maintained by the Nuclear Science Committee's Working Party on International Nuclear Data Evaluation Cooperation (WPEC). The database had been made available through the NEA Internet server, but very limited feedback had so far been received. The WPEC will organise a meeting in September 2003 to review and revise the list.

12. A. Nouri, NEA, presented the development of the JANIS software for displaying nuclear data. The new version, to be released in autumn 2003, would contain a number of new features and would as well incorporate the CINDA database.

13. S. Qaim, Germany, expressed his strong support for the nuclear data compilation effort. He also asked about the emphasis of the charged particle induced compilations, the coordination of decay data evaluations, and the completeness of the EXFOR database. The Data Bank secretariat answered that the emphasis, in the case of the charged particle compilations, were on light particle induced reactions, that the JEFF decay data library was well coordinated with the international ENSDF (Evaluated Nuclear Structure Data Evaluation) effort, and that the EXFOR neutron induced compilations were near to 100 percent complete. However, the charged particle-induced EXFOR compilations, which had started at a later date, were not complete and were performed according to request lists. M. Kellett encouraged nuclear data users to inform the Secretariat of data, or types of data, they wished to see compiled in the EXFOR database.

The JEFF project

14. A. Nouri, NEA, and A. Koning, the Netherlands and Chair of the JEFF project, presented the status and future plans for the Joint Evaluated Fission and Fusion (JEFF) project. Following the release of the JEFF-3.0 General Purpose library in April 2002, the work on the file was presently concentrating on the validation of the data. In parallel, some limited efforts were also being devoted to the assembling of the special purpose files, containing radioactive decay and fission yield data, and the evaluation or revision of a number of isotopes, some of which would be extended to 200 MeV. It was, however, noted that less and less manpower was available to complete the planned work within the JEFF project, and that efforts had been made to strengthen the co-operation with the EU nuclear data activities.

15. The JEFF Scientific Coordination Group asked the Executive Group to approve a prolongation of the mandate for 3 years and to nominate or confirm the nomination of their country representatives to the JEFF steering group.

16. The Executive Group approved the proposed JEFF mandate and agreed to review the nomination of JEFF representatives. Member countries were also strongly encouraged to allocate additional resources to the JEFF project to help complete the planned programme of work over the next 3 years.

Provision of expertise to other parts of NEA

17. C. Nordborg, NEA, reminded the delegates that the Data Bank provides expertise to other parts of the NEA, according to a long-standing agreement. The area of expertise is primarily in database development and maintenance. The main parts of these efforts, which represent less that 25 percent of the Data Bank's total resources, are allocated to the Thermochemical database (TDB) project and to the databases developed by the Nuclear Science Committee (NSC). The NSC related activities are described in the progress report for that committee. The Data Bank also assists the NEA Nuclear Safety Division by maintaining and distributing data from the Code Validation Matrix (CCVM), as well as archiving data from the CABRI, RASPLAV and MASCA experiments.

Chemical Thermodynamic Database (TDB) project

18. F. Mompean, NEA, reported on the Thermochemical database (TDB) project, which is a separately-funded project, carried out in close cooperation with the NEA Radioactive Waste Management Division. The review of data for inorganic species of Ni, Zr, Se, Tc, U, Np, Pu, and Am, as well as for selected organic ligands, was being completed and the reports would be published later this year or in mid-2004. A new 4-year phase of the project had been started in the beginning of 2003, comprising the review of chemical thermodynamic data for Th, Fe, Mo and Sn.

19. S. Qaim, Germany, asked about the criteria behind the selection of elements in the new phase of the project. F. Mompean answered that the choice of elements resulted from discussions with users of Thermochemical data, especially those participating in the Integration Group for the Safety Case (IGSC) under the NEA Radioactive Waste Management Committee.

In-house Computer System

20. P. Nagel, NEA, described the Data Bank's in-house computer system. It was noted that the Internet connections to the Data Bank had been upgraded and that the cluster of Linux computers were in

place. Future efforts would be devoted to upgrading the firewall, the Oracle databases, and the Internet server. Reduction of spam E-mail was also going to be addressed.

Proposed budget for 2003 and 2004 (NEA/SEN/NSC/EG(2002)3)

21. C. Kessler, the NEA Deputy Director General, informed the Executive Group of the OECD budget procedure and the decision by the OECD Council to agree on a 2003 and 2004 budget envelope, limited to a yearly increase of 1.8 percent. This agreement represented a compromise between zero nominal and zero real growth. Carol Kessler also reported on plans to use unspent funds from 2002 to renovate the NEA conference rooms and to establish a Loss Of Employment (LOE) indemnity fund. The proposals had been approved by the OECD budget committee and were pending decision by the OECD Council. C. Nordborg concluded the presentation by highlighting a few items in the document containing the detailed Data Bank budget figures.

Conclusions and recommendations

22. The Executive Group took note of the progress report and recorded the fact that the NEA Data Bank services were more and more solicited in Member countries.

23. The Executive Group recommended the Nuclear Science Committee to endorse the proposed Data Bank budget and programme of work for 2004.

Points for Presentation to the Nuclear Science Committee

24. The NEA secretariat was asked to prepare, in close consultation with the Chair, a short summary of the meeting for presentation at the Nuclear Science Committee meeting.

Twelfth Meeting of the
Executive Group of the NEA Nuclear Science Committee
4th June 2003

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Organisation de Coopération et de Développement Economiques
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04-Jul-2003

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NUCLEAR ENERGY AGENCY
NUCLEAR SCIENCE COMMITTEE

NEA/SEN/NSC(2003)3
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SUMMARY RECORD OF THE FOURTEENTH MEETING OF THE NUCLEAR SCIENCE COMMITTEE

4th – 6th June 2003
Château de la Muette

English - Or. English

JT00147090

SUMMARY RECORD OF THE FOURTEENTH MEETING OF THE NUCLEAR SCIENCE COMMITTEE

4th – 6th June 2003

1. The Chair, T. Lefvert, Sweden, opened the meeting and welcomed the delegates. The following new members of the committee were introduced: Y. Guerin, France, T. Mori, Japan, J. Bahna, Slovak Republic and J. Herczeg, USA. H. Herzog, Germany, was invited as expert for the in-depth discussion on "Medical Application of Radioisotopes".

2. Apologies for absence had been received from H. Leeb, Austria, R. Mach, Czech Republic, E. Nonbøl, Denmark, D. Cacuci, Germany, W. Wiesenack, Norway, and N. Olsson, Sweden. The observers from Slovenia, B. Glumac and P. Stegnar, were not able to participate.

Introduction by the Director General

3. L. Echavarri, Director General of NEA, informed the committee of recent events within the OECD and the NEA, with special emphasis on the spring meeting of the NEA Steering Committee. The budget envelopes for 2003 and 2004 had been decided at the end of March 2003 and resulted in a 1.8 percent increase each year. This was less than zero nominal growth and the needed economies would be met by delaying recruitment of some vacant posts.

4. The NSC was encouraged to increase its contacts and cooperation with scientists in Russia and China, and especially with Russia in view of their renewed interest to sign a joint declaration of cooperation. A time-schedule for the development of a new NEA Strategic Plan had been presented at the last NEA Steering Committee meeting and the policy debate had been devoted to issues related to radiation protection. The progress in the Generation-IV project had been slower than expected, but the role of the NEA, as the major player in the technical secretariat of the project, was still maintained.

Adoption of the Agenda (NEA/SEN/NSC(2003)1/REV1)

5. The points 4.1.2 Workshop on "R&D needs for Current and Future Nuclear Systems" and 4.2.1 "R&D needs in Nuclear Science" were proposed to be merged. The same was proposed for points 4.4 "NSC sponsored workshops and meetings in the second half of 2003" and 7 "Meetings, Conferences, Publications and NSC Web pages". It was suggested to hold the in-depth discussions on Thursday morning (5th June).

6. The proposed revisions were adopted.

Approval of the Summary Record of the 13th Meeting (NEA/SEN/NSC(2002)3)

7. The summary record of the thirteenth meeting of the NSC was approved without modifications.

Status of Committee Projects (NEA/SEN/NSC(2003)2)

Follow-up to recent NSC organised workshops and meetings

Seventh Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation

8. B.-C. Na, NEA, presented the highlights from the seventh Information Exchange meeting on Partitioning and Transmutation, which had been held on Jeju Island, Korea, on 14th to 16th October 2002. The meeting had been organised in close coordination with the NEA Nuclear Development Division, and had been hosted by Korea Atomic Energy Research Institute (KAERI), Korea Electric Power Research Institute (KEPRI), and Korean Nuclear Society (KNS). The European Commission (EC) and the International Atomic Energy Agency (IAEA) had also cooperated in the organisation of the meeting.

9. More than 160 participants from 16 countries and 4 international organisations had participated and 100 papers had been presented. The opening session was dedicated to national and international programmes on P&T and was followed by six technical sessions covering the following subjects:

- Fuel Cycle Strategy and Future Reactors
- Progress in Partitioning and Waste Forms
- Progress in Fuels and Targets
- Progress in Materials: Spallation Targets and Advanced Coolants
- Progress in Physics and Nuclear Data
- Transmutation Systems (Critical and Sub-critical): Design and Safety

10. A panel session was devoted to discussions on future developments in P&T concluded the meeting.

11. The next Information Exchange meeting on Partitioning and Transmutation will be held in Las Vegas, USA, on 9-11 November 2004. The NEA Nuclear Development Division will this time assume the main responsibility for the organisation of the meeting.

Short review of NSC expert groups and task forces

R&D needs in Nuclear Science

12. P. D'Hondt, Belgium, reminded the committee about the decision at the last NSC meeting to organise a workshop on "R&D needs for current and future nuclear systems" to review major scientific concerns in member countries. The workshop was held at the OECD Headquarters on 6-8 November 2002. Following presentations of former NSC activities and of R&D needs for new nuclear systems, the workshop split up in three working groups covering "Nuclear data", "Reactor physics and systems behaviour", and "Materials, coolants, fuels and chemistry". Each working group provided recommendations for future R&D in their assigned area of responsibility. The presented papers and the recommendations have been assembled in a report, which will be published in the summer of 2003.

13. R. Chawla, Switzerland, encouraged, in line with the recommendations from one of the working groups, the NSC to consider establishing separate funded joint projects in specific areas, especially in cases where experimental activities were involved. The NSC agreed to highlight this possibility in the final report, but indicated that proposals for such projects should preferably originate from outside the NSC established programme of work.

14. The “introduction”, “executive summary” and “conclusions and recommendations” parts of the final report on “R&D needs in Nuclear Science” were distributed and the NSC members were asked to provide the NEA secretariat with feedback on these parts of the document before the end of June 2003.

15. T. Happalehto, NEA, informed the committee about the outcome of the questionnaire the NEA Nuclear Development Committee (NDC) had circulated within its project on “International Collaboration to Achieve Nuclear Support Excellence”. It was noted that only a limited amount of data on human resources had been received. T. Happalehto presented a proposal on how to advance on the question of resources and asked the NSC for feedback on his proposal within three weeks.

16. T. van der Hagen, the Netherlands, asked how the NEA envisaged using the results of the NDC study on Nuclear Support Excellence. T. Dujardin, NEA, answered that the conclusions would be fed back to member countries, for them to act on according to their own policies, as had been done with the previous NDC study on ”Nuclear Education and Training: Cause for Concern?”. Many delegates confirmed that a number of actions had been taken as a result of the NDC study on “Nuclear Education and Training”, for example the creation of educational and training centres, fellowships, and specialised networks. P.E. Juhn, IAEA, informed the NSC about the IAEA activity on knowledge preservation and the proposal to establish a World Nuclear University (WNU).

Preservation of Reactor Physics Experiments (IRPhE)

17. J. Gado, Hungary, recalled the discussions at the last NSC meeting and the subsequent completion of the pilot project to compile and evaluate 6 test cases. He also asked the NSC to endorse the proposed mandate and programme of work for 3 years, as specified in the annex to the progress report, and to assign a limited number of NSC members to oversee the project.

18. The NSC expressed a unanimous strong support for a continuation of the project. It was noted that the success of the project would to a very large extent depend on the available funding. T. Dujardin, NEA, expressed his gratitude especially to Japan and Korea for their financial and in-kind contributions, respectively. He hoped that this support could be continued and that other countries would follow and provide resources to the project. He underlined the fact that the NEA resources alone would be insufficient to run the project successfully.

19. The NSC endorsed the proposed mandate and programme of work for 3 years and assigned J. Gado, Hungary, P. D’Hondt, Belgium, A. Hasegawa, Japan, and A. Zaetta, France to oversee the project.

Reactor-based Plutonium Disposition

20. P. D’Hondt, Belgium, described the ongoing and planned benchmark exercises in the areas of fuel behaviour and reactor physics. He underlined that the activities in the latter area was being pursued in close collaboration with the NSC Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles (WPPR). A new MOX benchmark exercises related to fluence and dosimetry studies was proposed.

21. J. Gado, Hungary, expressed his support for the new fluence and dosimetry benchmark. E. Menapace, Italy, asked if some of the benchmarks had provided feedback on nuclear data libraries. P. D’Hondt answered that both the KRITZ-2 and the VENUS-2 benchmarks had given relevant indications that would be communicated to WPEC. The feedback from the two benchmarks would be co-ordinated in order to express consistent conclusions or point out relevant discrepancies.