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Annual Report 1998/99

J Blomgren, C Johansson, J Klug,
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September 1999

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1 Introduction

The present project, supported as a research task agreement by Statens Kärnkraftsinspektion (SKI), Svensk Kärnbränslehantering AB (SKB), Barsebäck Kraft AB (BKAB) and Vattenfall AB, started according to the plan 1998-07-01. From 1999-01-01 the project also receives support from Försvarets forskningsanstalt (FOA). 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,
- push forward 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,
- constitute a basis for Swedish participation in the nuclear data activities at IAEA and OECD/NEA.

The project is run by the Department of Neutron Research 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 (1998-07-01–1999-06-30) of the project.

2 Accelerator-driven transmutation (ADT)

The basic idea behind ADT is to feed an undercritical core with external neutrons, produced via spallations of heavy nuclei by a high-intensity ion beam.

The neutron flux, which could be some orders of magnitude higher than in conventional power reactors, emanates from the stopping of a proton (or possibly deuteron) beam at high energy, $1 - 2$ GeV, of high intensity ($20 - 100$ mA). A majority of the neutrons arise from "evaporation" from highly excited states in the produced nuclei. The resulting energy spectrum resembles a $1/E$ spectrum, with a peak at low energy (about 1 MeV) and maximum energy at about the ion beam energy.

These fast neutrons are subsequently used in a surrounding reactor core. This core could be loaded with, e.g., long-lived actinides or fission products (like ^{99}Tc) from spent fuel. Fission or capture could then result in short-lived or stable elements, with the simultaneous release of energy from the fission reactions. This might reduce the amounts of high-level waste, and could potentially ease the design specifications for a deep repository. The released energy could be used to drive the ion accelerator and/or support the grid. In a longer time perspective, similar methods might be used to provide energy.

The main advantage with this method is that elements that are difficult to use in reactors based on self-supporting chain reactions could be burned. For instance, some elements are troublesome to destroy in conventional reactors because of a very low fraction of delayed neutrons, making the reactivity control difficult.

3 Nuclear data for ADT

Design and construction of a transmutation core requires extensive simulations, which in turn makes knowledge of basic nuclear parameters necessary. Therefore, nuclear data libraries extending up to about 2 GeV are of interest, with the region up to 200 MeV being the most important. The data files of today extend up to 20 MeV, which is sufficient for conventional reactors.

Measuring all reactions present in a future core is not only a formidably time-consuming task, it is even impossible in theory. Many short-lived nuclei play a vital role in such a core, but cannot be directly studied. Therefore, nuclear data activities should be directed to obtain a good theoretical understanding.

The nuclear data priority list at intermediate energies formulated by OECD/NEA, primarily for ADT applications, has been used to guide the project. This request list has been established after careful judgement and priority grading, where many research groups around the world has participated, and it contains both neutron- and proton-induced data. A number of laboratories around the world have proton beams, while the neutron beam at TSL is world-unique. We have decided to concentrate on neutron data because of this competitive edge.

Discussions with a variety of experts, especially at international conferences, revealed that elastic neutron scattering should be given very high priority. There are several reasons for this, the most important being that it allows a determination of the optical potential, which plays a role in every calculation including neutrons in either the entrance or exit channel [1]. The elastic cross section is also the largest of the individual partial cross sections contributing to the total cross section [2]. In fact, a consequence of the optical model is that the elastic cross section must be at least half the total cross section.

Elastic neutron scattering is of utmost importance for a vast number of applications. Besides its fundamental importance as a laboratory for tests of isospin dependence in the nucleon-nucleon, and nucleon-nucleus, interaction [3], knowledge of the optical potential derived from elastic scattering is an ingredient in virtually every application where a detailed understanding of nuclear processes are important. We therefore intend to measure scattering of 100 MeV neutrons on a series of nuclei.

It is very difficult to determine the intensity of a neutron beam to better than 10%. This mean that all measurements aiming at a better precision have been done relative to a "known" standard cross section, which is the neutron-proton scattering differential cross section. Recent data from Uppsala have questioned the precision of previous data on this reaction [4, 5, 6, 7]. There might be discrepancies as large as $10 - 15\%$. Accordingly, np scattering is also part of the project.

During this first year of the project, an EU supported "Concerted Action", in which our group participates, has resulted in that we have got in touch with a large French-Belgian collaboration (headed by J.-F. LeColley), which has directed their work towards gas production in transmutation cores. Their main interest is (n,p) and (n,α) reactions, which they planned to study using solid-state detector telescopes. Such a detector setup

(MEDLEY), developed for measurements of nuclear data relevant for optimization of fast-neutron cancer therapy, has already been installed at the TSL neutron beam. This facility suited the specifications of the French-Belgian group very well, and they have already run their first experiment with it, and have proposals for further measurements.

The data provided by this experiment series are used for determining the hydrogen and helium production in the core. Because it is explosive, there are obvious reasons to have hydrogen production under control. Helium is of interest because it embrittles structural material, primarily steel. In addition, these data are very useful for benchmarking of pre-compound models, which are used to calculate charged-particle production [8, 9, 10, 11].

4 Experiments and experimental equipment

4.1 Neutron production

At the neutron facility at the The Svedberg Laboratory (TSL), Uppsala, Sweden [12] (see fig. 1), quasi-monoenergetic neutrons are produced by the reaction ^{7}Li(p,n)^{7}Be in a target of 99.98% ^{7}Li. After the target, the proton beam is bent by two dipole magnets into an 8 m concrete tunnel, where it is focused and stopped in a well-shielded carbon beam-dump. A narrow neutron beam is formed in the forward direction by a system of three collimators, with a total thickness of more than four metres.

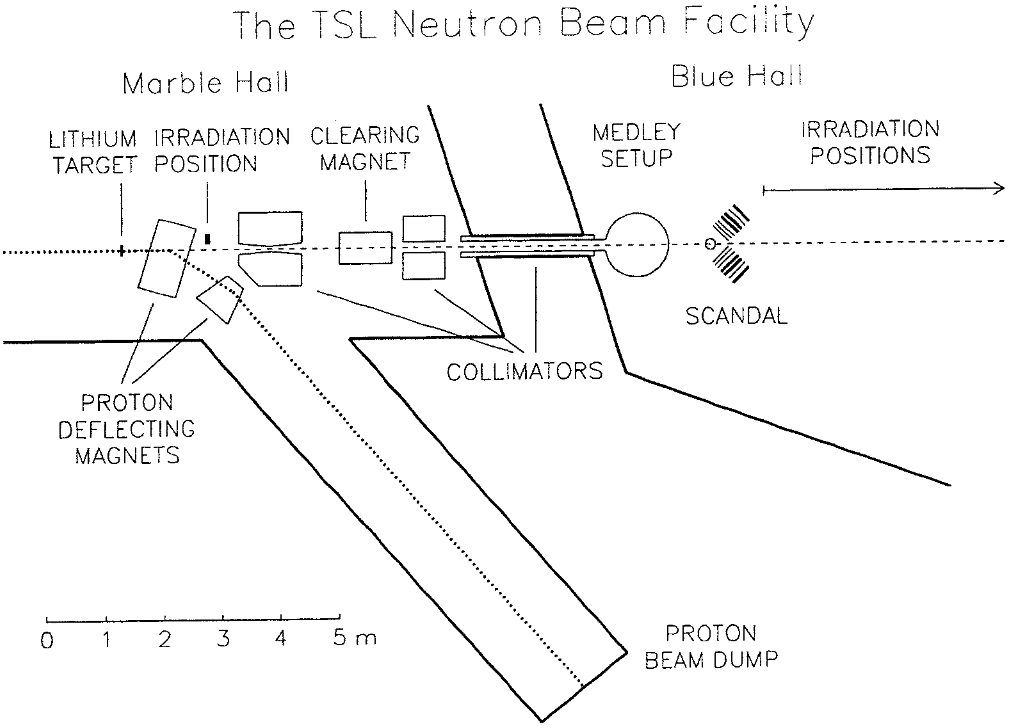

Figure 1: The TSL neutron beam facility.

The energy spectrum of the neutron beam is shown in fig. 2. About half of all neutrons appear in the high-energy peak, while the rest are roughly equally distributed

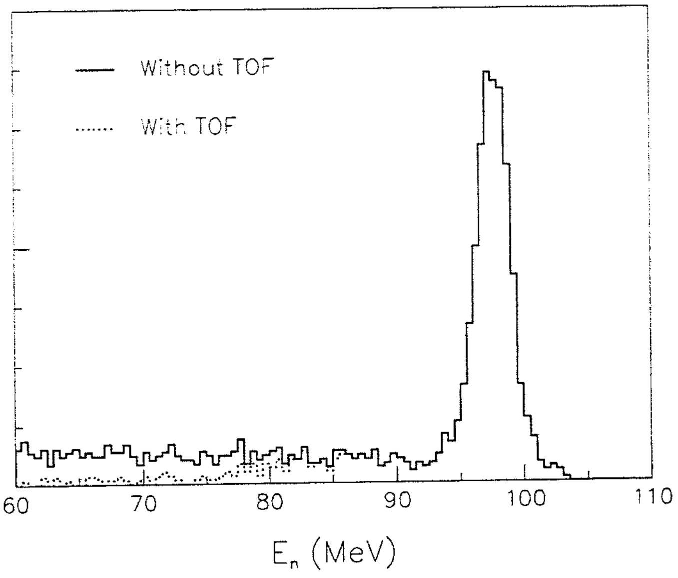

Figure 2: The neutron energy spectrum with and without time-of-flight rejection of low-energy neutrons.

in energy, from the maximum energy and down to zero. The thermal contribution is small. The low-energy tail of the neutron beam can be reduced by time-of-flight measurements (see fig. 2). With a proton beam of 5 μA onto a 4 mm lithium target, the total neutron yield in the full-energy peak at the experimental position, 8 m from the production target, is about $5 \cdot 10^4$ cm^{-2}s^{-1}. The energy resolution of the full-energy peak depends on the choice of lithium target thickness. For most experiments a resolution of about 1 MeV (FWHM) has been selected.

4.2 Monitoring

Absolute normalization of the neutron flux is a notorious problem in all high-energy neutron-beam applications. For direct neutron monitoring, fission counters are available, which have been calibrated relative to *np* scattering, allowing an uncertainty of no more than 5%.

Relative monitoring can be provided by many different means. Charge integration of the primary proton beam is one of the standard techniques. In addition, for most of the experiment periods, many different experiments (up to seven so far) can be running simultaneously, and then it is common to use signals from the other experiments as relative monitors.

4.3 Base equipment

Two major experimental setups are semi-permanently installed. These are the MEDLEY detector telescope array, housed in a scattering chamber and operated in vacuum (see fig. 3). At the exit of this chamber, a 0.1 mm stainless steel foil terminates the vacuum system, and from here and on the neutrons travel in air. Immediately after

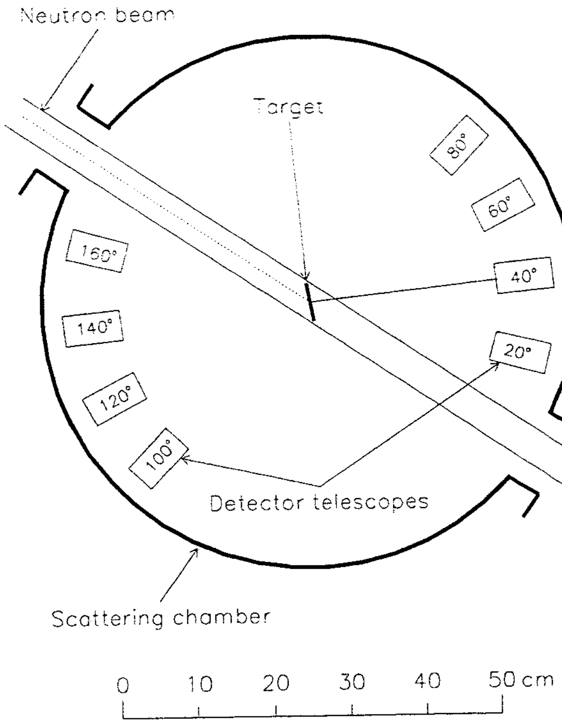

Figure 3: The MEDLEY facility, showing the scattering chamber and the eight telescopes.

MEDLEY follows SCANDAL (SCAttered Nucleon Detection AssembLy), a setup designed for large-acceptance neutron and proton detection (see fig. 4).

4.4 The MEDLEY facility

The MEDLEY detector array consists of eight particle telescopes, placed at 20° – 160° with 20° separation. Each telescope is a $\Delta E - \Delta E - E$ detector combination, with sufficient dynamic range to distinguish all charged particles from a few MeV up to maximum energy, i.e., about 100 MeV. All the equipment is housed in a 100 cm diameter scattering chamber, so that the charged particles can be transported in vacuum.

4.5 The SCANDAL facility

The SCANDAL (SCAttered Nucleon Detection AssembLy) setup has been developed for detection of scattered neutrons in the energy interval 50 – 160 MeV. One should keep in mind that measuring high-energy neutrons with good energy resolution is a formidable task. The highest energy for which resolved nuclear states have been detected was 65 MeV before this project. Thus, this project breaks new ground not only concerning physics, but also when it comes to measurement techniques.

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

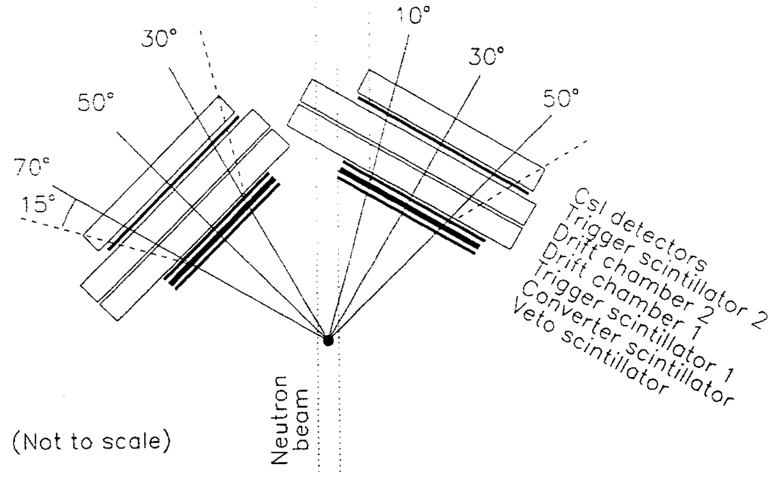

Figure 4: Schematic figure of the SCANDAL setup.

The device is illustrated in fig. 4. It consists of two identical systems, typically 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, it 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 CsI detectors for energy determination. The trigger is provided by a coincidence of the two trigger scintillators, vetoed by the front scintillator. If used for (n,p) studies, the veto and converter scintillators can be removed, and additional drift chambers can be mounted if desired.

We use active converters, which have the advantage that they can be thicker, because the proton energy loss from straggling on the way out of the scintillator can be measured and compensated for. The maximum thickness of an active converter is thereby set by the energy resolution of the detector. A typical plastic scintillator has a resolution in the 10% range, and the proton energy loss is about 1 MeV/mm for 100 MeV protons. Thereby, a converter thickness of 10 mm gives up to 10 MeV deposited energy, and the resolution contribution is henceforth up to 1 MeV.

The most frequently used converters contain hydrogen and carbon, which allows unambiguous measurements up to 12 MeV excitation energy. For higher excitation energies, the ^{12}C(n,p) channel opens in the converter, and therefore an unambiguous identification of the target excitation is no longer possible.

The setup has in total 24 CsI detectors, 12 in each system. In a recent test, a 1.9 MeV resolution was obtained for 88 MeV protons. This is about as good as it is possible to get with this detector material. This good resolution is the result of a new electronics read-out implemented during the spring.

The drift chambers serve two main purposes; they improve the resolution - both in energy and angle - and they allow rejection of spurious events. The H(n,p) cross section used for conversion is rather uniform in angle. This effect, combined with the relatively large front-area of the CsI's, make the effective subtended angular range for each detector quite large. This would be a major contribution to the angular resolution without proton tracking, and this problem is cured by placing drift chambers between the converter and the CsI's. Hence, the conversion point is well determined. This has also the potential of allowing rejection of spurious events.

The energy resolution has contributions from the neutron beam, the converter, straggling, kinematics and the CsI detectors. The contributions (FWHM) are 1.2, 0.7, 0.7, 1.2 and 1.9 MeV, respectively. This makes a total energy resolution of 2.7 MeV, which is dominated by the CsI resolution. This resolution is comparable with the separation of the ground state and the first excited state in most of the nuclei of interest, e.g., ^{12}C (4.4 MeV), ^{16}O (6.1 MeV), ^{40}Ca (3.3 MeV), ^{90}Zr (1.8 MeV), and ^{208}Pb (2.6 MeV).

In a typical experiment, the two arms will be located such as to cover 10° – 50°, and 30° – 70°, respectively. For a one-week run on ^{208}Pb, the total number of counts for a one-degree angular bin is expected to be about 5 000 at 10°, and 1 at 70°, illustrating that the cross section falls off rapidly with angle.

4.6 Present status

This first year of the project was planned to be spent on tests, commissioning and possibly first experiments with the SCANDAL setup. This ambition has not only been fulfilled; it has been surpassed.

Analysis of one of the first test experiments provided results that indicate that the specifications in general have been met. An example is given in fig. 5, which displays the ^{12}C(n,n) reaction for 96 MeV neutrons at 9° scattering angle. The prominent peak is elastic scattering, while the 4.4 MeV state in ^{12}C is seen as a small shoulder on the elastic peak, and the 9.6 MeV peak is clearly seen. The structure in the 12 – 30 MeV region are not excitations in the target, but instrumental background from ^{12}C(n,p) reactions in the converter. The solid line in the spectrum is the expected spectrum, where

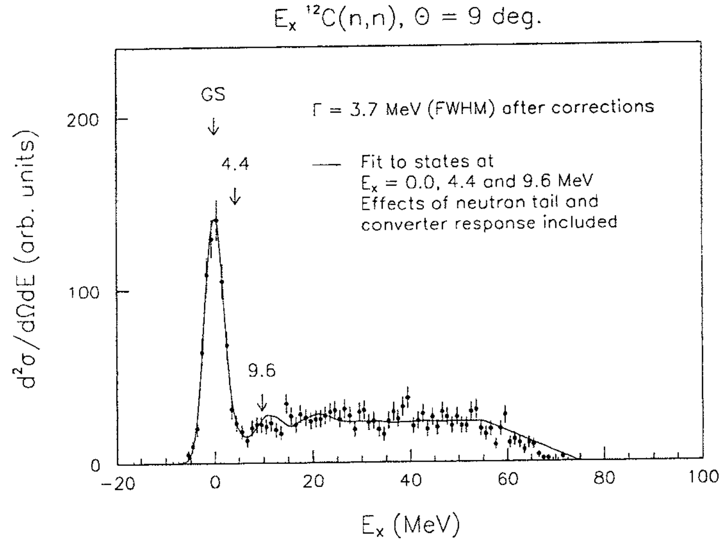

Figure 5: Neutron spectrum at 9° from the ^{12}C(n,n) reaction at 96 MeV detected with SCANDAL

contributions from the three excited states above and instrumental background effects from the converter estimated from a previous measurement of the ^{12}C(n,p) reaction are included. As can be seen, it accounts well for the data.

The first experiment for production of elastic scattering data took place in March, 1999. The target used was carbon, and at present the data analysis is in progress. These data will be used to characterize the detector equipment, as well as in the coming physics development of an optical potential at 100 MeV.

In April, both the SCANDAL and MEDLEY setups were used in a two-week study of (n,xp) and (n,xα) reactions on lead at 100 MeV. This was part of the project run by the groups from Caen, Nantes and Louvain-la-Neuve, in which also our own group participates. Data analysis is now in progress at LPC in Caen. The April experiment benefitted from the new CsI read-out electronics, and preliminary results indeed show improvement in the energy resolution.

The present status of the SCANDAL setup is that we consider the commissioning phase completed. The last major improvement was the implementation of the new read-out technique of the CsI detectors. With this installation, we have reached the design specifications for all critical parameters, and there are no known ambiguities or malfunctions of the system.

In summary, we have obtained data of publication quality from one experiment, ^{12}C(n,n), within the realm of this project. In addition, the large French-Belgian collaboration has used SCANDAL for another transmutation-related experiment, ^{208}Pb(n,xp), for which the data is currently under analysis, aiming at producing a publication and a PhD.

The ambition for the next two years is to get into a steady production phase, taking data for 2-4 weeks per year for this project, and possibly assist other users of SCANDAL for a few additional weeks. One should keep in mind that data from one run week requires about one year of analysis.

4.7 Experimental nuclear data activities at CERN

During the last year, a new facility for measurements of neutron data has been proposed, accepted and funded at CERN, and is now under construction. At an early stage, it was advertised as having competitive performance over the entire range from 1 eV to 250 MeV. Since this overlaps our energy range, one of our staff (Jan Blomgren) participated in a workshop and a collaboration meeting to assess the potential of the facility. He was also asked to join the expert panel for the concluding debate at the workshop, and later he co-chaired a nuclear physics expert group and co-convened a working party on detectors for high-energy (above 1 MeV) experiments.

Our judgement is that the facility as such does not have a competitive edge at energies above 1 MeV. Whether it can play a key role at lower energies remains to be demonstrated. It seems as its best potential is for eV–keV experiments with radioactive targets.

In spite of that we deem the facility to be of less interest for our research, we find it noteworthy that CERN, the world's leading particle physics laboratory, makes a commitment to go in this very applied direction.

5 International activities

5.1 Collaboration

The Uppsala group participates in a European collaboration on nuclear data for transmutation. This collaboration, organized as a Concerted Action called "Physical aspects of lead as a neutron-producing target for accelerator transmutation devices" (Contract No. FI4I-CT98-0017, DG 12 - WSMN), started on August 1, 1998. The project aims at collecting and structuring available information on lead, thus obtaining a better knowledge for this target material, and suggestions on what additional data are needed. The institutes involved are: UCL Louvain-la-Neuve (Belgium), U. de Liège (Belgium), CNRS Nantes (France), CNRS Caen (France), CNRS Orsay (France), CEA Saclay (France), U. Hannover (Germany), PTB (Germany), GSI Darmstadt (Germany), Jülich (Germany), KVI (The Netherlands), ECN Petten (The Netherlands) and Uppsala University (Sweden). The project is organized in ten work packages, of which our group is fully or partly involved in four.

Collaboration meetings with the partners of the Concerted Action have been held in Brussels October 29 – 30, 1998, and February 5 – 6, 1999. A large fraction of the last meeting was devoted to discussions of a more ambitious application within the 5th CEC program. Work is at present in progress to formulate a coherent application for submission in October, 1999.

The participation in the Concerted Action has given several opportunities to exchange information on the work being pursued in Uppsala, and to expose the activities and the potential at TSL in Uppsala. This has resulted in a closer collaboration with some of the participating partners. It has also attracted new groups to use the neutron beam at TSL. The above-mentioned collaboration with the groups from Caen, Nantes and Louvain-la-Neuve, to measure (n,xp) reactions at 100 MeV at the neutron beam in Uppsala, is in fact a by-product of the Concerted Action.

Large interest for our forthcoming elastic scattering data has been shown by the leading theory groups in the field, e.g., from the T2 division at Los Alamos National Laboratory in New Mexico, and a group from Ohio University, Athens, Ohio. In a later stage of the project, we will collaborate with these groups in the theoretical analysis of the data, and specifically in the development of more reliable optical model potentials.

5.2 Meetings and conferences

As part of his education, Joakim Klug participated in a graduate summer school on nuclear physics at NORDITA in Copenhagen during two weeks in September, 1998.

Jan Blomgren participated as observer in two meetings organized by CERN (September 21 – 22, 1998, and January 7 – 8, 1999), which were related to the Rubbia proposal to construct a spallation neutron source at the existing PS synchrotron. Blomgren gave a talk about the activities and plans in Uppsala, which attracted a large interest. Blomgren also acted as panel member in the concluding discussion of the first meeting. As was mentioned above, we do not consider this facility being a serious competitor to the one in Uppsala.

Three INF students, including Joakim Klug, have taken part in a CEC-funded

"Study week on nuclear physics applications", organized by the Research School FANTOM in Tecklenburg, Germany, November 9 – 13, 1998.

Nils Olsson participated in a WPEC/WPMA meeting, organized by the OECD/NEA Nuclear Science Committee, at Brookhaven National Laboratory, USA, on April 19 – 21, 1999. The meeting approved the proposal to merge the two working parties to gain efficiency. In the technical session, Nils Olsson presented the status of the intermediate energy nuclear data activities worldwide. The meetings furthermore commissioned Nils Olsson and Arjan Koning, Petten, to submit a proposal for a new, merged subgroup on intermediate energy data.

An EU-supported workshop on "Application of neutron beams" was arranged jointly by TSL and INF on April 22, 1999. There were four sessions, namely Dosimetry, Medical applications, Single-event upsets in electronics and Transmutation applications. Each session was opened by a review talk by invited specialists from the international community and, in addition, there were a number of shorter contributed talks. A few of these were given by scientists from INF (Jan Blomgren and Jan Källne). In addition, Nils Olsson participated in the final panel discussion. The workshop attracted in total about 60 – 70 participants.

Two of our students, including Cecilia Johansson, participated in a CEC-funded "FANTOM study week on Physics of the early universe" for PhD students in Dourdan, France, May 17 – 21, 1999.

An international conference on "Accelerator-driven transmutation" (ADTTA'99) was held in Prague, June 7 – 11, 1999. The Uppsala group gave two oral contributions, namely "Neutrons for science and industry" by Jan Blomgren and "SCANDAL – a facility for elastic neutron scattering studies" by Joakim Klug.

The Uppsala group had two contributions at the "Particles and nuclei international conference" (PANIC), which was held in Uppsala, June 10 – 16, 1999, namely "Neutrons for science and industry" (poster) and "Development of a tagged neutron facility for neutron scattering experiments at intermediate energies" (oral, by Todd Petersen, IUCF).

In connection with PANIC, our group organized a workshop on "Critical points in the determination of the pion-nucleon coupling constant", June 7 – 8, 1999, with about 20 participants from most of the important international experimental and theory groups. The purpose was to shed light on the inconsistencies and controversies regarding experimental data on the important neutron-proton scattering cross section, and its theoretical interpretations. Although this workshop might seem very fundamental, the question also has a very applied aspect: It is directly related to the *np* scattering cross section, which is a primary reference for all other measurements of neutron-induced cross sections. Oral contributions were given by Jan Blomgren ("Implications of the existing inconsistencies in the *np* data") and Nils Olsson ("Uppsala *np* scattering experiments and the πNN coupling constant"). A special issue of Physica Scripta will be edited as proceedings from the workshop.

6 Administrative matters

6.1 Personnel and PhD students

Two full-time PhD students, two part-time supervisors and a supervisor/project leader is involved in the project. The first student, Joakim Klug, was accepted on September 1, 1998. Before being accepted as PhD student, Klug got some experience of the project during spring 1998, on a temporary scholarship, while finishing his masters degree. The second student engaged in the present project, Cecilia Johansson, was accepted on February 2, 1999. She is funded partly by this project, partly by FOA, and partly with faculty money. Thomas Lefvert from Vattenfall acts as industry supervisor for Joakim Klug, while Anders Ringbom from FOA has taken the same responsibility for Cecilia Johansson.

Doc. Jan Blomgren has taken the main responsibility for supervising the two students, and he has also been in charge of constructing the SCANDAL facility. Per-Ulf Renberg at TSL acts as coordinator between the neutron group and the laboratory, and is also given invaluable contributions to the construction of the equipment and in preparations and running of the experiments. Nils Olsson has mainly taken on the responsibility as project leader, including all administrative matters concerning the project, as well as the department as a whole.

Within a related project, "Nuclear data for fast neutron cancer therapy", also headed by Nils Olsson, we have since a few years a PhD student, Somsak Dangtip, who is now approaching his PhD examination. Within that project, we have recently employed doc. Ayşe Ataç as a future supervisor, and Bel Bergenwall as PhD student. The present project will gain from this growth, since the total number of persons working on similar problems has increased.

The three students Bel Bergenwall, Cecilia Johansson and Joakim Klug have also been accepted at the research school AIM (Advanced Instrumentation and Measurements), which at present is mainly funded by the Foundation for Strategic Research, but where an increasing support from Swedish industry is expected. Within AIM, our students have regular contacts with about 20 other students working on projects in the interface area between fundamental and applied research.

Another student at our department, Johan Thun, successfully defended his PhD thesis on May 28, 1999. Part of the thesis was on nuclear data for ADT applications. Experiments had been performed at Saturne in Saclay, France, and at TSL in Uppsala.

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. During the fall semester, 1998, Jan Blomgren gave two courses for senior high schools teachers: "Nuclear physics for pedestrians", which is a distance course running over the semester, and "Nuclear physics in the classroom", which is a weekend course that involves several of the scientists from our department. Nils Olsson gave a lecture on another course for senior high schools teachers on April 17, 1999, with the title "Neutron radiation - more beneficial than harmful".

Jan Blomgren contributed to the course on "Transmutation" for PhD students, given in collaboration by KTH, Lund University and Uppsala University. Six students from Uppsala attended, and three of these were from INF. In addition, Jan Blomgren guided the students of the KTH course on accelerator technology on a tour at TSL, and gave some information about transmutation on February 9, 1999.

Jan Blomgren has also been active in more outreach activities. As an example, he has given public lectures about "Transmutation and radioactive waste" in connection with the SKB studies of the final waste disposal, in Oskarshamn on October 20, 1999, in Uppsala for politicians from Östhammar and Tierp on February 1, 1999, and in Nyköping on May 17, 1999. The lectures have been followed up by newspaper articles and radio interviews in Oskarshamnstidningen (October 22), Uppsalademokraten (February 11), Radio Kalmar (October 22), and Radio Uppland (October 23 and February 16). In addition, he had an article in Upsala nya tidning on June 24, where he notified the inconsistencies in the official governmental policy regarding energy generation.

6.2 Reference group

A reference group is organized for the project, with the task to monitor and advice the research group. The reference group members were from July 1, 1998: Per-Eric Ahlström (SKB), Thomas Lefvert (Vattenfall AB), Benny Sundström (SKI) and Fredrik Winge (BKAB). From January 1, 1999, Anders Ringbom (FOA) was also included. Nils Olsson is chairman of the reference group.

Two meetings has been held during the year, namely at SKB on December 17, 1998, with participation of Per-Eric Ahlström, Thomas Lefvert and Benny Sundström, and in Uppsala on May 17, 1999, with participation of Per-Eric Ahlström, Thomas Lefvert, Anders Ringbom, Benny Sundström and Fredrik Winge. At both occasions, most of the Uppsala group were also present.

Scientific and administrative reports on the progress of the ADT project have been given, as well as some information on other neutron projects within the department. Especially the project on nuclear data of relevance for cancer therapy with fast neutrons, which utilizes the charged particle detector setup MEDLEY, has been discussed. This setup has recently been used also in the collaboration with the French-Belgian group, aiming at measurement of gas production (H and He) cross sections in target and construction materials for ADT. Thus, there is a considerable overlap in interest between the two projects, and there would be a gain in efficiency by bringing them closer. The reference group has expressed a positive attitude to a closer collaboration between these groups.

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

6.3 PAC meetings and beam time at TSL

The international Program Advisory Committee (PAC) at TSL, who judges the scientific quality of proposed experiments at the laboratory and allocates beam time, held its 22nd meeting on May 8 – 9, 1998. Since several of the new proposals were related to transmutation technology, the directors of TSL decided to deepen the knowledge of the PAC members within this subject. Thus, the PAC meeting was preceded by a "Mini-Symposium on Transmutation of Nuclear Waste", with talks by Francesco Venneri (Los Alamos), Arjan Koning (Petten), Rolf Michel (Hannover) and Nils Olsson (Uppsala).

The workshop was concluded with a panel discussion, where also Per-Eric Ahlström (SKB) participated. The invited speakers F. Venneri and A. Koning were in addition used as advisors in the closed session of the PAC meeting.

PAC found that neutron data are important to tune nuclear models needed to simulate the behaviour of an accelerator-driven system, and that such information is needed up to considerably higher energies than for conventional reactors. Elastic neutron scattering was identified as a relevant measurement in this context.

Four new proposals for experiments relevant to transmutation were treated by PAC, and they were all granted beam time. The projects are "Elastic neutron scattering at 100 MeV" (the present project), "Measurements and comparison of proton- and neutron-induced fission cross sections at 20 – 200 MeV" (Vilen Eismont, S:t Petersburg), "Residual nuclide production by medium-energy neutrons" (Rolf Michel, Hannover), and "Measurement of double-differential cross sections for light charged particle production in neutron-induced reactions" (Jean-Francois LeColley, Caen). Some of these experiments are performed in collaboration with our group, using our equipment.

We judge the outcome of the PAC meeting being very positive for coming transmutation research at TSL. The PAC members demonstrated a sincere interest in the projects, and we expect good possibilities for pursuing this research over the coming years.

The 24th meeting of PAC was held on April 23 – 24, 1999. Two new proposals were related to transmutation, namely "Exploratory studies of forward-angle *np* scattering" (spokesman: Jan Blomgren) and "Measurement of double-differential cross sections for light charged particle production in neutron induced reactions at 100 MeV" (spokesman: Jean-Francois LeColley, Caen). Both experiments were granted adequate beam time by PAC. In addition, LeColley had submitted a Letter-of-intent: "Neutron emission spectra measurements in neutron-induced reactions of interest for ADT research".

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Appendix I

Comment on "Total and Differential Cross Sections of $p+p \rightarrow \pi^+ + d$ Reactions Down to 275 keV above Threshold"

In a recent article, "Total and differential Cross Sections of $p + p \rightarrow \pi^+ + d$ Reactions Down to 275 keV above threshold" [1], new high-quality data on the $pp \rightarrow d\pi^+$ total cross section close to threshold are being compared with data on the $np \rightarrow d\pi^0$ reaction [2] as a means to study possible violations of isospin independence.

A major problem with this approach is the absolute normalization of the $np \rightarrow d\pi^0$ data of Hutcheon *et al.* [2]. The data were measured relative to np scattering, by a simultaneous detection of the recoil proton in the same magnetic spectrometer. The np scattering cross section assumed in the normalization was taken from the VPI program SAID [3], which provides well-known and commonly used phase-shift analyses of NN scattering data. The authors of ref. [2] estimated the uncertainty in this normalization procedure to be 5 %, which made sense at that time. However, recent experimental results [4,5] indicate that the np scattering cross section close to 180 ° can be uncertain by as much as 10–15 % in this energy region.

In addition, there might to some degree be a circular chain of interdependence involved. The VPI phase-shift solution was at that time dominated by one single np scattering experiment by Bonner *et al.* [6]. This experiment was a relative measurement of np scattering, normalized by a simultaneous measurement of the $np \rightarrow d\pi^0$ reaction, by detecting protons and deuterons from the two reactions in the same magnetic spectrometer. Thus, the Bonner *et al.* experiment and the Hutcheon *et al.* measurement were rather similar, although with opposite approach with respect to which reaction to measure, and which to use for calibration.

Up to now, no truly absolute measurement of the $np \rightarrow d\pi^0$ reaction has been undertaken, due to the inherent - and notorius - problem of determining the absolute intensity of a neutron beam to high precision. Thus, the Bonner *et al.* measurement inferred the $np \rightarrow d\pi^0$ cross section from data on the $pp \rightarrow d\pi^+$ total cross section, assuming isospin independence to be valid. At the time of the Bonner *et al.* experiment, the only $pp \rightarrow d\pi^+$ data available were from the Rose measurement [7]. It is not evident how the Bonner *et al.* data affects the solution of the VPI PWA, and therefore some caution is recommended.

To summarise, the $pp \rightarrow d\pi^+$ total cross sections in the present paper are being compared with $np \rightarrow d\pi^0$ data as a possible test of charge independence. The $np \rightarrow d\pi^0$ data, however, might have been implicitly normalized, although through many complicated steps, to older data on the $pp \rightarrow d\pi^+$ reaction. Thus, the reliability of this approach to test charge independence seems uncertain, since the data themselves might not be fully independent. This does not necessary mean that any of the involved data sets are wrong, but it makes it difficult to estimate the systematic uncertainties involved.

Besides this questioning of the basis of this comparison, there are also practical difficulties to point out. It is far from trivial to interrelate the $np \rightarrow d\pi^0$ and $pp \rightarrow d\pi^+$ total cross sections for normalization purposes, even if isospin were a perfect symmetry. The reason is that the $n - p$ and $\pi^0 - \pi^+$ mass differences requires non-trivial corrections, which has recently been studied in detail [8,9]. In the present work of Drochner *et al.*, these effects are very well taken care of, but that is not the situation for some older experiments. In fact, it is today impossible to reconstruct the full chain of normalizations and corrections in the process described above, because key information has been lost, i.e. it was never published. It has been shown, however, that at least one correction on the 10 % level has not been carried out in older work [8]. The use of these data for precision comparisons is therefore discouraged.

Valuable discussions with T.E.O. Ericson, B. Loiseau and J.A. Niskanen are gratefully acknowledged. This work was supported by the Swedish Natural Science Research Council.

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Appendix II

NEUTRONS FOR SCIENCE AND INDUSTRY - THE UPPSALA NEUTRON BEAM FACILITY

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1 Introduction

Recently, a large number of applications involving high-energy ($>$ 20 MeV) neutrons have become important. Transmutation - the subject of this conference - is an obvious example, but also fast-neutron cancer therapy, dose effects for airflight personnel due to cosmic-ray neutrons, as well as electronics failures induced by the same cosmic-ray neutron flux have all got increasing attention.

This has led to intense experimental activities. Briefly, this can be divided into two main chategories: measurements of nuclear data, and direct testing. Of these, nuclear data measurements is the by far largest activity, while the in-beam testing of electronics circuits is presently small, but rapidly growing.

2 The neutron beam facility

2.1 Neutron production

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

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

2.2 Base equipment

Two major experimental setups are semi-permanently installed. These are the MEDLEY detector telescope array, housed in a scattering chamber and operated in vacuum (see fig. 3). At the exit of this chamber, a 0.1 mm stainless steel foil terminates the vacuum

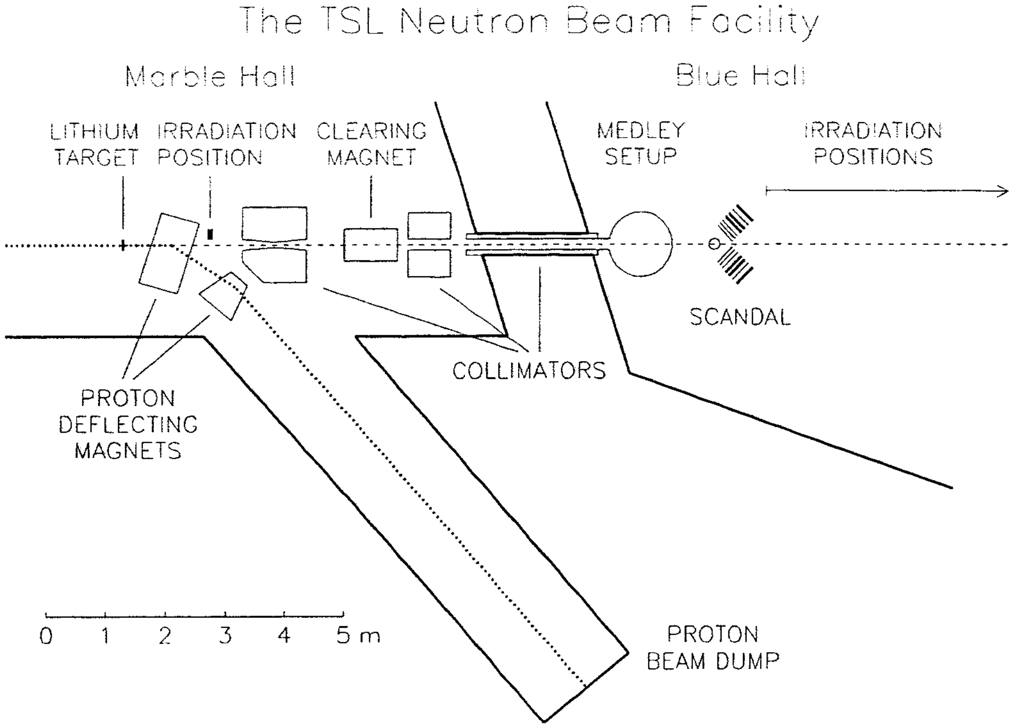

Figure 1: The TSL neutron beam facility.

system, and from here and on the neutrons travel in air. Immediately after MEDLEY follows SCANDAL (SCAttered Nucleon Detection AssembLy), a setup designed for large-acceptance neutron and proton detection (see fig. 4). The magnetic spectrometer LISA (Light Ion Spectrometer Assembly) has previously been used for (n,p) studies. Presently, it is partly unequipped, but can easily be resurrected.

2.3 Monitoring

Absolute normalization of the neutron flux is a notorious problem in all high-energy neutron-beam applications. For direct neutron monitoring, fission counters are available, which have been calibrated relative to *np* scattering, allowing an uncertainty of no more than 5 %.

Relative monitoring can be provided by many different means. Charge integration of the primary proton beam is one of the standard techniques. In addition, for most of the experiment periods, many different experiments (up to seven so far) can be running simultaneously, and then it is common to use signals from the other experiments as relative monitors.

3 Nuclear data for applications

3.1 Transmutation

Almost all proposed transmutation techniques involve high-energy neutrons created in proton-induced spallation of a heavy target nucleus. Therefore, the neutron spectrum in a transmutation core will contain one significant difference compared to present reactors:

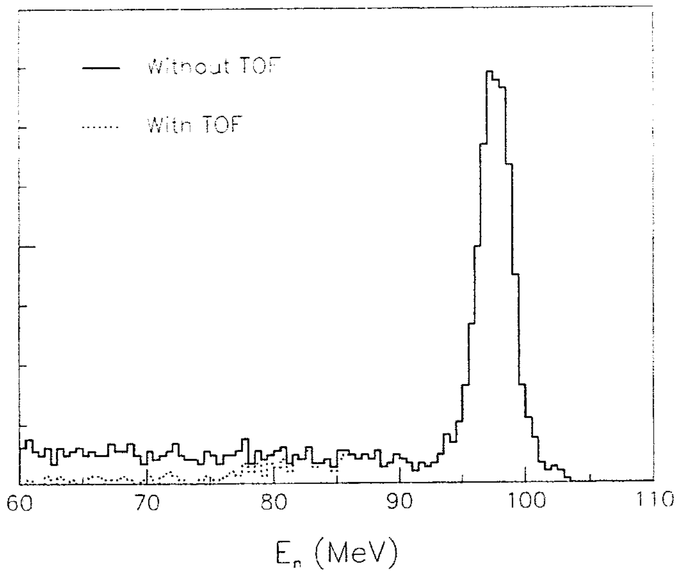

Figure 2: The neutron energy spectrum with and without time-of-flight rejection of low-energy neutrons.

the presence of neutrons at very high energies. The 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. Spallation results in neutron spectra with an intensity distribution roughly like $1/E_n$. The small number of neutrons at very high energies make such data not being as important as mid-range data. Above, say, 200 MeV direct reaction models assuming a single interaction (impulse approximation) works reasonably well, while at lower energies nuclear distortion plays a non-trivial role. This makes the $20 - 200$ MeV region the most important for new data.

Very little high-quality neutron-induced data exist in this domain. Only the total cross section and the (n,p) reaction has been investigated extensively. There are high-quality neutron total cross section data on a series of nuclei all over this energy range. In addition, there are (n,p) data in the forward angular range at modest excitation energies available at a few energies and for a rather large number of nuclei.

Today, several groups are working on transmutation-related cross sections. Neutron elastic scattering is being studied with the SCANDAL setup (see the contribution by Klug *et al.* in these proceedings, and sect. 4.1). Hydrogen and helium production is measured with a combination of SCANDAL and MEDLEY, residue production by activation techniques, and fast-neutron fission by thin-film breakdown counters and ionization chambers.

3.2 Medical applications

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 e.g. ref. [2].

The interaction of neutrons with tissue is very complex, and to a large extent unknown. Thus, the existing methods and techniques employed are based on experience, rather than

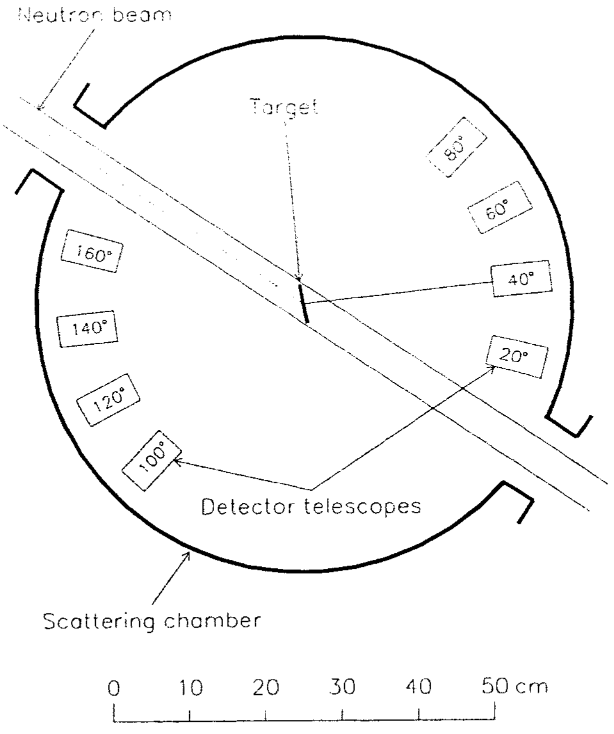

Figure 3: The MEDLEY facility, showing the scattering chamber and the eight telescopes.

on knowledge on fundamental physics. Because of the recent development of neutron beams with good intensity and energy resolution, it is today possible to study all the processes involved in detail, and thus dramatically improve the dose and radiation quality planning in connection with tumour therapy. The neutron facility at the The Svedberg laboratory (TSL) in Uppsala has unique properties in this respect.

In the commonly used energy range (up to about 70 MeV), it is unfortunately difficult to describe nuclear processes theoretically in a simple way, and in addition, the data base is meagre. In this energy region, compound nuclear processes, direct processes and intermediate or pre-compound processes are important and nuclear reaction models must take into account all these processes and, where appropriate, the competition between them. 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 data bases at higher energies makes it difficult to estimate correctly the dose given by the neutron beam and to plan and optimize the radiation therapy.

A substantial improvement in the knowledge of fundamental nuclear data is therefore needed for a better understanding of the processes occuring on a cellular level. Besides the applications in cancer treatment, the same data will improve the understanding of fast neutron dosimetry for radiation protection purposes, e.g. for a future transmutation facility. In addition, neutron dosimetry problems for airplane crew have recently received widespread attention (see sect. 4.5).

3.3 Fundamental physics

The TSL neutron beam facility has now been running for about a decade. The main activity up to now has been studies of the (n,p) reaction at about 100 MeV on a series of nuclei ranging from ^{9}Be to ^{208}Pb [3, 4, 5, 6, 7, 8, 9, 10], and np scattering at 96 and 162

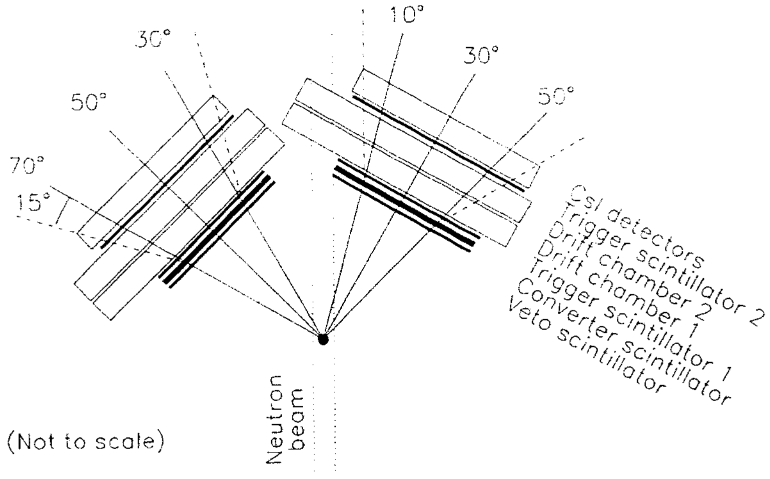

Figure 4: Schematic figure of the SCANDAL setup.

MeV [11, 12, 13].

Although carried out for other reasons, these fundamental studies have important consequences for applications. The (n,p) data on nuclei give partial contributions to code developments for transmutation core design. The *np* scattering cross section has been used to normalize other neutron-induced data, and thus a precise knowledge of this cross section is important also for applications.

Recently, the *np* scattering cross section in this energy range has been under intense debate, motivated by the Uppsala results presented in fig. 5, which are steeper at backwards angles than the bulk of previously published data. This is clearly illustrated by a comparison with the partial-wave analyses represented by the lines in the figure; the analyses are fits to the older data.

This discrepancy does not only influence the normalization of nuclear data for applications, but it is also of great fundamental importance, because *np* scattering data are being used for determinations of the pion-nucleon coupling constant, i.e. the absolute strength of the strong interaction in the nuclear sector. This coupling constant is of great relevance not only to basic nuclear physics, but also on a cosmological scale. Its strength governs the properties of the deuteron to a very high degree. If all other nucleon-nucleon potential information were known, the value of it could be determined very accurately, because then a difference of only a few percent in its value would be sufficient to either unbind the deuteron or to produce a bound diproton, in both cases with major consequences for the world as we know it.

These issues have motivated a critical re-examination of the entire *np* data situation [14]. Simultaneously with this conference, a workshop is held in Uppsala to address these problems [15]. New experiments are underway to resolve the discrepancy [16, 17].

4 Research programme

4.1 Elastic neutron scattering

Elastic neutron scattering is of utmost importance for a vast number of applications. Besides its fundamental importance as a laboratory for tests of isospin dependence in the nucleon-nucleon, and nucleon-nucleus, interaction, knowledge of the optical potentials de-

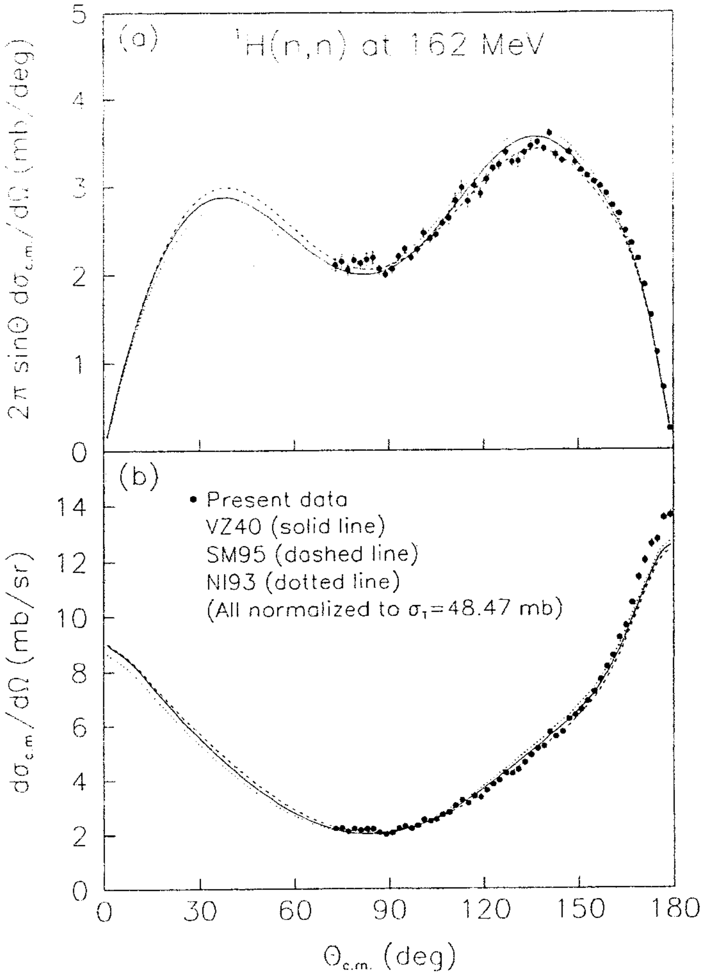

Figure 5: *np* scattering at 162 MeV.

rived from elastic scattering come into play in virtually every application where a detailed understanding of nuclear processes are important.

After thorough investigation, we have arrived at the conclusion that for transmutation purposes, neutron elastic scattering is the single most important intermediate-energy quantity to measure that remains to be done. There are several reasons for this, the most important being that it allows a determination of the optical potential, which plays a role in every calculation including neutrons in either the entrance or exit channel. The elastic cross section is also the largest of the individual partial cross sections contributing to the total cross section. In fact, a consequence of the optical model is that the elastic cross section must be at least half the total cross section.

Given the time and cost to carry out such experiments, the main focus must be on developing theoretical models rather than systematically measuring all nuclei. The obvious nuclei to study are then the magic or semi-magic nuclei, i.e. ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr and ^{208}Pb. Here it is fortunate that lead and zirconium are also important materials in future transmutation facilities, and carbon, oxygen and calcium are all of medical relevance, so the gain is twofold. Besides the elements above, there are plans to study H(n,n) for normalization purposes. Important materials for transmutation cores, like iron, chromium, bismuth, thorium and uranium might be investigated in a second phase.

Elastic neutron scattering is important also for fast-neutron cancer therapy, because the nuclear recoils account for 10-15 % of the dose. For a detailed description of the elastic neutron scattering project, we refer to the contribution to this conference by Klug *et al.*

4.2 Charged-particle production

About half the dose in fast-neutron cancer therapy comes from np scattering, 10-15 % from elastic neutron scattering and the remaining 35-40 % from neutron-induced emission of charged particles, such as protons, deuterons, tritons, ^{3}He- and α-particles. Double-differential cross sections for all these reactions in tissue-relevant nuclei, i.e. carbon, nitrogen, oxygen and calcium, are to be measured with the MEDLEY setup in an energy region of greatest relevance for fast neutron therapy, i.e., up to 70 – 100 MeV [18, 19].

Although intended for medical purposes, the requirements from these led to a multi-purpose detector design, which has turned out to be useful for many different applications. One of these is hydrogen and helium production in a transmutation environment. Besides the use of proton and alpha production data for benchmarking of precompound models, direct use of the data can provide limits on hydrogen and helium production, which has to be kept under control to avoid for instance safety concerns and material embrittlement. Experiments on lead are already under analysis, and other transmutation-relevant materials are to be studied.

The MEDLEY detector array consists of eight particle telescopes, placed at 20-160 degrees with 20 degrees separation. Each telescope is a $\Delta E - \Delta E - E$ detector combination, with sufficient dynamic range to distinguish all charged particles from a few MeV up to maximum energy, i.e., about 100 MeV. All the equipment is housed in a 100 cm diameter scattering chamber, so that the charged particles can be transported in vacuum.

4.3 Fast-neutron fission

Although the main fission effects in a transmutation concept arise from neutrons at lower energies, the high-energy neutron fission gives significant contributions to the power released. Very little data exist on high-energy fission, but the situation is under rapid improvement. This can be exemplified by the ongoing work at the TSL neutron beam, manifested in the contributions to this conference by Eismont *et al.*

4.4 Residue production

Production of residual nuclei in neutron-induced nuclear reactions are studied by activation techniques [20]. These experiments are carried out at two target locations. Besides placing the targets to be irradiated in the experiment hall, a second target station has been installed in the neutron production hall, much closer to the neutron production target, thereby allowing higher flux.

4.5 Neutron-induced electronics failures

Recently, the importance of cosmic radiation effects in aircraft electronics has been highlighted. (For reviews, see e.g. refs. [21, 22] 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.

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

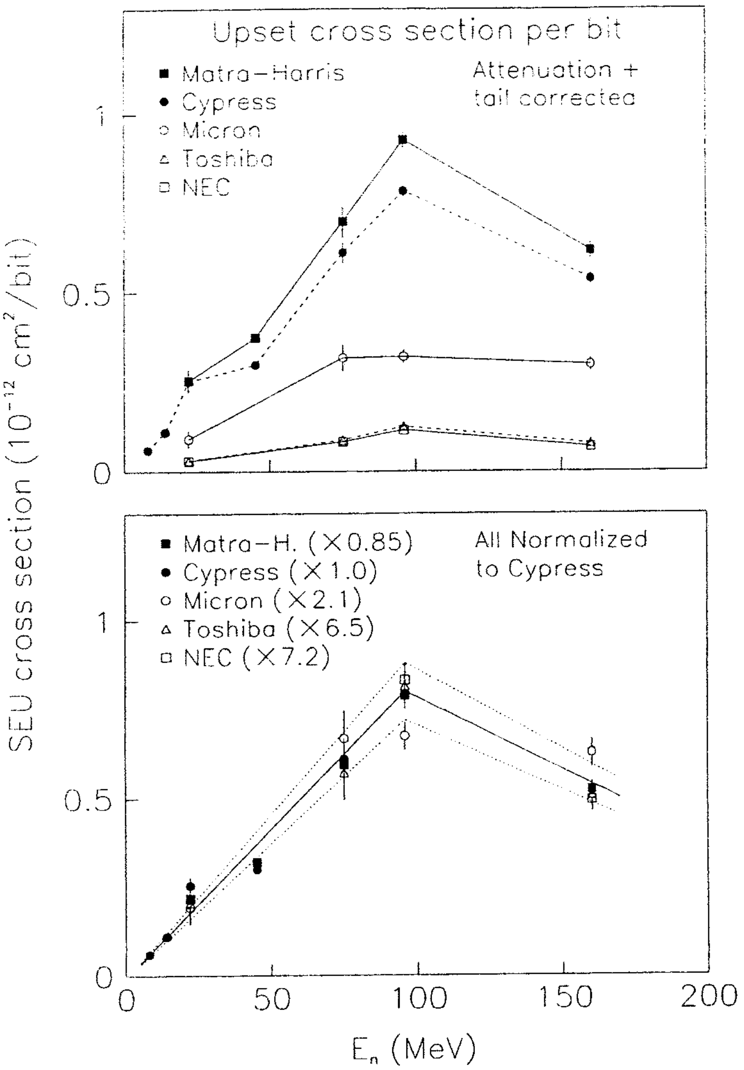

Figure 6: The energy dependence of the SEU cross section for a few devices. See the text for details.

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

If the neutron-induced charged-particle production cross sections were known, and thus the energy deposition on a microscopic level, it might be possible to calculate the SEU rate with reasonable precision also for any future components. Up to now, direct in-beam component testing has been carried out to characterize the effect, especially its neutron energy dependence [23, 24].

As can be seen in the upper panel of fig. 6, the upset cross section rises slowly with neutron energy for all devices tested, up to a maximum at about 100 MeV. It is notable that the most modern components (Matra-Harris and Cypress) are the most sensitive. This is because they use less charge to represent a digit, thereby making the component faster, but also more sensitive to this kind of perturbation. In the lower panel, all data have been normalized to the same relative rate, to illustrate that the energy dependence is very similar for all of them.

Already from these simple measurements, important conclusions about the origin of the effect can be drawn. The fact that the rise is rather slow seems to indicate that heavy ions are primarily responsible. If the effect were mostly due to protons or alpha particles, the cross section should peak at a much lower energy.

There are plans to develop these studies further by measuring cross sections for production of light charged particles and light heavy ions. For the light particles, the MEDLEY setup (see above) should be used. For light heavy ions, major modifications will probably be needed because of the very short range of the ejectiles.

4.6 Dosimetry research

Nuclear data measurements for dosemeter modelling are to be carried out using the SCANDAL and MEDLEY setups. In addition, direct testing of existing dosemeters are regularly undertaken, involving national radiation protection institutes from a number of European countries. The large number of simultaneous users has been a great asset in this research, because it has provided good normalization possibilities, but also interdisciplinary collaboration. A good example of the latter is the development of dosemeters based on fission in bismuth, which has benefitted very much on the fast-fission programme.

5 Summary

The quasi-monoenergetic 20 – 180 MeV neutron beam at the The Svedberg Laboratory (TSL), Uppsala, Sweden, has been - and will be used - to provide data for a large number of applications. These involve transmutation, fundamental physics, medicine, dosimetry and electronics effects. The comparatively high flux, good energy resolution, precise monitoring and easy access to the beam has resulted in a large user community (presently about 70 users from about 10 countries). Two major multi-purpose experiment setups, MEDLEY and SCANDAL, are available, as well as a magnetic spectrometer (LISA).

The largest research programmes involve studies of elastic neutron scattering, neutron-induced light ion production, fast-neutron fission and in-beam testing of electronics devices.

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Appendix III

SCANDAL - A FACILITY FOR ELASTIC NEUTRON SCATTERING STUDIES

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1 Introduction

A facility for detection of scattered neutrons, SCANDAL (SCAttered Nucleon Detection AssembLy), has recently been installed at the The Svedberg Laboratory (TSL) in Uppsala, Sweden. It is primarily intended for studies of elastic neutron scattering, but can be used for the (n,p) and (n,d) reactions as well. The energy interval for detected neutrons is 50–130 MeV, which makes the facility suitable for studies of transmutation-related cross sections.

1.1 Nuclear data for transmutation

As transmutation techniques involve high-energy neutrons created in proton-induced spallation of a heavy target nucleus, the neutron spectrum in a transmutation core will contain one significant difference compared to standard nuclear reactors: the presence of neutrons at much higher energies. The 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. Spallation results in neutron spectra with an intensity distribution roughly like $1/E_n$. The small number of neutrons at very high energies make such data not being as important as mid-range data. Above ~200 MeV, direct reaction models based on the free interaction (impulse approximation) work reasonably well, while at lower energies nuclear distortion plays a non-trivial role. This makes the 20–200 MeV region the most important for new data.

Very little high-quality neutron-induced data exist in this domain. Only the total cross section [1] and the (n,p) reaction has been investigated extensively [2, 3]. There are high-quality neutron total cross section data on a series of nuclei all over this energy range. In addition, there are (n,p) data in the forward angular range at modest excitation energies available at a few energies and for a rather large number of nuclei.

Besides this, there are data on neutron elastic scattering from UC Davis at 65 MeV on a few nuclei [4]. Programmes to measure neutron elastic scattering have been proposed or begun at Los Alamos [5] and IUCF [6], with the former resulting in a thesis on data in the 5–30° range on a few nuclei [5]. The design of SCANDAL has been inspired by the latter two projects.

1.2 Why elastic scattering?

For transmutation purposes, neutron elastic scattering is the single most important intermediate-energy quantity that remains to be measured. There are several reasons for this, the most important being that it allows a determination of the optical potential, which plays a role in every microscopic calculation including neutrons in either the entrance or exit channel. In addition, the elastic cross section is also the largest of the individual partial cross sections contributing to the total cross section. In fact, a consequence of the optical model is that the elastic cross section must constitute at least half the total cross section. Thus, enhanced data on elastic scattering will improve the understanding of neutron transport in a spallation target, as well as fast neutron dosimetry for radiation protection purposes.

Given the time and cost to carry out elastic scattering experiments, the main focus must be on developing theoretical models rather than systematically measuring all nuclei. The obvious nuclei to study are then the magic or semi-magic nuclei, i. e. ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr and ^{208}Pb. Here it is fortunate that lead and zirconium are also important materials in future transmutation facilities, and carbon, oxygen and calcium are all of direct medical and dosimetric relevance, so the gain is twofold. Besides the elements above, H(n,n) will be studied for normalization purposes. Important materials for transmutation cores, like iron, chromium, bismuth, thorium and uranium might be investigated in a second phase.

In addition to the elastic scattering measurements to be done, there is an ongoing project with groups from Caen and Nantes in France and Louvain-la-Neuve in Belgium, to measure (n,xp) reactions at 100 MeV at the neutron beam in Uppsala.

1.3 Elastic scattering for other applications

Elastic scattering is a common denominator for transmutation and several other applications. One example is fast-neutron cancer therapy, where 10–15 % of the dose comes from elastic neutron scattering, ~50 % from *np* scattering, and the remaining part from neutron-induced emission of charged particles, such as protons, deuterons, tritons, ^{3}He- and α-particles. Double-differential cross sections for all these reactions in tissue-relevant nuclei, i. e. carbon, nitrogen, oxygen and calcium, are to be measured with another setup at TSL, called MEDLEY. This will be done in an energy region of greatest relevance for fast neutron therapy; i. e., up to 70–100 MeV [7, 8] (see the contribution by Blomgren *et al.* in these proceedings).

Recently, the importance of cosmic radiation effects in aircraft electronics has been highlighted. (For reviews, see e. g. refs. [9, 10] 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.

At flight altitudes, as well as at sea level, the cosmic ray flux is dominated by neutrons and muons. The latter do not interact strongly with nuclei, and therefore neutrons are most important for SEU. Since neutrons have no charge, they can only interact via violent, nuclear reactions, in which charged particles are created, that occasionally induce an SEU. Thus, knowledge of the nuclear interaction of neutrons with silicon is needed to obtain a full understanding of the SEU problem.

If the neutron-induced charged-particle production cross sections were known, and thus the energy deposition on a microscopic level, it might be possible to calculate the

SEU rate with reasonable precision also for any future components. Up to now, direct in-beam component testing has been carried out to characterize the effect, especially its neutron energy dependence [11, 12]. There are plans to develop these studies further by measuring cross sections for production of light charged particles and light heavy ions; where, for the light particles, the MEDLEY setup (see above) can be used.

2 The neutron beam facility

2.1 Neutron production

At the neutron facility at TSL [13] (see fig. 1), almost monoenergetic neutrons are produced by the reaction ^{7}Li(p,n)^{7}Be in a target of 99.98 % ^{7}Li. After the target, the proton beam is bent by two dipole magnets into an 8 m concrete tunnel, where it is focused and stopped in a well-shielded carbon beam-dump. A narrow neutron beam is formed in the forward direction by a system of three collimators, with a total thickness of more than four metres.

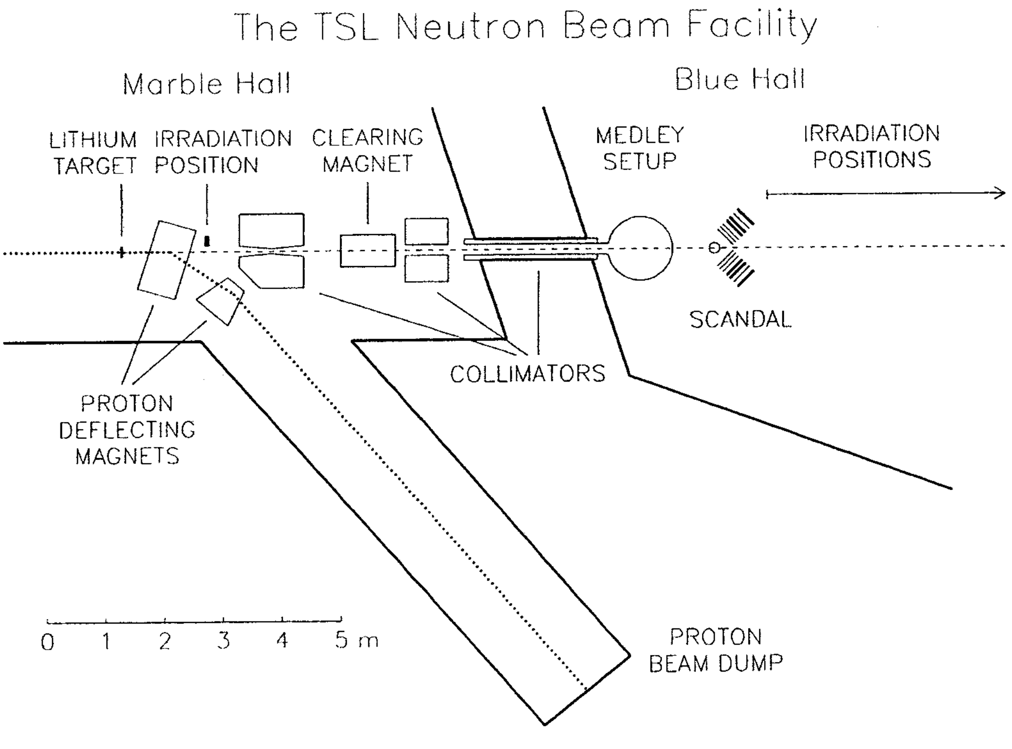

Figure 1: The TSL neutron beam facility.

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

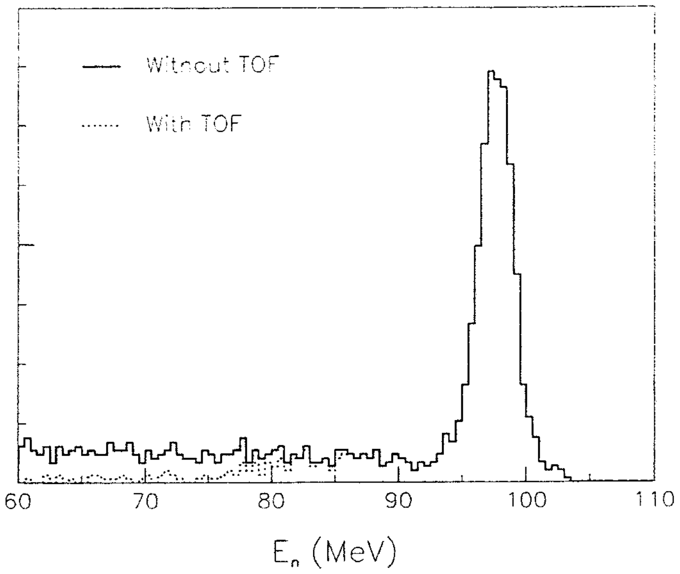

Figure 2: The neutron energy spectrum with and without time-of-flight rejection of low-energy neutrons.

2.2 Monitoring

Absolute normalization of the neutron flux is a notorious problem in all high-energy neutron-beam applications. For direct neutron monitoring, fission counters are available, which have been calibrated relative to *np* scattering, allowing an uncertainty of no more than 5 %.

Relative monitoring can be provided by many different means. Charge integration of the primary proton beam is one standard technique. In addition, for most of the experiment periods, many different experiments (up to seven so far) can be running simultaneously, and then it is common that they use signals from each others experiments as relative monitors.

3 The SCANDAL setup

3.1 General layout

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

The device is illustrated in fig. 3. It consists of two identical systems, typically 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 CsI detectors for energy determination. The trigger is provided by a coincidence of the two trigger scintillators, vetoed by the front scintillator. If used for (n,p) studies, the veto and converter scintillators can be removed, and additional drift chambers can be mounted if desired.

3.2 Design features

The only realistic neutron-to-proton conversion reaction is H(n,p), which has a cross section of above 50 mb/sr at small angles. Two main approaches can in principle be used; passive or active converters.

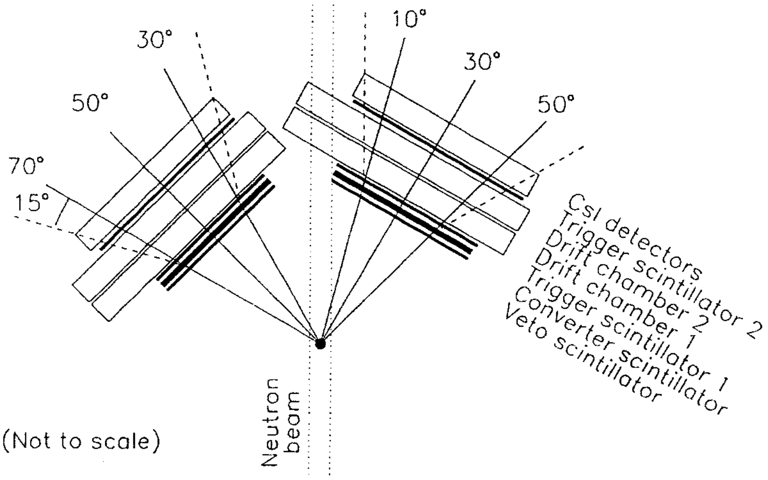

Figure 3: Schematic figure of the SCANDAL setup

Active converters have the advantage that they can be thicker, because the proton straggling on the way out of the scintillator can be measured and compensated for. The maximum thickness of an active converter is thereby set by the energy resolution of the detector. A typical plastic scintillator has a resolution in the 10 % range, and the proton energy loss is about 1 MeV/mm for 100 MeV protons. Thereby, a converter thickness of 10 mm gives up to 10 MeV deposited energy, and the resolution contribution is henceforth up to 1 MeV.

The most frequently used converters contain hydrogen and carbon, which allows unambiguous measurements up to 12 MeV excitation energy. For higher excitation energies, the ^{12}C(n,p) channel opens in the converter, and therefore a unique identification of the target excitation is no longer possible. This is obviously not a problem for elastic scattering, or inelastic scattering to low-lying states, but complicates future developments, like neutron excitation of giant resonances, or quasielastic experiments. This problem is the same for active and passive converters.

The problems above can be circumvented by using a passive liquid hydrogen converter, but the technique is both non-trivial and expensive. Another prize to pay is that the converter must be an order of magnitude thinner for the same resolution. Based on these discussions, we have chosen to use active plastic scintillator converters.

The setup has in total 24 CsI detectors, 12 in each system. In a recent test, a CsI energy resolution of 1.9 MeV was demonstrated for 88 MeV protons.

The drift chambers serve two main purposes; they improve the angular resolution and they allow rejection of spurious events.

The H(n,p) cross section close to zero degrees is rather flat over several degrees in the lab system. This effect, combined with the rather large front-area of the CsI's, makes the effective subtended angular range for each detector quite large. This would be a major contribution to the angular resolution without proton tracking.

Furthermore, the Q-value for ^{12}C(n,p) is -12.6 MeV. Thus, at forward angles energy detection can isolate the protons which are due to conversion via H(n,p). At about 20° conversion angle, the proton energies from the two processes are the same, and thereby it can no longer be determined whether the energy lost was due to excitations in the neutron scattering sample or in the conversion. By applying a 15° maximum opening angle criterion on the conversion (see fig. 3), such problems can be avoided.

Sufficient angular information is obtained by placing drift chambers between the converter and the CsI's. Hence, the conversion point is well determined. This has also the potential of allowing rejection of spurious events. With this technique, the remaining contribution to the angular resolution is the width of the neutron beam (or the scattering sample). The only way to improve the angular resolution further would be to use a narrower beam or target, but that would be at the expense of count rate.

3.3 Resolution

The energy resolution in neutron mode has contributions from the neutron beam, the converter, straggling, kinematics and the CsI detectors. The contributions (FWHM) are estimated to be 1.2, 0.7, 0.7, 1.2 and 1.9 MeV, respectively. This makes a total energy resolution of 2.7 MeV. This resolution is comparable with the distance from the ground state to the first excited state in most of the nuclei of interest, e.g., ^{12}C (4.4 MeV), ^{16}O (6.1 MeV), ^{40}Ca (3.3 MeV), ^{90}Zr (1.8 MeV), and ^{208}Pb (2.6 MeV).

The angular resolution is solely due to the neutron beam and target width. With the present setup dimensions and a 5 cm wide sample, it is about 1.4° (rms). The angular resolution is most crucial at small angles, where the cross section falls very rapidly. For these angles, the cross section is also very large, and thereby a narrow strip target could be used to improve the angular resolution, without making the total beam time considerably longer.

3.4 Solid angle and count rate

The solid angle subtended by each system in the proton detection mode is about 240 msr for a point target. Applying the maximum opening angle criterion on the second scattering in the converter (see above), required for neutron detection, makes the effective solid angle smaller – about 130 msr per setup at full coverage of the 15° cone. The conversion efficiency is then about $5 \cdot 10^{-4}$.

In a typical experiment, the two arms will be located such as to cover 10–50°, and 30–70°, respectively. For a one-week run on ^{208}Pb, the total number of counts for a one-degree angular bin is expected to be about 5 000 at 10°, and 1 at 70°, illustrating that the cross section falls off rapidly with angle.

3.5 Normalization

Normalization of neutron-induced cross sections is a notorious problem because of the difficulties in monitoring the absolute intensity of neutron beams. Precisions better than 10 % have very rarely been achieved. Therefore, most data have been measured relative to another cross section assumed to be known. Most often, the neutron-proton scattering cross section has been used as the primary standard.

Recent experimental investigations [14, 15, 16, 17] have indicated that the *np* scattering cross section might have larger uncertainties than previously estimated. It seems now that the cross section can be uncertain by as much as 10-15 % in the energy range of 100 MeV and up.

A recent high-precision measurement of *np* scattering at 96 MeV in the 74–180 degree range claims an absolute uncertainty of 1.9 % [18], but this is outside our angular range. This is where the planned H(n,n) measurement comes in. By making a relative measurement of the angular distribution of H(n,n) from (close to) zero degrees and out to angles overlapping with the existing data, a normalization to the total cross section can be made with a very small uncertainty (about 1 %).

The reason for this high precision is that the total cross section has been possible to determine with a very high precision (1 %), because knowledge of the absolute beam intensity is not required. Instead, it can be inferred from intensity ratio measurements in attenuation experiments. Furthermore, in the case of hydrogen, integration of the elastic scattering cross section accounts for more than 99 % of the total cross section, with very small corrections for capture and bremsstrahlung processes.

For practical experimental reasons, we plan to measure this in a CH_2-vs-C difference measurement. By this technique, we can normalize the C(n,n) cross section to the H(n,n) cross section. This is very useful, because thereby we can establish the much larger C(n,n) cross section as a secondary standard, allowing all other nuclei to be measured relative to C(n,n).

A second normalization method will be provided by comparisons with the total elastic cross section. This cross section has been derived from the difference of the total cross section and the total inelastic cross section. Both these quantities have been measured in attenuation experiments, and are therefore known to high precision, i. e. 1-2 %. (See for example ref. [19]). By covering 0–70 degrees, far more than 99 % of the contribution to the total elastic cross section will be accounted for, providing a second normalization technique. This method works the best with light nuclei, however, and is therefore well suited for e. g. C(n,n), but is not as reliable for ^{208}Pb(n,n). Hence, this is another reason to establish C(n,n) as a secondary standard.

4 Results

The SCANDAL setup was completed in 1998, and the experiments of that year were dedicated to checking its performance, troubleshooting, improving the equipment, and interpreting the data. Subsequently, elastic neutron scattering data on carbon have been collected.

First – and very preliminary – results on ^{12}C(n,n) are presented in fig. 4. The excitation energy spectrum illustrates ^{12}C(n,n) at 96 MeV and 9° scattering angle. The large peak at $E_X = 0$ is due to elastic scattering, and the excited states at 9.6 MeV, and possibly at 4.4 MeV, are small but visible.

The solid line is a response function for the SCANDAL setup, consisting of several components. It includes fits to $E_X = 0$, 4.4 and 9.6 MeV, as well as background contributions. Peaks of the excited states have been folded with a gaussian representing the intrinsic resolution in the CsI detectors, while the background was obtained by folding contributions from ^{12}C(n,p) reactions in the converter and neutrons in the low-energy tail of the neutron beam.

We conclude that the full spectrum can be explained in terms of these effects, and that we see no unexpected contributions. In addition, the absolute rate is compatible with theory expectations. The energy resolution is 3.7 MeV (FWHM) for this test experiment, in which a very large target was used to obtain high count rate at the expense of energy resolution.

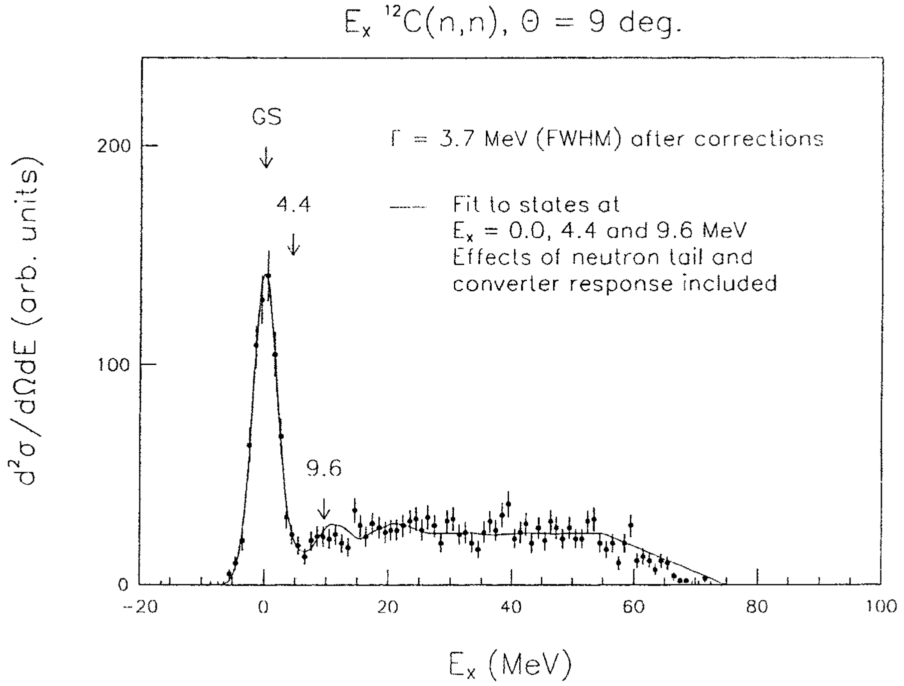

Figure 4: Excitation energy spectrum for ^{12}C(n,n) at 9°. For details, see text.

5 Summary

The experiment setup SCANDAL, for detection of primarily neutrons in the energy interval 50–130 MeV, together with the quasi-monoenergetic 20–180 MeV neutron beam facility at the The Svedberg Laboratory (TSL), Uppsala, Sweden, will be used to provide elastic neutron scattering data for transmutation applications. This will be done in an energy region which has been identified as very important for characterizing neutron transport in a spallation target, and in which there exist very little high-quality data.

The magic or semi-magic nuclei ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr and ^{208}Pb will be studied for developing theoretical models. As lead and zirconium are important materials in future transmutation facilities, modelling of neutron transport in these materials will also benefit directly from our measurements. There are plans to study H(n,n) for normalization purposes, and in a second phase other materials for transmutation cores might be investigated.

First results, for ^{12}C(n,n), show that we are able to separate the ground state and first excited states reasonably well in closed-shell nuclei.

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Appendix IV

np Scattering Measurements at 96 MeV

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(July 27, 1999)

The differential *np* scattering cross section has been measured at 96 MeV in the angular range $\theta_{c.m.} = 74^\circ - 180^\circ$ at the neutron beam facility of the The Svedberg Laboratory in Uppsala. A subset of the data, covering 116° – 180°, was published previously. The new, extended angular distribution has been normalized to the experimental total *np* cross section. Between 150° and 180°, the angular distribution is steeper than for most previous measurements and nucleon-nucleon potential predictions. At 180°, the difference amounts to about 10%, implying serious consequences because of the fundamental importance of this cross section. A value of the charged πNN coupling constant consistent with our earlier result at 162 MeV has been extracted from the data.

I. INTRODUCTION

Recently, we have performed a *np* scattering measurement at 162 MeV [1,2], aiming at a higher accuracy than previous experiments. The *np* scattering cross section is not only of importance for investigations of the fundamental properties of the *NN* interaction, but has also a large impact on several applications, such as fast neutron cancer therapy and accelerator-driven transmutation technologies. The reason is that the *np* cross section is used as a primary standard for measurements of other neutron-induced cross sections in the 0 – 350 MeV region [3], i.e., other cross sections are normalized to that of *np* scattering. In particular the 180° *np* cross section, i.e., the H(n,p) cross section at 0°, is used for normalization purposes. This cross section therefore has to be known to high precision.

We also showed in our previous work that precision data of the *np* cross section in the backward hemisphere are useful for a determination of the charged πNN coupling constant. Both the shape of the angular distribution and the absolute normalization of the data are of crucial importance in this context. The πNN coupling constant is fundamental for quantitative discussions of many phenomena in nuclear and particle physics, and it is important to have determinations with full control of uncertainties. At present a discussion goes on concerning appropriate methods to determine this quantity. One of the aims of the present experiment is to contribute additional experimental material for a discussion of this issue. For the status of the debate we refer the interested reader to our recent answer [4] to the criticism [5] of our findings and our method of extraction of the coupling constant [1,2].

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An investigation of the *np* scattering data situation, from 100 to 1000 MeV, up to the present date [6], shows that most of the data seem to fall into two main "families" with respect to the angular shape. Two of the largest data sets, i.e., those of Bonner *et al.* [7] (160 – 800 MeV) and of Hürster *et al.* [8] (200 – 590 MeV), agree reasonably well in shape above 500 MeV, but differ at 200 MeV by as much as 10% – 15% close to 180°. Our previous angular distribution at 162 MeV is in good agreement with the Hürster data, but is accordingly in conflict with the Bonner data.

Normalization of *np* scattering cross sections has been - and is - a notorious problem [6]. To measure absolute cross sections, either the neutron beam intensity, or some other cross section to which the *np* scattering can be related, has to be known to high precision. The beam intensity can only be measured using a nuclear reaction, most frequently *np* scattering. Therefore, most experimental data are assigned an absolute precision of no better than 5% – 10%, or just given as relative cross sections.

Below the opening of the pion-production channel at about 270 MeV there is, however, a very direct and precise way of solving the normalization problem in principle. The total *np* cross section can be determined very accurately (better than 1%) without knowledge of the absolute beam intensity. The total cross section and the differential *np* cross section are closely linked; if the full angular distribution of the differential cross section is known, an unambiguous normalization to the total cross section can be performed, because all channels but elastic scattering are very small. This technique has been employed in several previous measurements, and is also utilized in the present work. A prerequisite is, however, that a large fraction of the angular distribution is measured.

Recently, the development of a well characterized tagged neutron beam at IUCF [9] opens up another possibility to measure absolute neutron cross sections directly of, e.g., *np* scattering, to the 1% – 2% level. Agreement between precision data taken with these very different techniques would strongly increase the confidence in the absolute scale.

These facts motivate new, precise determinations of the *np* scattering cross section at several energies, with an angular coverage that is as large as possible. In this paper, we present data from a measurement of the differential *np* scattering cross section at 96 MeV in the angular range $\theta_{c.m.} = 74^\circ - 128^\circ$. These data have been linked to the angular distribution measured in 1991 at $\theta_{c.m.} = 116^\circ - 180^\circ$ by Rönnqvist *et al.* [10]. Both experiments were performed by the same collaboration and with the same experimental setup at the neutron beam facility at the The Svedberg Laboratory (TSL) in Uppsala. Thus, the present work is an extension of the Rönnqvist data, now covering the angular range $\theta_{c.m} = 74^\circ - 180^\circ$.

Section II of the paper contains a brief description of the experimental arrangement, while the analysis procedure and the important normalization technique is described and discussed in Sect. III. The results are presented and compared with other data, partial wave analyses (PWA's) and *NN* potential predictions in Sect. IV. The data have been used for a determination of the charged πNN coupling constant, and the analysis and results are presented and discussed in section V. Finally, a summary and the conclusions are given in Sect. VI.

II. EXPERIMENTAL ARRANGEMENT

The experimental setup and procedure have been described in detail recently [2,11], and therefore only a brief summary will be given here.

The TSL neutron beam facility is shown in Fig. 1. Protons from the cyclotron impinge on the neutron production target from the left in the figure. Neutrons are produced by the ^{7}Li(p,n)^{7}Be reaction, using a 214 mg/cm^2 thick lithium target, enriched to 99.98% in ^{7}Li. After the target, the proton beam is bent into a well-shielded beam dump. The neutron beam is defined by a 1 m long collimator, with two other collimators serving as beam scrapers. The vacuum system is terminated after the first collimator with a 1 mm thick aluminium plate. Charged particles produced in this plate are deflected by a clearing dipole magnet. The diameter of the neutron beam at the *np* target position, 8 m from the neutron production target, is about 7 cm. The neutron yield is in the order of 10^6 s^{-1} over the full target area. The centroid of the full energy peak in the neutron spectrum is determined to 96 ± 0.5 MeV. The total energy spread in the peak is estimated to be 0.9 MeV (FWHM).

To maximize the count rate without impairing the energy resolution, a sandwiched multi-target system is used. It consists of thin target layers interspaced by nine multi-wire proportional chambers (MWPCs), each having an efficiency of $\geq$ 99%. In this way, it is possible to determine in which target the scattering or reaction takes place, so that corrections for energy losses in the subsequent targets can be applied. The first two MWPCs provides veto signals for rejection of the few charged particles that contaminate the neutron beam. The target box contains five 35 mg/cm^2 thick CH_2 targets and two 85 mg/cm^2 ^{12}C targets, the latter for subtraction of the carbon contribution to the CH_2 spectra. The targets are stacked in the following (downstream) order: 2 CH_2, 2 carbon and 3 CH_2 layers.

The momentum determination of the charged particles emitted from the targets is performed with a spectrometer consisting of a dipole magnet and four drift chambers (DCHs) [12], two in front of and two behind the magnet. The scattering angle is determined by the trajectory through the first two DCHs. The detection efficiency for a drift chamber plane is typically ≥ 98%. To minimize the multiple scattering of charged particles in air, the space between the first two DCHs and the volume in the pole gap is filled with helium gas.

The trigger signal is generated by a coincidence between a small 1 mm thick plastic scintillator, located immediately after the multi-target box and a large 2 mm thick plastic scintillator, positioned behind the last DCH. In addition, two large plastic scintillators of thicknesses 4 and 10 mm, respectively, are added behind the 2 mm plastic scintillator, to facilitate particle identification.

The entire setup can be rotated around a pivot point, located below the centre of the multi-target box. With one position and one magnetic field setting, the spectrometer has a horizontal angular acceptance of about 15° in the laboratory system. Measurements are performed with two different settings of the spectrometer position, covering the proton recoil angular ranges $\theta_{LAB} = 26° - 41°$ and $35° - 53°$, respectively. Under these conditions, the energy resolution in the measured spectra is typically in the range $3 - 5$ MeV (FWHM). The angular resolution due to multiple scattering is estimated to be $0.6° - 1.3°$ (rms).

III. DATA ANALYSIS

A. Data reduction and corrections

The data are analyzed off-line on an event-by-event basis. Before an event is accepted, a number of tests is applied. A brief summary of the analysis procedure is given below. More detailed information about the data reduction has been given in Ref. [2].

Events originating from charged particles contaminating the neutron beam, or from charged-particle production in the thin scintillator just after the target system, are rejected. The scattering angle is determined by calculating the particle trajectory through the first two DCHs, using both the horizontal and vertical coordinate information. The particle momentum is determined by a ray-tracing procedure, using magnetic field maps and position information from the DCHs. Three DCHs are required for this purpose. The use of the fourth DCH offers a possibility for a redundancy check. The few events with dubious energy determination, or with a trajectory outside the magnetic field limits or an origin outside the neutron beam spot are rejected. To avoid vertical acceptance corrections, a narrow software gate of ±0.8° is applied on the vertical scattering angle, ensuring that no events are lost in the magnetic gap. The momentum information, in combination with the pulse heights from two of the large scintillators, is used to discriminate between protons and other charged particles (almost exclusively deuterons).

All accepted events are stored in matrices with angular and energy binning in the laboratory system of 1° and 0.25 MeV, respectively. Before extracting the hydrogen peak content, the carbon contribution to the CH_2 spectra is subtracted. This is illustrated for a few angles in Fig. 2, where an energy binning of 1 MeV is used. The open histograms represent the energy spectra from the CH_2 foils, while the cross-hatched histograms are those of the pure carbon targets, after normalization to the same number of target nuclei.

The np scattering peak contents are determined by integration. Since the energy resolution varies with angle, different integration windows are used. These are defined in a consistent way, and the final peak contents are determined by integrating the data in a region of $\pm\Delta E$ around the centroid, where ΔE is the peak FWHM. With this definition, the carbon background amounts to maximum 15% of the hydrogen peak for the largest recoil angles.

The variation of the width of the np peak with angle also causes an angular dependence in the background contribution from the low-energy continuum of the ^{7}Li(p,n) reaction. The data are corrected for this effect by using experimental neutron spectra from this reaction determined by Byrd and Sailor [13] at $E_p = 90.1$ MeV and 139.9 MeV. To simulate the finite resolution of our experiment, the Byrd and Sailor spectra, which have a much better resolution than in the present experiment, are folded with Gaussian resolution functions. From these folded spectra, the neutron continuum contribution to the peak, as defined above, can be determined as a function of peak width, and appropriate relative correction factors (< 3%) can be determined.

Since the energy of the recoil protons varies with scattering angle, the variation of the proton absorption with energy in the detector system has to be taken into account. To first order, elastic in- and out-scattering of protons cancel, and thus only non-elastic losses have to be considered. We have calculated these losses in the targets, detectors and helium gas, using the total reaction cross sections given by Carlson [14]. The proton attenuation gives non-negligible corrections only in the angular region $\theta_{c.m.} = 74° - 110°$, and the maximum correction amounts to 1.8% (at 74°).

B. Relative cross sections and uncertainties

The relative cross section data from the different spectrometer settings, together covering the 74° – 128° (c.m.) angular region, are used to extend the data of Rönnqvist *et al.* [10]. The three individual data sets, all treated as relative cross sections, are matched pairwise in the two uncorrelated overlapping regions using a minimum χ^2 criterion [2]. The χ^2 per degree of freedom is around 0.5 for both regions. The result of this matching is shown in the c.m. system in Fig. 3. As can be seen, the agreement in shape in the overlapping regions is very good. Final relative *np* scattering cross sections are obtained by averaging the data from the different data sets in each 2° (c.m) angular bin. A similar matching procedure was used by Rönnqvist *et al.* for the five data sets to generate the full angular distribution. Also in this case the χ^2 per degree of freedom is < 1 for all overlapping regions. It should be pointed out that that the five Rönnqvist sets, which were taken at different occasions, essentially fall into two main angular regions, i.e., 148° – 180° and below about 156°, respectively. Thus, there is a significant overlap of these two regions. Furthermore, there is no systematic shape difference between distributions with similar angular coverage, which is also verified by the small χ^2's mentioned.

Many sources of uncertainties contribute to the total error in the relative cross section. These errors are of both random and systematic character. Since the measurement is relative, only those systematic errors that affect the shape of the angular distribution have to be considered.

The random error is dominated by counting statistics, giving a contribution in the range 1.0% to 2.7% per point for the new data. The smaller value is valid for the data points close to 127°. Another small, random error contribution is due to bin truncation when integrating the *np*-peak. This error is at most 0.6% per point.

The most important contribution to the systematic error is related to the subtraction of the carbon background in the CH_2 energy spectra. Above about 145° the hydrogen peak is well separated from the carbon spectrum (Q-value $= -12.6$ MeV), and below 125° the hydrogen peak is superimposed on a flat carbon continuum. In the latter region the uncertainty in the relative thickness of the CH_2 and pure carbon targets introduces an error in the *np* cross section. With an estimated relative thickness uncertainty of 5%, the error in the angular region 75° – 127° is less than 0.7%.

In the angular range 125° – 145° the hydrogen peak interferes with the rising slope of the carbon background. Hence, a small error in the relative energy loss corrections for the CH_2 and carbon spectra, respectively, affects the background subtraction. This causes an error in the determined *np* cross section of $< 2\%$, using an estimated relative energy uncertainty of ±1 MeV. The problems arising from this effect can be seen in the Rönnqvist *et al.* [10] data around 133° in Fig. 3. Since the effect occurs in the middle of one of the Rönnqvist angular settings, it is not expected to contribute significantly to a possible progressive shape uncertainty arising from the overlap normalization procedure.

The correction ($< 3\%$) for the contribution from the low-energy continuum of the ^{7}Li(p,n) spectrum to the *np* scattering peak introduces a systematic error that varies with the peak width and thus with the angle. Assuming a relative uncertainty of 10% in the correction, an error in the data of at most 0.3% arises.

The error from the small correction due to the energy-dependent attenuation of the protons is estimated to be less than 0.6%.

When adding the various systematic uncertainties quadratically, the total systematic error varies from 0.5% to 2.0% in the full angular region. The largest errors are found in the range $\theta_{c.m.} = 125° - 145°$.

In addition to the random and systematic errors discussed, the shape of the full angular distribution is affected by the matching of the data sets. A quadratic addition of the uncertainties in the fitted coefficients, emerging mainly from the finite counting statistics, results in a shape error of ±2.1% between the most forward and most backward data sets, i.e., in the 75° to 179° cross section ratio. This slope error includes the corresponding uncertainty of ±1.3% from the Rönnqvist *et al.* data. There could in principle be additional slope errors caused by small inhomogenities in the drift chamber efficiencies, which could amplify from one setting to the next one. This does not seem probable, however, since 75% of the angular distribution, i.e., from 74° to 154°, is extremely well described by the PWA's. Thus, the χ^2 per degree of freedom, after optimum normalization, is 0.95 and 1.27 with respect to the NI93 [15] and SM95 [16] PWA's, respectively. Deviation from these models is found only beyond 154°, which is within one of the angular settings, and more or less outside the overlap region for the next setting.

C. Normalization procedure

Absolute *np* scattering cross sections are obtained by normalization to the total *np* cross section, which can be done since other reaction channels are negligible at 96 MeV. The total cross section σ_T has been experimentally determined around 100 MeV by several groups, and is considered to be well known. If the entire angular range, i.e., from 0° to

180°, had been measured in the present experiment, it would have been possible to normalize the data to the total cross section directly by integration. Since that is not the case, we consider our angular distribution as a measurement of a *fraction* of the total cross section, i.e., the part between 74° and 180°. By using a number of PWA's or potential models, it is possible to estimate the magnitude F of this fraction, to which the data should be normalized. Thus, we require that the integral over the solid angle of our data should be equal to

$$\sigma_{74^\circ-180^\circ} = \int_{74^\circ}^{180^\circ} \frac{d\sigma}{d\Omega} d\Omega = F\sigma_T^{exp}, \tag{1}$$

where

$$F = \sigma_{74^\circ-180^\circ}^{PWA} / \sigma_T^{PWA}. \tag{2}$$

To obtain σ_T^{exp}, we have used the Los Alamos data of Lisowski *et al.* [17], and the Harvard data of Measday and Palmieri [18]. The total error of the former is below 1% and of the latter about 4%. These data are in very good agreement. At slightly higher energies, i.e., above 125 MeV, one has also excellent agreement between these data and those from PSI by Grundies *et al.* [19], for which the errors are less than 1.5%.

The total cross section at 96 MeV is determined by fitting the absolute scale of the Nijmegen energy-dependent PWA NI93 [15] to the experimental data in the energy region 80 – 120 MeV, as illustrated in Fig. 4. A slight renormalization of 0.995 is needed to obtain a good fit. Also other PWA's and potentials have been tested, but it is found that NI93 gives the best description of the energy dependence of σ_T^{exp}. The resulting total cross section at 96 MeV is

$$\sigma_T^{exp} = 77.74 \pm 0.78 \pm 0.43 = 77.74 \pm 0.89 \text{ mb}, \tag{3}$$

where the first error corresponds to the 1% systematic error of the Lisowski data, and the second error is due to the ±0.5 MeV uncertainty in the neutron beam energy, because the total cross section has a slope of 1.11%/MeV.

The fraction F of the total cross section covered in the present experiment is determined from the PWA's SM95 [16], VL40 [3] and VZ40 [20] of VPI, and NI93 of Nijmegen [15]. VL40, VZ40 and NI93 are energy-dependent PWA's based on data in the 0 to 350 or 400 MeV region, while SM95 was obtained by fitting up to 1.6 GeV. The result is given in Table I, together with integrated cross sections and fractions for the Paris [21], Bonn [22] and Nijmegen [23] potentials for comparison. For the final value of F we take the average of the four mentioned PWA's to obtain $F = 0.613$. The potential models are not included in the determination, because we believe that the PWA's are more reliable since they describe the total cross section better. Thus, the integrated np scattering data have been normalized to

$$\sigma_{74^\circ-180^\circ}^{exp} = F\sigma_T^{exp} = 0.613 \times 77.74 = 47.65 \text{ mb}. \tag{4}$$

The result is shown in Fig. 5a, where the differential cross section has been multiplied with the solid angle element $2\pi \sin\theta$. In this representation, each angle bin directly shows its contribution to the total cross section. Also shown in the figure are the PWA's used to determine F, after normalization to $\sigma_T^{exp} = 77.74$ mb. As was discussed in the previous section, the data are well represented by any of the PWA's in most of the covered angular region. Deviations occur only at the extreme backward angles which, however, carry only small contributions to the total cross section (see Fig. 5a).

The spread in F for the various PWA's and NN potential models can be used to estimate the precision of this normalization procedure. One can see from Table I that the maximum deviation from the average value is −1.3% for the SM95 solution and +2.6% for the Bonn potential. From this comparison, we believe that it is fair to say that the normalization uncertainty is within ±1.5%. In addition, we have the "intrinsic" uncertainty in σ_T^{exp} of 1.1%. Summing these effects yields a total normalization uncertainty of ±1.9%. However, a word of caution should be given here: The estimated uncertainty relies on the assumption that the various models give a reasonable account of the main characteristics of the angular distribution. If the balance between the two humps at about 40° and 130° seen in Fig. 5a is considerably different, our normalization would of course be affected. If, e.g., the cross section in the forward hemisphere is larger than predicted by the models, this has to be compensated by lower backward cross sections to conserve the total cross section, and in this case our normalization would have to be lower.

IV. EXPERIMENTAL RESULTS

The final experimental differential cross sections are given in Table II and are shown as filled circles in Fig. 5b. The errors given are the quadratic sums of the statistical and systematic uncertainties of the relative cross sections discussed above. They do not include, however, the normalization uncertainty of ±1.9% and the shape uncertainty of ±2.1% between the most forward and backward data sets, i.e., in the 75° to 179° cross section ratio. These errors are correlated, and thus no individual point has a normalization error larger than about 2.2%. Also shown in the figure are the PWA's used to determine the normalization. As can be seen, the data are steeper than the PWA's in the 154° – 180° region, while they are well described at smaller angles, as has been discussed earlier. As can be expected from the figure, and as has been mentioned in Ref. [5], these data and those of our previous measurement at 162 MeV [2] lead to a very high χ^2 for the PWA NI93 [15].

The present extension in angular range of the previous Rönnqvist *et al.* data [10] leads to a 1% higher normalization for the latter, which is well within the 4% normalization error stated in that work.

The new 96 MeV data are compared with other experimental data from measurements performed close to that energy in Fig. 6a. Thus, we give in the figure the data of Stahl and Ramsey [24], Chih and Powell [25], Scanlon *et al.* [26] and Bersbach *et al.* [27]. Although these older data show a larger spread than the present ones, it is obvious that the new data are at least 10% higher at the most backward angles.

The Stahl and Ramsey data [24] at 91 MeV from Harvard are included in the fits of the VPI PWA's, but not in that of the Nijmegen group. The experiment covered scattering angles between 60° and 180°, comprising in total 25 data points. The data were normalized to the total cross section, at that time believed to be 78.5 ± 3 mb (the present value is 82.0 mb [17]). For the region not covered by the experiment, other *np* experimental data were used. The normalization error was assumed to be ±5%.

The Chih and Powell [25] data at 90 MeV consist of 18 points distributed over the angular range 8° – 180°. The measurement, which was performed with a cloud chamber, was relative and was normalized to a total *np* cross section of 76.0 mb (the present value is 82.8 mb). The normalization uncertainty is not discussed in the paper. The data are included in the Nijmegen PWA fit, but are not present in the VPI data base.

The Scanlon *et al.* data [26] at 99 MeV from Harwell cover the angular range from 7° to 173° in the c.m. system. Absolute cross sections between 7° and 120° were deduced by measuring the count-rate ratio between scattered neutrons and those of the direct neutron beam. Between 80° and 173°, the recoil protons were detected and only relative values for the cross sections could be obtained. This data set was normalized to the small-angle set in the 80° – 120° region. Absolute values were also determined by normalizing to the *np* total cross section. The final differential cross sections, shown in Fig. 6a, were obtained by combining the results of the two methods. The normalization uncertainty was claimed to be better than ±4%. The Scanlon data have been under critical examination by Hammans *et al.* [28] and Henneck [29], who recommend rejection of these data, based on experimental problems. The Nijmegen group has removed these data from their PWA fit, while the VPI group includes them in all their PWA versions.

The 97 MeV data of Bersbach *et al.* [27] were measured between 10° and 50° in the c.m. system, and are included in both the Nijmegen and VPI PWA fits. The normalization uncertainty was estimated to be ±10%. Like the Scanlon forward-angle data, absolute cross sections were obtained from scattered versus direct beam count-rate ratios.

In Fig. 6b, the present data are compared with three *NN* potential models, namely the Paris [21], Bonn [22] and Nijmegen [23] potentials. The angular distributions of the Paris and Nijmegen potentials are rather similar, and describe the data reasonably well in the 160° – 180° region, while a 7% overprediction is seen in the 110° – 160° region. One should keep in mind, however, that both the Paris and Nijmegen potentials overpredict the total cross section by 3%. It is interesting to note that although the Nijmegen potential and the present data do not agree over the entire interval studied, the 90°-to-180° cross section ratio is in good agreement. The Bonn potential describes the data fairly well in the 74° – 150° region, while it underpredicts by 6% at 180°. This potential gives, on the other hand, a total *np* cross section which is in good agreement with the experimental one.

V. DETERMINATION OF THE πNN COUPLING CONSTANT

We have now achieved our primary aim which is to give normalized *np* cross sections. We now briefly explore the bearing these data have on the discussion of the πNN coupling constant. We closely follow the procedure previously discussed in our work at 162 MeV to which we refer for details [2]; here we only sketch the procedure. The analysis is based on the fact that the charged pion exchange contributes importantly to the *np* charge exchange at small momentum transfers. This was realized already in 1958 by Chew, who suggested a model-independent extrapolation to the pion pole for the determination of the coupling constant.

The Chew extrapolation procedure [30,31] is based on a polynomial expansion in the square of the momentum transfer, q^2. The technique used to extrapolate to the pion pole is to first construct a smooth physical function, the Chew function, by multiplying the cross section by $(q^2 + m_\pi^2)^2$, which removes the pole term, after which the extrapolation can be made far more safely and controlled. More exactly, in the physical region the function $y(x)$ is defined by:

$$y(x) = \frac{sx^2}{m_\pi^4 g_R^4} \frac{d\sigma}{d\Omega}(x) = \sum_{i=0}^{n-1} a_i x^i . \tag{5}$$

Here s is the square of the total energy and $x = q^2 + m_\pi^2$. At the pion pole $x = 0$, the Chew function gives

$$y(0) \equiv a_0 \equiv g_{\pi\pm}^4 / g_R^4 \tag{6}$$

in terms of the pseudoscalar coupling constant $g_{\pi\pm}^2 \simeq 14$. The quantity g_R^2 is a reference scale for the coupling chosen for convenience. It is important to realize that the model-independent extrapolation requires accurate data with absolute normalization of the differential cross section. If the differential cross section is incorrectly normalized by a factor N, the extrapolation gives $\sqrt{N} g_{\pi\pm}^2$. This is one of the most important sources of uncertainty in the practical extrapolation from data.

An improvement on this rather slowly converging expansion is the difference method introduced in our previous work at 162 MeV [1,2], and also applied to $\bar{p}p$ charge exchange [32]. The difference method applies the Chew method to the difference between the function $y(x)$ obtained from a model with exactly known coupling constant and from the experimental data, i.e.,

$$y_M(x) - y_{exp}(x) = \sum_{i=0}^{n-1} d_i x^i \tag{7}$$

with g_R of eqs. (5) and (6) replaced by the model value g_M. At the pole

$$y_M(0) - y_{exp}(0) \equiv d_0 \equiv \frac{g_M^4 - g_{\pi\pm}^4}{g_M^4} . \tag{8}$$

This procedure should diminish systematic extrapolation errors and remove a substantial part of the irrelevant information at large momentum transfers.

As previously, we apply the difference method using four comparison models, i.e., the Nijmegen [23] and Bonn B [22] potentials, the Nijmegen energy-dependent PWA NI93 [15], and the VPI energy-dependent PWA SM95 [16]. The resulting $y_M(x) - y_{exp}(x)$ are shown in Fig. 7, together with polynomial fits in x of different orders $n-1$. As can be seen, the error bars blow up at large x, which is a consequence of the multiplication of the cross section with x^2, leading to a smaller weight for the large q^2 region in the extrapolation. In all cases the extrapolation to the pole can be made easily, and already a visual extrapolation gives an acceptable result, especially if one ignores the few points around $x = 2.5$, which might be affected by the carbon background subtraction problem around 133° discussed in Sect. III B. The polynomial fits cause no problem as long as the data are not overparametrized. If this is the case, edge effects in the fitting begin to influence the results (see Fig. 13e of Ref. [2]), and the uncertainty becomes large.

The corresponding values of the charged coupling constant obtained from the extrapolation using the polynomial fits are given in Table III. Let us recall that n is the number of terms in the polynomial expansion, χ^2/N_{df} is the average χ^2 per degrees of freedom and $g_{\pi\pm}^2$ is the obtained value of the coupling constant, with its statistical and extrapolation error. The behaviour of χ^2/N_{df} as a function of n is characteristic. It falls with increasing n to a value close to unity. Additional terms give only small gains, and the data become rapidly overparameterized. One can then adopt several statistical strategies leading to similar results. One possibility is to extract results at the minimum χ^2/N_{df}. In practice this minimum is very shallow, and as a consequence, values of n close to $n([\chi^2/N_{df}]_{min})$ are nearly equally probable statistically. Another method is to extract $g_{\pi\pm}^2$ from the smallest value of n consistent with a χ^2/N_{df} well within the range expected from the experimental sample[1].

As can be seen, the difference method requires only a few terms in the polynomial expansion, and this gives a small, statistical extrapolation error. We find optimum fits to the experimental data for $n = 3$ when using the Nijmegen potential and NI93 PWA, while we have to go to $n = 4$ for the Bonn B potential and the SM95 PWA of VPI. The reason is easily understood after a glance at Fig. 7, where the SM95 and Bonn B fits show a slightly more complicated

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[1] Recall that there is about 47% probability of the experimental χ^2/N_{df} to be larger than 1, about 20% to be larger than 1.2, and about 7% to be larger than 1.4.

x-dependence. The statistical extrapolation errors are small, especially for the $n = 3$ fits. Going to $n = 4$ for these models, which gives approximately the same quality of the fits, does not really change the extrapolated value of $g^2_{\pi\pm}$, but the statistical errors become larger.

As in our preceeding work, we establish the systematic uncertainties of the extrapolation procedure from pseudo-data with uncertainties corresponding to the present experiment, according to the following procedure. The coupling constant is determined from 10 000 computer simulations with exact data points from the four models mentioned above, which have known coupling constants. One furthermore adds to these exact data points a Gaussian, random error distribution [33]. For each of these "experiments" we applied the difference method with one of the other three theoretical models as comparison model. The average value for this sample of simulations is obtained to high accuracy. We list the result of this exercise, with all six permutations, in Table IV. The model in quotation marks is the one used to generate the "experimental" pseudo-data. $g^2_{\pi\pm}$ is here the mean value of the coupling constant for 10 000 pseudo-experiments, while the errors quoted are standard deviations for individual pseudo-experiments. In addition, we also list the systematic deviation $\delta g^2_{\pi\pm}$ of the mean value in the sample from the true value in the model.

We first note that for all values of n there are only a few systematic deviations clearly outside the statistical uncertainty, whenever χ^2/N_{df} is close to 1. For the Bonn B-"Nijmegen" difference this occurs (Table IV) for $n = 4$ with $\delta g^2_{\pi\pm} = -0.43$. The origin of this systematic shift is apparent from Fig. 7d, which shows the difference Bonn B-Uppsala. The extrapolated value for $n = 3$ is 15.43 a high value clearly associated with the not so good fit to the data. The corresponding differences for the Nijmegen potential and the NI93 PWA have good χ^2/N_{df}, which indicates a considerable similarity in shape to the data, as can be seen in Fig. 7a and b. Since the systematic shift for the NI93-"Bonn B" difference follows mathematically by subtracting the Bonn B-"Nijmegen" systematic shift from the NI93-"Nijmegen" one, a large systematic error, $\delta g^2_{\pi\pm} = 0.36$, will occur also for the NI93-"Bonn B" difference for $n = 4$, as seen in Table III. The next higher similar sysematic effect is for SM95-"Nijmegen" (see Table IV) with $\delta g^2_{\pi\pm} = -0.24$ for $n = 4$. These systematic effects determine the systematic error of our analysis.

To conclude, we find optimum fits to the present experimental data for $n = 3$ or 4, with systematic shifts being at most 3%. The systematic shifts are larger for $n = 3$, but going to $n = 4$ (or in some cases $n = 5$) brings them down to about 1%. The corresponding change in the $g^2_{\pi\pm}$ determined from the experimental data is nevertheless sizable. Averaging the values from the extrapolations, we find $g^2_{\pi\pm} = 14.73 \pm 0.14$. The systematic extrapolation uncertainty is realistically estimated to be ± 0.23, while the uncertainty from normalization is 1%, i.e., ± 0.15. Thus, the final value for the charged πNN coupling constant from the present work is $g^2_{\pi\pm} = 14.73 \pm 0.14$ (extrapolation and statistical) ± 0.23 (systematic) ± 0.15 (normalization) $= 14.73 \pm 0.31$. This result is consistent with our previous finding, $g^2_{\pi\pm} = 14.52 \pm 0.26$, extracted at 162 MeV [1,2].

VI. SUMMARY AND CONCLUSIONS

The np differential cross section has been measured at 96 MeV using the neutron beam facility at the The Svedberg Laboratory in Uppsala. The data from Rönnqvist *et al.* have been extended to cover the 74° – 180° region. The data were normalized using the total np cross section, which has been experimentally determined with high precision by Lisowski *et al.* Since our data do not cover the full angular range, the experiment was considered as a measurement of a fraction of the total cross section. This fraction was determined by using the angular shape of a number of energy-dependent PWA's. The data were normalized to the average fraction, obtained from those PWA's, multiplied with the experimental total cross section. We estimate the normalization error to ±1.9%.

A general feature is that our data have a steeper slope in the 150° – 180° angular region than most of the existing data in the same energy region. As a consequence, the slope is also steeper than several of the current PWA's and NN potential models. A similar situation is also present at higher energies, where large data sets disagree significantly in shape.

The np scattering cross section at 180° is used as a primary standard for normalization of most other neutron-induced cross sections. Uncertainties of the order of 10% in this cross section are therefore unacceptable. Remeasuring the absolute np scattering cross sections with high precision and at several energies should be of high priority.

As a by-product of the present investigation we obtain an extrapolated value $g^2_{\pi\pm} = 14.73 \pm 0.31$ ($f^2_{\pi\pm} = 0.0813 \pm 0.0017$) for the charged πNN coupling constant using the difference method. This is consistent with the value found in our previous work at 162 MeV [1,2].

Our future plans include measurements of np scattering between 10° and 170° (c.m) at a few energies in the 50 – 180 MeV range. To this end, a new experimental setup is under construction [34]. The new detector system has been designed to detect either recoil protons or scattered neutrons. In this manner, it will be possible to cover both the backward angles by detecting the recoil protons and the forward angles by detecting the scattered neutrons. In particular, we plan to extend the data we have at 96 and 162 MeV to cover the full angular range, i.e., also the forward angles $\theta_{c.m.} = 10^\circ - 70^\circ$. By including these forward-angle data, we could normalize our angular distributions to the total *np* cross section directly, without any assumptions about the angular shape.

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TABLE I. Total cross sections (σ_T) and angular fractions ($F = \sigma_{74^\circ-180^\circ}/\sigma_T$) for different PWA's and NN potential models. The weighted experimental value is 77.74 mb (see the text for more details).

PWA or Potential	σ_T	$\sigma_{0^\circ-74^\circ}$	$\sigma_{74^\circ-180^\circ}$	F	σ_T^{exp}/σ_T
SM95 [16]	78.22	30.88	47.34	0.6052	0.9939
VZ40 [20]	77.52	30.22	47.30	0.6102	1.0028
VL40 [3]	77.70	30.19	47.51	0.6115	1.0005
NI93 [15]	78.07	29.30	48.77	0.6247	0.9958
Average	77.88	30.15	47.73	0.6129	0.9982
Paris [21]	79.75	29.80	49.95	0.6263	0.9748
Bonn [22]	77.96	28.95	49.01	0.6287	0.9972
NY93 [23]	79.99	30.12	49.87	0.6235	0.9719

TABLE II. Differential cross sections for np scattering at 96 MeV.

$\theta_{c.m.}$ (Deg.)	$d\sigma/d\Omega$ (mb/sr)	$\theta_{c.m.}$ (Deg.)	$d\sigma/d\Omega$ (mb/sr)	$\theta_{c.m.}$ (Deg.)	$d\sigma/d\Omega$ (mb/sr)
75.0	4.075 ± 0.109	111.0	4.985 ± 0.068	147.0	8.492 ± 0.151
77.0	3.957 ± 0.108	113.0	5.181 ± 0.068	149.0	8.886 ± 0.101
79.0	3.956 ± 0.106	115.0	5.240 ± 0.069	151.0	9.128 ± 0.101
81.0	4.080 ± 0.106	117.0	5.393 ± 0.063	153.0	9.401 ± 0.101
83.0	4.098 ± 0.105	119.0	5.556 ± 0.064	155.0	10.067 ± 0.121
85.0	3.988 ± 0.103	121.0	5.836 ± 0.066	157.0	10.522 ± 0.121
87.0	4.083 ± 0.103	123.0	6.073 ± 0.068	159.0	10.915 ± 0.141
89.0	4.038 ± 0.102	125.0	6.190 ± 0.069	161.0	11.178 ± 0.141
91.0	4.132 ± 0.102	127.0	6.371 ± 0.069	163.0	11.834 ± 0.141
93.0	4.111 ± 0.101	129.0	6.634 ± 0.121	165.0	12.329 ± 0.151
95.0	4.170 ± 0.100	131.0	7.119 ± 0.131	167.0	13.056 ± 0.162
97.0	4.110 ± 0.098	133.0	7.260 ± 0.131	169.0	13.520 ± 0.121
99.0	4.328 ± 0.055	135.0	7.391 ± 0.141	171.0	13.934 ± 0.131
101.0	4.442 ± 0.056	137.0	7.452 ± 0.141	173.0	14.429 ± 0.131
103.0	4.560 ± 0.056	139.0	7.735 ± 0.141	175.0	14.783 ± 0.141
105.0	4.660 ± 0.056	141.0	7.947 ± 0.141	177.0	15.075 ± 0.151
107.0	4.789 ± 0.057	143.0	8.038 ± 0.141	179.0	14.944 ± 0.172
109.0	4.898 ± 0.057	145.0	8.280 ± 0.141		

TABLE III. Values of the coupling constant obtained from polynomial fits with n terms to data at 96 MeV using the difference method for the full range of data ($0 < q^2 < 5.8\ m_\pi^2$). The experimental values at the minimum χ^2/N_{df} are indicated in boldface. The comparison models are the Nijmegen [23] (Nijmegen) and Bonn B [22] (Bonn B) potentials, and the Nijmegen [15] (NI93) and VPI [16] (SM95) energy-dependent PWA's. The model coupling constants are $g^2_{\pi\pm,\ \mathrm{Nijmegen}} = g^2_{\pi\pm,\ \mathrm{NI93}} = 13.58$, $g^2_{\pi\pm,\ \mathrm{SM95}} = 13.75$ and $g^2_{\pi\pm,\ \mathrm{Bonn\ B}} = 14.40$.

n	χ^2/N_{df}	$g^2_{\pi\pm}$	χ^2/N_{df}	$g^2_{\pi\pm}$	χ^2/N_{df}	$g^2_{\pi\pm}$	χ^2/N_{df}	$g^2_{\pi\pm}$
	Nijmegen-Uppsala		NI93-Uppsala		SM95-Uppsala		Bonn B-Uppsala	
2	1.917	14.11 ± 0.04	1.292	14.16 ± 0.04	1.333	14.02 ± 0.04	1.118	15.31 ± 0.03
3	0.956	$\mathbf{14.69 \pm 0.09}$	0.966	$\mathbf{14.49 \pm 0.09}$	1.359	14.03 ± 0.09	1.096	15.43 ± 0.08
4	0.956	14.54 ± 0.18	0.974	14.61 ± 0.18	0.962	$\mathbf{14.77 \pm 0.18}$	0.918	$\mathbf{14.95 \pm 0.18}$
5	0.971	14.71 ± 0.39	0.970	14.98 ± 0.39	0.955	15.17 ± 0.38	0.937	14.90 ± 0.38

TABLE IV. Values of the coupling constant obtained from polynomial fits with n terms to "pseudo-data" at 96 MeV using the difference method for the range $0 < q^2 < 5.8\ m_\pi^2$. The comparison models and the model coupling constants are the same as in Table III. $\delta g^2_{\pi\pm}$ is the systematic shift from the true model value.

n	χ^2/N_{df}	$g^2_{\pi\pm}$	$\delta g^2_{\pi\pm}$	χ^2/N_{df}	$g^2_{\pi\pm}$	$\delta g^2_{\pi\pm}$	χ^2/N_{df}	$g^2_{\pi\pm}$	$\delta g^2_{\pi\pm}$
		NI93-"Nijmegen"			SM95-"Nijmegen"			Bonn B-"Nijmegen"	
2	1.27	13.63 ± 0.04	−0.05	2.00	13.50 ± 0.04	0.08	1.71	14.83 ± 0.03	−1.25
3	1.07	13.35 ± 0.10	0.23	1.62	12.86 ± 0.10	0.72	1.10	14.37 ± 0.09	−0.79
4	1.01	13.65 ± 0.20	−0.07	1.01	13.82 ± 0.19	−0.24	1.01	14.01 ± 0.19	−0.43
5	1.00	13.86 ± 0.42	−0.28	1.00	14.06 ± 0.41	−0.48	1.00	13.73 ± 0.42	−0.15
		NI93-"Bonn B"			SM95-"Bonn B"			NI93-"SM95"	
2	1.44	13.16 ± 0.04	1.24	2.23	13.01 ± 0.04	1.39	1.56	13.90 ± 0.04	−0.15
3	1.33	13.37 ± 0.10	1.03	2.22	12.88 ± 0.10	1.52	1.29	14.22 ± 0.09	−0.47
4	1.03	14.04 ± 0.19	0.36	1.03	14.21 ± 0.19	0.19	1.00	13.58 ± 0.20	0.17
5	1.00	14.47 ± 0.40	−0.07	1.00	14.66 ± 0.39	−0.26	1.00	13.55 ± 0.43	0.20

FIG. 1. Overview of the Uppsala neutron beam facility. The neutron production, shielding and collimation are shown, as well as the magnetic spectrometer arrangement.

FIG. 2. Proton energy spectra from CH_2 (open histograms) and carbon (cross-hatched histograms) targets, respectively, at various scattering angles. The part of the CH_2 spectra at lower energies not accounted for by the carbon contribution originates from *np* scattering of neutrons from the low-energy neutron tail.

FIG. 3. Relative differential *np* scattering cross sections at $E_n = 96$ MeV. The open symbols represent data from the two magnetic settings, while the filled circles are the previously published backward-angle data [10]. The three data sets were normalized to each other in the overlapping regions.

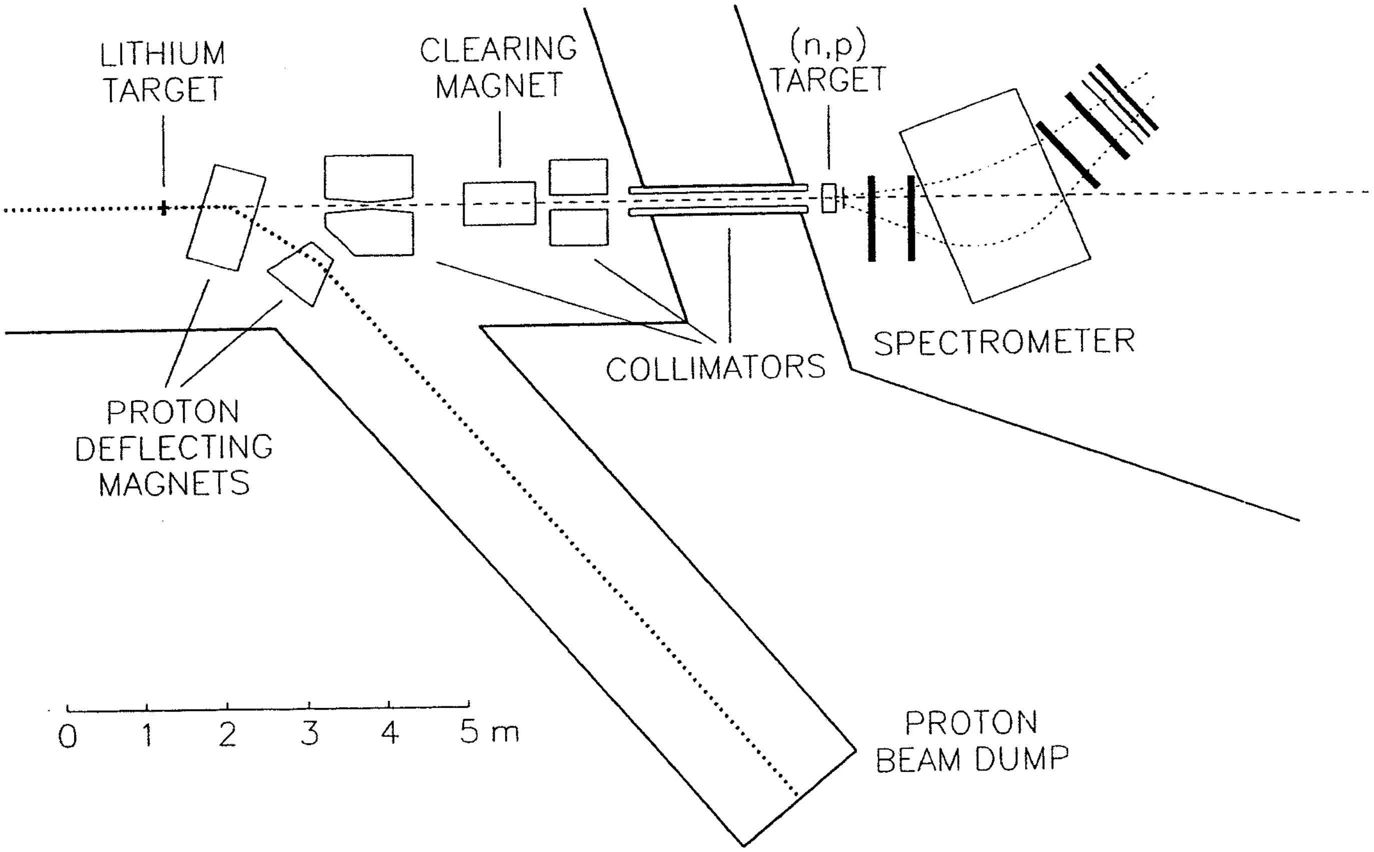
FIG. 4. Total *np* cross section versus energy in the range 80 – 120 MeV. The different symbols represent experimental data [17,18], while the lines are from PWA's and *NN* potentials, renormalized by us to the data in the shown energy region.

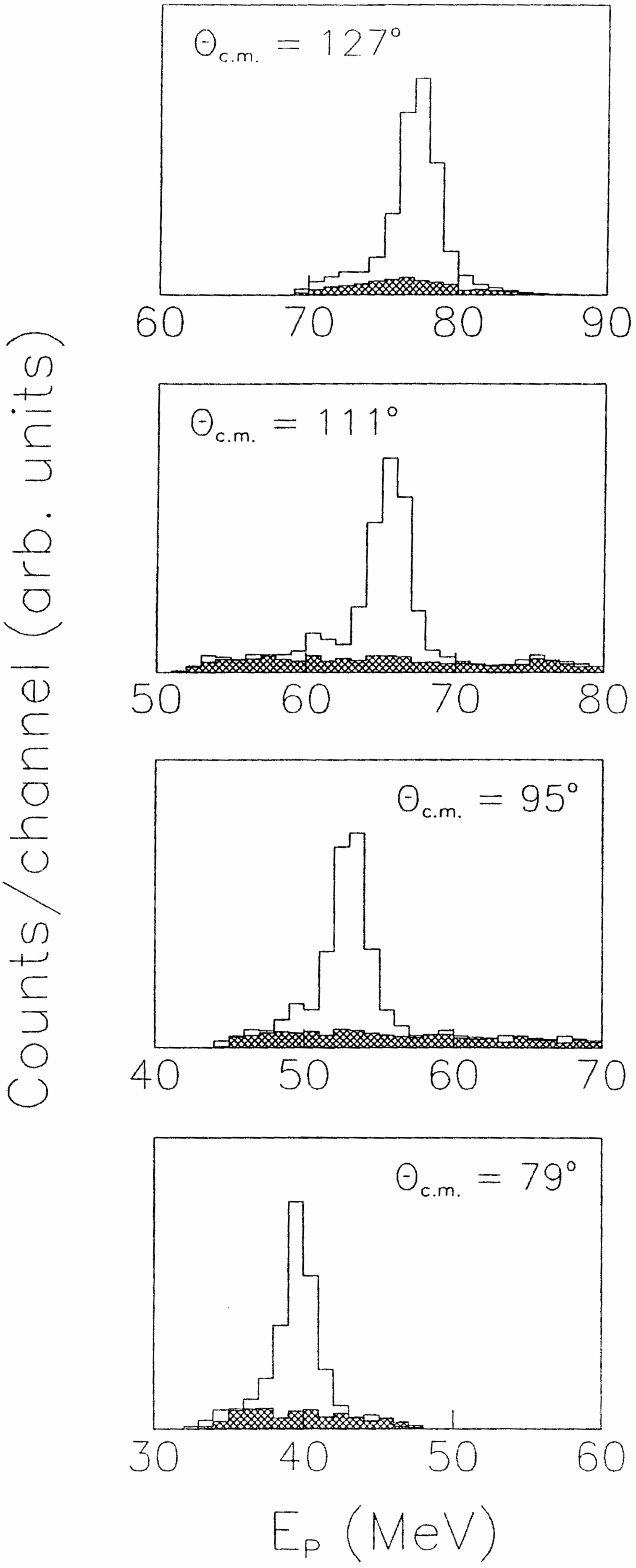
FIG. 5. Angular distributions for the SM95 [16], VZ40 [20] and NI93 [23] PWA's, and the present experimental data (filled circles) at 96 MeV. The VL40 [3] PWA solution is almost identical to VZ40 and is not shown for clarity. a) Differential *np* scattering cross sections multiplied by the solid angle element $2\pi \sin\theta$. b) Differential cross sections for *np* scattering.

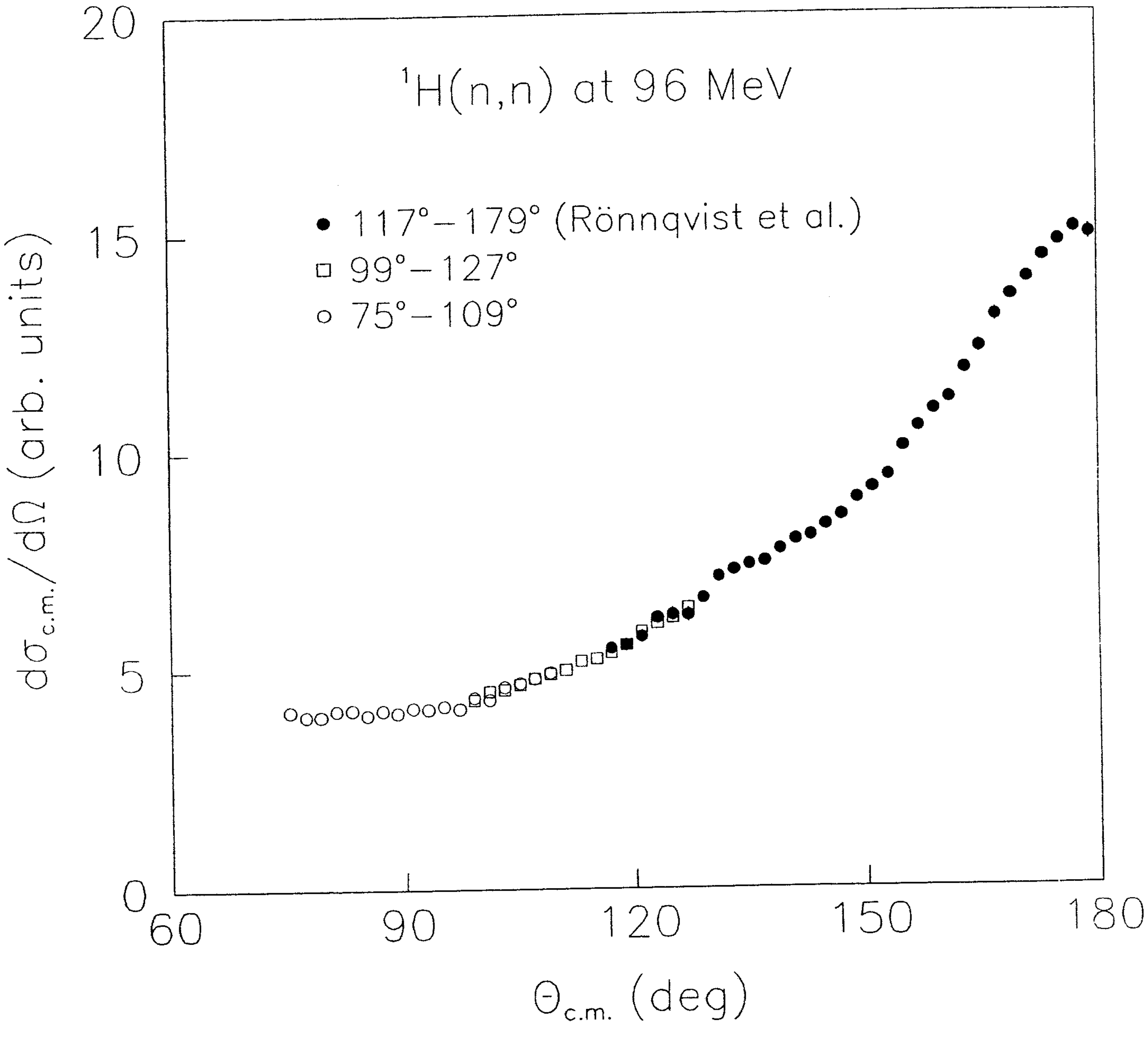
FIG. 6. a) Differential *np* scattering cross sections of the present work (filled circles). Also plotted are other data from the literature at energies close to 96 MeV [24–27]. b) The present differential cross sections plotted together with the Paris [21], Bonn [22] and Nijmegen [23] *NN* potentials.

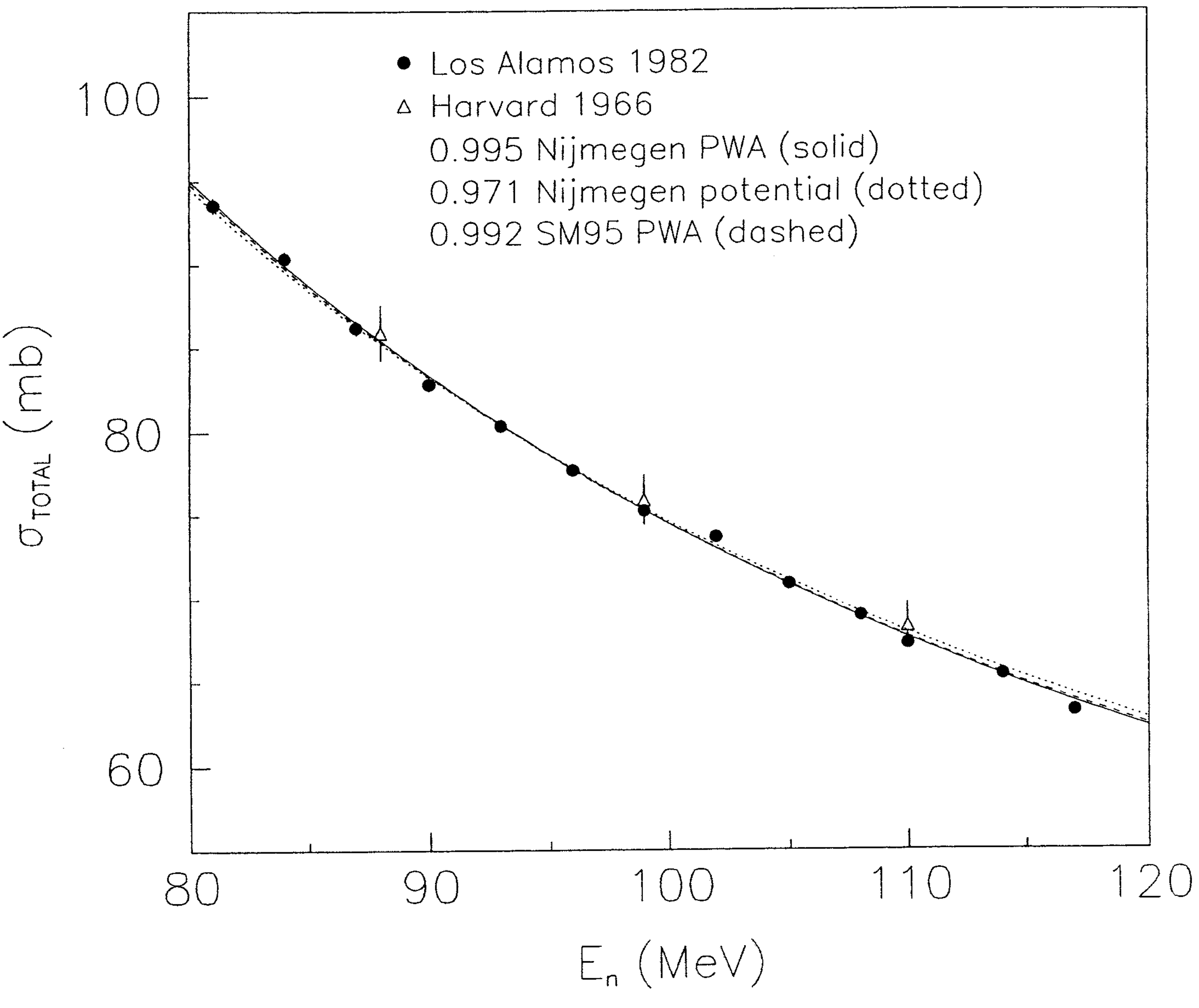
FIG. 7. Extrapolations of the Chew function $y(q^2)$ to the pion pole at 96 MeV with the Difference Method using different comparison functions and different polynomials orders. The comparison functions are: (a) the Nijmegen potential model [23]; (b) the Nijmegen energy-dependent PWA NI93 [15]; (c) the Virginia energy-dependent PWA SM95 [16]; and (d) the Bonn B potential model [22].

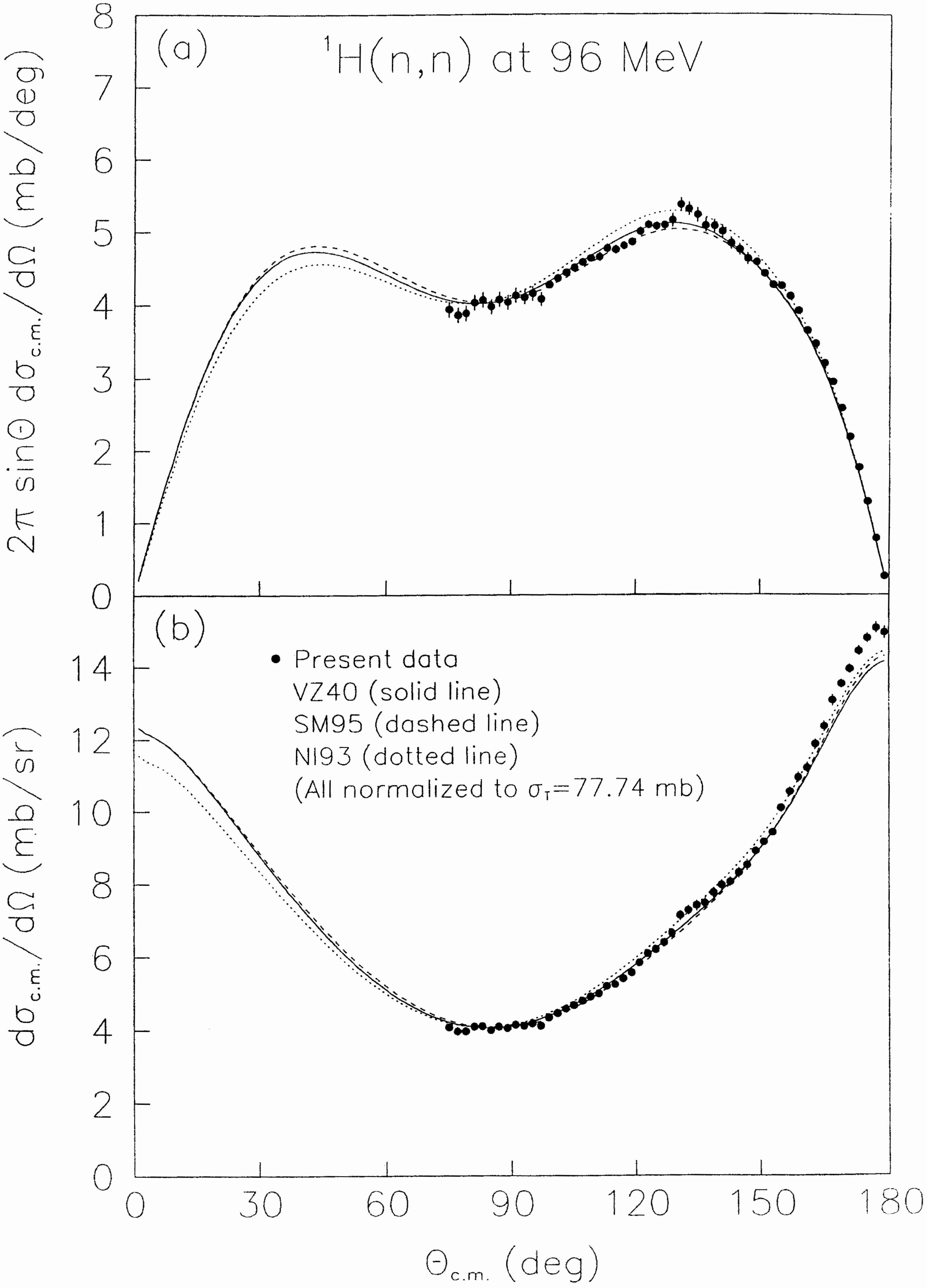
The TSL Neutron Beam Facility

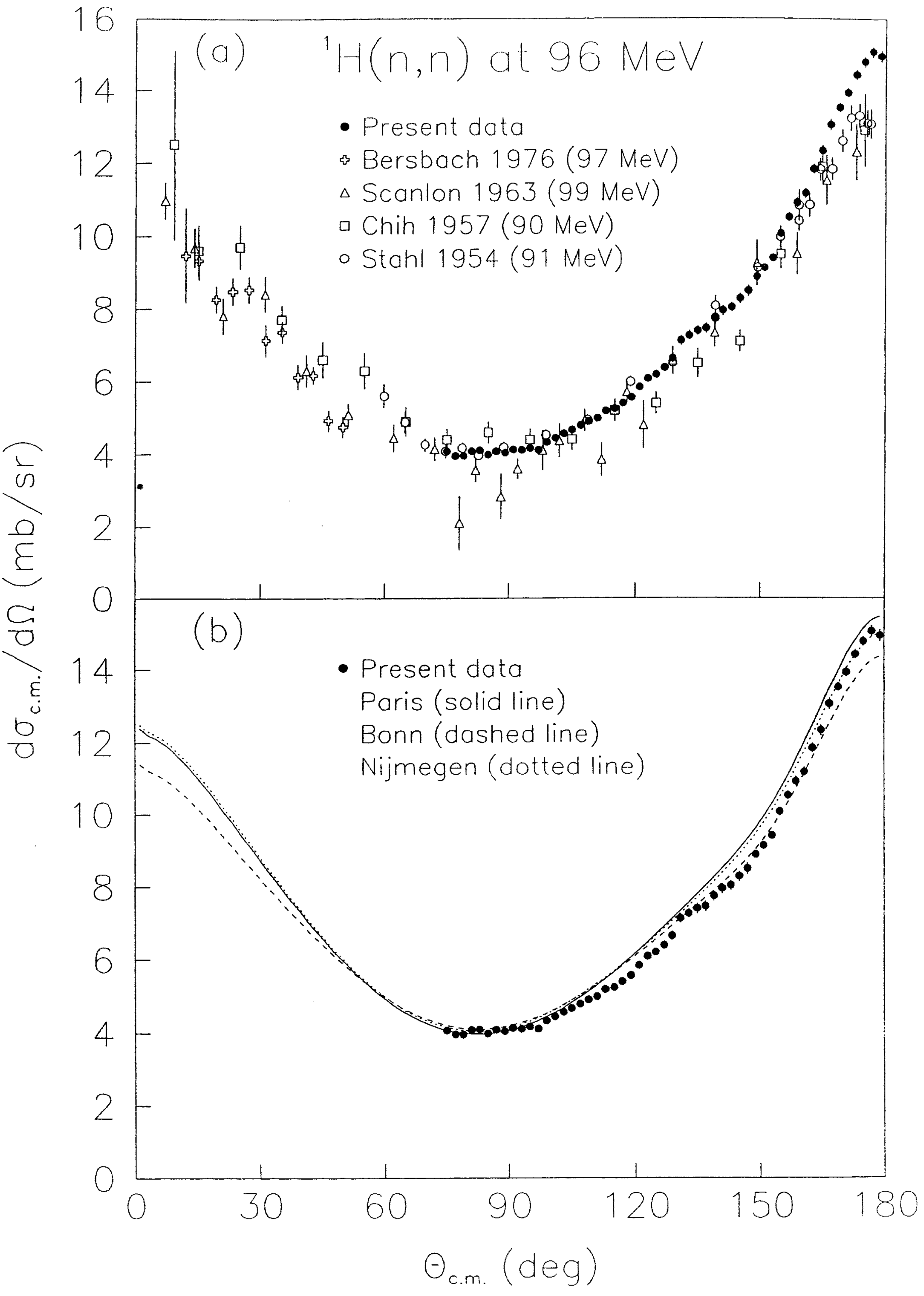


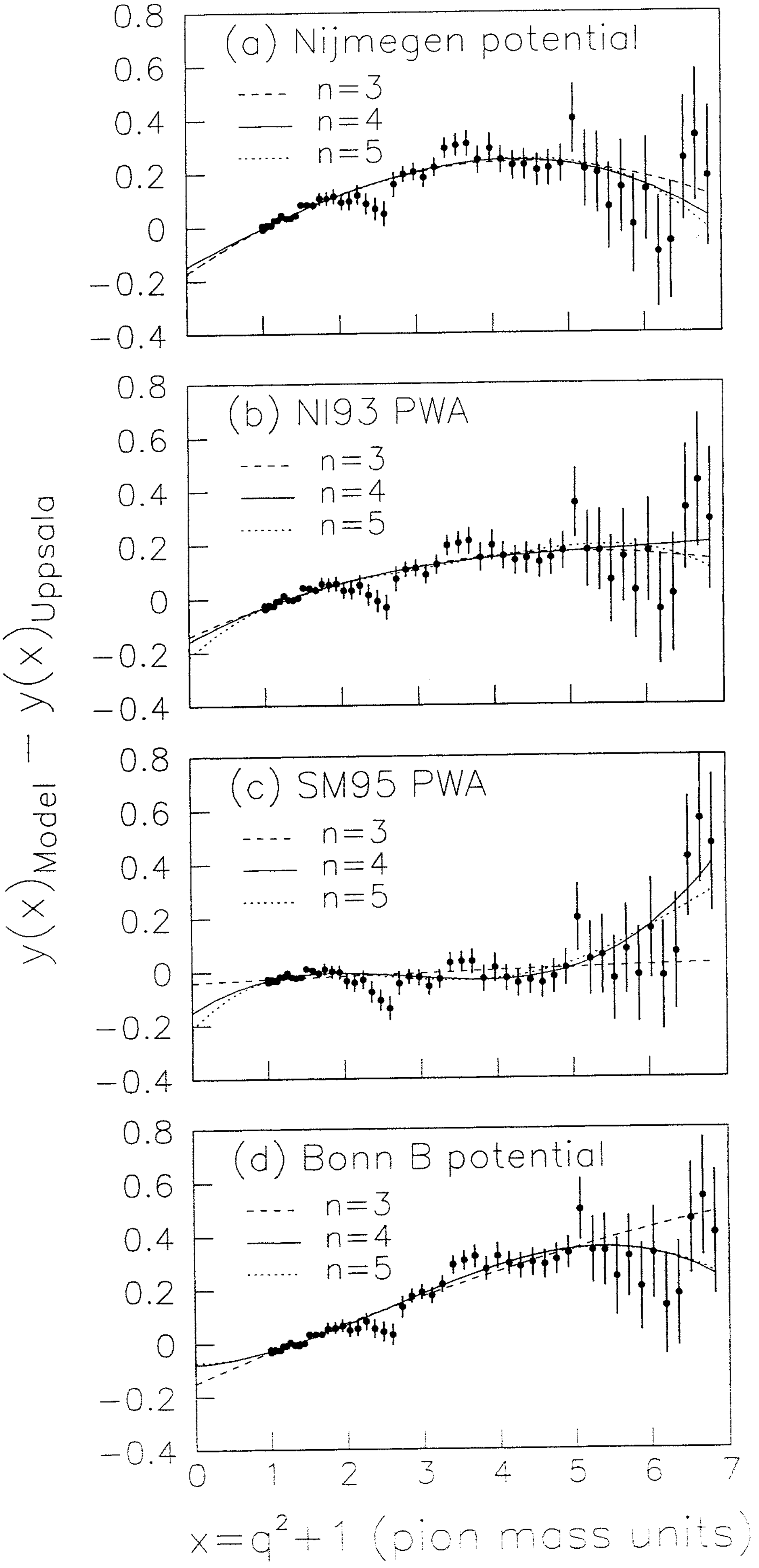

$\Theta_{c.m.} = 127°$
60
70
80
90
$\Theta_{c.m.} = 111°$
50
60
70
80
$\Theta_{c.m.} = 95°$
40
50
60
70
$\Theta_{c.m.} = 79°$
30
40
50
60
Counts/channel (arb. units)
E_p (MeV)


$^1H(n,n)$ at 96 MeV
● 117°–179° (Rönnqvist et al.)
□ 99°–127°
○ 75°–109°
$d\sigma_{c.m.}/d\Omega$ (arb. units)
$\Theta_{c.m.}$ (deg)
0
5
10
15
20
60
90
120
150
180


● Los Alamos 1982
△ Harvard 1966
0.995 Nijmegen PWA (solid)
0.971 Nijmegen potential (dotted)
0.992 SM95 PWA (dashed)
σ_{TOTAL} (mb)
100
80
60
80
90
100
110
120
E_n (MeV)


(a)
^{1}H(n,n) at 96 MeV
$2\pi \sin\Theta\, d\sigma_{c.m.}/d\Omega$ (mb/deg)
0
1
2
3
4
5
6
7
8
(b)
● Present data
VZ40 (solid line)
SM95 (dashed line)
NI93 (dotted line)
(All normalized to σ_T=77.74 mb)
$d\sigma_{c.m.}/d\Omega$ (mb/sr)
0
2
4
6
8
10
12
14
0
30
60
90
120
150
180
$\Theta_{c.m.}$ (deg)


(a)
$^1H(n,n)$ at 96 MeV
● Present data
✚ Bersbach 1976 (97 MeV)
△ Scanlon 1963 (99 MeV)
□ Chih 1957 (90 MeV)
○ Stahl 1954 (91 MeV)
(b)
● Present data
Paris (solid line)
Bonn (dashed line)
Nijmegen (dotted line)
$d\sigma_{c.m.}/d\Omega$ (mb/sr)
$\Theta_{c.m.}$ (deg)
0
2
4
6
8
10
12
14
16
0
30
60
90
120
150
180


(a) Nijmegen potential
(b) NI93 PWA
(c) SM95 PWA
(d) Bonn B potential
n=3
n=4
n=5
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
1
2
3
4
5
6
7
y(x)_Model − y(x)_Uppsala
x=q²+1 (pion mass units)

Appendix V

For Official Use **NEA/SEN/NSC/WPMA(99)2**

OECD
OCDE
PARIS

Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development

OLIS : 30-Jun-1999
Dist. : 02-Jul-1999

Or. Eng.

NUCLEAR ENERGY AGENCY
NUCLEAR SCIENCE COMMITTEE

Working Party on International Nuclear Data Measurement Activities

SUMMARY RECORD OF THE FIFTH MEETING OF THE WORKING PARTY ON INTERNATIONAL NUCLEAR DATA MEASUREMENT ACTIVITIES

Held at Brookhaven National Laboratory
19-21 April 1999

79738

NEA/SEN/NSC/WPMA(99)2
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Summary Record of the Fifth Meeting of the Working Party on International Nuclear Data Measurement Activities

19-21 April 1999

Prepared by D.L. Smith and H. Weigmann

Joint meeting of WPEC and WPMA

The WPMA meeting was preceded by a joint meeting with the Working Party on International Evaluation Cooperation (WPEC). This joint meeting dealt with the following subjects:

1. The proposal from the NEA Nuclear Science Committee to merge the two Working Parties;
2. The status of the High Priority Request List for Nuclear Data;
3. The status of the three joint subgroups;
4. The list of upcoming meetings and conferences of interest to the WP members.

The discussion of the first two points has been summarised in detail in the summary record of WPEC (NEA/SEN/NSC/WPEC(99)2); no additional remarks will be made in this report.

Also the reports from the three joint subgroups have been summarized in NEA/SEN/NSC/WPEC(99)2; some additional remarks on the discussions in these subgroups will be given below.

Standards Subgroup

The Chairman of the subgroup, A. Carlson made available copies of the Poenitz report from Argonne documenting the data base used for the simultaneous evaluation. Also, copies of the report which describes the work for the ENDF/B-VI standards evaluation were also provided. Carlson discussed the procedure used in this evaluation and listed the measurements that would be added to the original data base. Some of these measurements are completed and others are pending. It was noted that the schedule originally established during the Antwerp meeting was probably unrealistic since adhering to that schedule would mean that some important new measurements in progress would be excluded. It was decided to extend the period of data collection for approximately another year (until 2001). Following that date, it would be about 1.5 years until the evaluations were completed according to his schedule.

It was pointed out that only about 7 people appeared to be available to work on this project [Haight, Shibata, Hale, Mannhart, Leal, Carlson, and Hambsch were mentioned]. Mannhart will look at the combining procedure for merging R-matrix and simultaneous evaluation results. Hambsch discussed the problems encountered at Geel with the ^{10}B (n,alpha) experiment (e.g., variable background). Currently the Geel Van de Graaff facility is being refurbished so measurements will move to GELINA for the near term. Madland inquired about the use of relativistic kinematics in the standards evaluations. Carlson responded that the issue had not been resolved.

Intermediate Energy Subgroup

The Chairman of the WPMA subgroup, N. Olsson, pointed out that both WPEC and WPMA had subgroups on this topic. A. Koning chairs the corresponding evaluation subgroup. In Olsson's opinion the merging of the two working parties (WPEC/WPMA) would be beneficial because it would lead to improved co-ordination in the area of intermediate energy nuclear data. Olsson proceeded to give brief summaries of ongoing work by region:

Europe

A European concerted action was started during 1998 under the auspices of the European Union. 13 groups working at 5 sites (GSI, COSY-Julich, KVI, Louvain-la-Neuve, TSL) are included. A proposal for future work to be submitted to the EC will be prepared in the near future.

Russia

A group from Khlopin Radium Institute, St. Petersburg, is working at Uppsala on several projects including fission measurements to 160 MeV. This work is being supported by an ISTC grant.

Japan

Several laboratories are involved in intermediate energy work including JAERI and some universities. This work is being carried out at the Takasaki Facility and at KEK.

U.S.

The work is centered at LANSCE-Los Alamos. Sigma-total measurements are performed on many nuclei ranging from H to ^{238}U at energies from 5 to 500 MeV. Gamma-ray measurements are made with the new GEANIE detector up to 200 MeV. (n,z) measurements are performed to 50 MeV on O, Si, and Ca. Also, (n,γ) measurements are performed from thermal to 300 keV on rare target materials including radioactive ones.

There was some discussion on the issue of high-energy evaluated data files. There seems to be a misconception that there had to be different files for low and high energy applications. Madland pointed out that the ENDF format allows coverage of energies from thermal to several hundred MeV and that a single file can be used for both purposes. Recent work at LANL has focused on extending the files from 20 to 150 MeV. The energy 150 MeV was chosen because it is just above the pion emission threshold where pion emission is still a minor perturbation. At higher energies the simplified nuclear reaction models, found in such codes as LAHET and HETC, can be used. At lower energies more complex models based on HF and FKK are needed to obtain reliable results. The present high energy cross sections are largely based on nuclear model calculations, but they have been benchmarked against microscopic experimental information and KERMA data where available.

ACTION

It was suggested that Olsson and Koning should get together and submit a proposal to NEA for future work under the banner of the combined working party.

There was also some discussion on high energy data needs in the context of SNS (ORNL spallation neutron source).

Subgroup on Prompt Fission Neutron Spectra

The complete summary record of the meeting of this subgroup has been prepared by D. Madland and is enclosed in Annex 1 to these minutes.

^{238}U(n,n') Subgroup

H. Weigmann indicated that nothing much new had occurred on this topic during the past year. He then proceeded to review the status and to show angular distributions and angle-integrated energy-dependent cross sections. In particular, he focused on details of the Geel experiment of Goddio and Plompen, which was performed at 3 angles and 3 - 4 energies. Since individual levels could not be resolved in this experiment, cross sections involving groups of levels were reported. The angular distributions for the first inelastic group above the elastic scattering peak seemed to be forward peaked, indicating either difficulties in separating the inelastic events from elastic scattering or influences of a direct reaction mechanism. Vonach pointed out that direct reaction contributions would be very likely in this situation.

Madland asked about the motivation for this subgroup. The response was that inelastic scattering from ^{238}U is a very important issue in reactor physics because of its impact on the neutronics behavior, and that discrepancies and a lack of data at the higher energies (in this case 2-3.5 MeV) led to highest priority demands from the reactor physics community for new measurements.

In general it appeared that after the recent experimental activities in this area at several labs (besides IRMM mainly ANL, Tohoku University and Obninsk) little more experimental work would be done. M. Baba of Tohoku University is preparing a status report on ^{238}U(n,n') data. The incorporation of the new data into a new evaluation is needed next; such a new evaluation should then also provide indications for the possible need of further experimental work.

Separate meeting of WPMA

The main agenda items of the WPMA meeting, apart from brief reports from the subgroup meetings in the joint session, were a presentation on the status of the CERN proposal for a new time-of-flight facility and reports from the individual laboratories.

Approval of Summary Record of the fourth WPMA meeting, Antwerp, 1998

It was noted by Dr. Mannhart that there appeared to be some difference in the reports on the prompt fission neutron spectrum discussion as they appeared in the 1998 WPEC and WPMA reports, respectively. This issue was examined and there was some discussion. It was concluded that neither report was particularly in error but that perhaps the WPEC report adhered more closely to what was actually stated concerning actions for this subgroup.

CERN Facility

A detailed presentation of the newly proposed spallation neutron source facility at CERN - motivation and features - was given by S. Andriamonje from the University of Bordeaux. The facility would utilize a 24 GeV proton beam from the CERN PS. The neutron producing target presently foreseen would be a fairly large (80 cm diameter, 40 cm height) Pb cylinder. The peak pulse current would be very high, but the repetition rate would be about one pulse every 3 seconds. The resolution would not be good by comparison, e.g., to GELINA, except for low energies ($<$ a few keV). In the domain where it would be superior to other facilities like GELINA - low energies - this facility would offer unprecedented neutron flux levels. In particular, because of the high flux per pulse, it would be well suited for measurements with small quantities of rare or radioactive materials.

Individual Activity Reports

Uppsala University (N. Olsson)

Olsson reviewed the activities at Uppsala and provided a brief overview description of the experimental facilities there.

At TSL: using the ^{7}Li(p,n) reaction as a source of quasi-monoenergetic neutrons, measurements at intermediate energies (20 to 180 MeV) of various neutron induced reactions, among others:

- differential neutron-proton scattering cross section: observed differences in 180-degree data when compared with earlier measurements and ENDF/B;
- neutron elastic scattering with the SCANDAL facility;
- (n,charged particle) cross sections with the MEDLEY facility employing 8 counter telescopes ($2*\Delta E + E$) for particle identification;
- fission cross sections of ^{208}Pb, Bi and ^{238}U in collaboration with the Khlopin-Radium Institute, St. Peterburg.

At Studsvik: the spectroscopy of exotic neutron rich nuclei at the OSIRIS facility, and the measurement of fission product yields.

Argonne National Laboratory (D.L. Smith)

Measurements at Geel in 1996 have been analyzed and published. Recent measurements in 1998 are awaiting analysis and supplementary measurements will be required in the future to complete this second phase of the joint Geel/ANL project. A long standing discrepancy in the ^{51}V(n,np) reaction has been resolved by re-examination of experimental data and new model calculations. Hydrogen production is reduced by a factor of 3. The data compilation and evaluation project for (p,γ) and (p,α) reactions on A=30-50 nuclei for astrophysics continues. The use of >6 MeV gamma-rays from ^{19}F(n,$\alpha\gamma$) or ^{16}O(n,p)^{16}N(β^-)^{16}O*(γ)^{16}O processes for diagnostic purposes is being explored.

RPI (R.C. Block)

Measurements of total cross section, capture, and self-indication in the thermal to unresolved resonance region are either in progress or completed for samples of Zr, Ho, Er, Tm, W, Nb, Mo, Sm, Nd, and Hf. Many of these investigations correspond to Ph.D. thesis projects. Analysis of the data with such codes as REFIT or SAMMY is part of each such project. The RPI Linac is undergoing a refurbishment program at a cost of $1.4M. This is expected to extend its operating life for 10-20 years. A new target design has been introduced as well as new detectors, including a 16-sectional NaI multiplicity detector.

NIST (A.D. Carlson)

Carlson discussed status of H(n,n) measurements at 10 MeV in a LANL/Ohio University/NIST collaboration. The new data appear to differ from both ENDF/B-V and - VI, and are closest to the Arndt evaluation. NIST is also performing cold neutron scattering length measurements to very high accuracy (<< 1%) using a novel approach and neutrons from the NIST research reactor. Measurements are being carried out for Si and ^{208}Pb. Another project is geared toward improvement in the accuracy of the NBS-1 neutron source standard. This is being accomplished using a 4 meV filtered monoenergetic neutron beam from the reactor, a calorimeter, and a manganese bath setup for flux transfer. Spherical shell transmission measurements for Fe are also planned. Monte Carlo simulation will be employed to handle the inevitable effects of anisotropy.

Los Alamos LANSCE facility (R.C. Haight)

Sigma-total measurements are being performed from 5 - 500 MeV for a large number of materials ranging from H to ^{238}U; motivation is the APT project. Gamma-ray emission measurements up to 400 MeV neutron energy are being performed with the GEANIE γ-ray detector system (26 Compton-suppressed Ge detectors), among others also on ^{235}U, ^{238}U, ^{239}Pu. Measurements of (n,z) data are being performed to 50 MeV for O, Si, and Ca. Proton reaction cross sections for Be, C, Al, Cu, W, and Pb are being performed at AGS-BNL from 580 MeV to 10 GeV for the purpose of developing a high-energy optical model; APT is again the motivation. Detailed γ-ray production measurements are being performed for O. Also, (n,γ) measurements for rare or radioactive targets are being studied for energies up to a few hundred keV. A new barium fluoride detectors system (DANCE) is being developed in collaboration with Karlsruhe. Data for Ba and F photon production are needed. The electronics for GEANIE are being upgraded to allow for faster data throughput.

The LANSCE facility is currently in a stand down mode in order to address safety issues (since February). The intent is to return to operation in June 1999.

University of Lowell (G. Kegel could not attend, but submitted a written report)

A brief progress report was submitted. The most controversial result that was noted was a prediction that the ^{235}U total cross section should be about 10% lower than ENDF/B-VI in the few hundred keV range. There was considerable discussion about this issue at the meeting. Most participants were sceptical about this point.

JINR, Dubna (Yu. Popov)

The IBR-30 facility (subcritical reactor pulsed by linac) is presently shut down. Experiments are being carried out at the IBR-2 pulsed reactor and at the 4-MV Van de Graaff using the ^{7}Li(p,n) source. Measurements are being performed using various detectors such as scintillation detectors and Ge detectors. The following measurement program is in progress:

- Measurements of angular anisotropy of fission fragments from aligned ^{235}U;
- cross section measurements for ^{243}Am(n,f) in the resonance region;
- measurements of two quanta γ-ray cascades for ^{188,190}Os are being made to determine level density parameters; data are being interpreted with level-density models such as Fermi gas and the Ignatyuk model;
- measurements of (n,γ) cross sections are being performed on several isotopes at thermonuclear energies for the stellar nucleosynthesis applications in collaboration with FZ Karlsruhe. Along these lines mention was made of determinations of E1 and M1 transition strengths for ^{59}Ni at energies corresponding to kT = 10-20 keV, applicable to Red Giant star evolution. Data will be used to check calculations by Russian theorists.
- delayed neutron measurements on ^{237}Np have been completed and other targets like ^{239}Pu are being considered.

Future plans at Dubna include:

- Continuation of self indication and γ-multiplicity measurements for Th, U, and Pu isotopes from 1 eV - 20 keV;
- Doppler effect measurements will be made on samples of Th and Np;
- gamma-gamma cascades following (n,γ) reactions on Br isotopes will be studied;
- measurement of delayed neutrons will be continued at IBR-2 for ^{241}Am, ^{242m}Am, and ^{245}Cm;

- fragment mass- and energy distributions will be measured for ^{235}U fission;
- partial (n,γ) cross sections leading to the ground state will be measured for Ni isotopes to 70 keV.

In addition, Dubna is proposing to collaborate with CERN and Obninsk in performing measurements at the newly proposed CERN spallation neutron facility under conditions of neutron density similar to supernovae explosions. The goal will be to search for multiple neutron capture as well as (n,p) and (n,α) processes for astrophysics. Gas samples may be used, e.g., ^{39}Ar. An activation method will be used along with a fast rabbit system.

PTB (W. Mannhart)

DDX neutron scattering measurements have been done for ^{12}C and ^{16}O and natural Ti, V, Cr, Fe, and Pb. He pointed out the difficulties in performing DDX measurements with the D(d,n) source in the presence of D(d,np)D breakup reaction at the higher energies up to 14 MeV. An iterative Monte-Carlo approach is used to extract scattering cross sections from the measured data.

There followed a discussion concerning experimental methods used to check the corrections for breakup neutrons. One approach is to use a ^{4}He gas target. Carlson pointed out that Grimes has used both ^{3}He and ^{4}He targets. No single approach appears to be entirely satisfactory.

Work on the evaluation of the ^{235}U(n,f) thermal incident neutron fission-neutron spectrum integral activation data is progressing at PTB in support of the fission spectrum subgroup activity led by Madland. It is helpful that the Cf spontaneous fission spectrum is so well known. It enables cross section problems to be differentiated from integral measurement and spectrum uncertainties.

Activation cross section measurements for Al, ^{39}K, ^{46,47,48}Ti, and ^{58}Ni(n,p) are in progress in the range from 8-14 MeV. The ^{58}Ni(n,2n) and (n,np) reactions are also being investigated.

IRMM, Geel (H. Weigmann)

H. Weigmann reported on the work in progress at IRMM. The main activities are as follows:

- Doppler broadening of neutron resonances: After the measurements on U-metal and UO_2, further resonance measurements were performed on UO_3, Hg_2Cl_2, NpO_2 and Ta at different temperatures between 14 and 300 K; data on the lowest resonances in ^{237}Np are well described by the DOPUSH routine (Naberejnev et al., CEA-Saclay). Further measurements were started on the average transmission in the keV energy region at 77, 300, (900) K; samples to be studied: Hf, ^{232}Th, ^{238}U; to be compared to predictions based on data from various data files (JEF, ENDF, JENDL).
- Cross section measurements for transmutation studies (collaboration CEA,Saclay - IRMM): The total and capture cross sections of ^{99}Tc were measured for $E_n < 100$ keV; analysis of the data (in the resonance region analysis with REFIT) are in progress. The total and capture cross sections of ^{237}Np were measured for $E_n < 3$ keV.
- High resolution inelastic scattering: Measurements were done on ^{208}Pb(n,n') for $E_n < 4$ MeV; additional pointwise measurements are ongoing at Van de Graaff. Earlier data for Al have been analysed (together with the total cross section) with SAMMY, and an acceptable fit is obtained.
- Capture cross sections (collaboration with FZK): Work is in progress on the capture cross section of ^{232}Th: measurements (gamma detection) are done at FZK Van de Graaff, and are

in progress at Geel linac; at Geel Van de Graaff activation measurements are in preparation. Further capture measurements on ^{84}Kr and ^{86}Kr are being performed.

- ^{239}Pu(n,f) mass- and kinetic energy distributions in resonances: Measurements are in progress at the linac; to be analysed in terms of the Brosa model.
- Fission cross section of ^{234}U (collaboration with University of Gent): The thermal cross section was measured at ILL (for the first time) and yields a value of (300 ± 20) mb; measurements between 10 meV and 1 keV are started at linac.
- Inelastic scattering cross section of ^{238}U: see above.
- Activation cross sections (collaboration KFA, Julich-ANL-IRMM): Cross sections for about 30 short-lived activation products were measured in the energy region 16-21 MeV (9-12 MeV at Julich); publications: (1) Excitation functions for (n,2n), (n,p), (n,np+pn+d) and (n,α) reactions on Cr isotopes: Phys.Rev.C58 (1998) 996; (2) Excitation functions for ^{50}Cr(n,np+pn+d), ^{58}Ni(n,α), ^{58}Ni$(n,\alpha p+p\alpha)$ and ^{62}Ni(n,α) reactions, Radiochem.Acta. Planned measurements are: ^{50,51}V$(n,n'\alpha)$, $^{60.61}$Ni(n,xp)^{60}Co, ^{99}Tc(n,p),(n,α), and cross sections for long-lived activ. products, e.g. ^{14}N(n,p)^{14}C, ^{94}Mo(n,p)^{94}Nb, ^{204}Pb(n,p)^{204}Tl.
- ^{10}B(n,α) and branching ratio $\alpha 0/\alpha 1$: A gridded ion chamber is used for these measurements which are performed at the Van de Graaff (MeV region, rel. to ^{238}U(n,f)) and at the linac (keV region, rel. to ^{235}U(n,f)).

Next meeting

The first organisational meeting of the new joint Working Party will be held in Paris in fall 1999. The first regular meeting is foreseen to be held in Japan, probably in June 2000.

ANNEX 1

Minutes of the Second Meeting of the Subgroup on Fission Neutron Spectra

19 April 1999, Brookhaven National Laboratory

Prepared by D. Madland

The meeting was held in a joint WPMA/WPEC session. A short summary is available in the minutes of WPEC, NEA/SEN/NSC/WPEC(99)2.

Four presentations were given:

1. New Calculations of the Prompt Fission Neutron Spectrum Matrix for the n + ^{235}U System using the Los Alamos Model and Recent Experimental Data.
   D. Madland

2. Evaluation of a "Best Set" of Average Cross Section Measurements Performed in the Neutron Field of ^{235}U.
   W. Mannhart

3. Comments on the n + ^{235}U Prompt Fission Neutron Spectrum Matrix.
   N. Kornilov (presented by Madland)

4. New Evidence of Scission Neutron Existence.
   F. -J. Hambsch

Madland reported on his analysis of seven differential experiments (one of these is a reanalysis) using the Los Alamos model (two more remain). The conclusion at this point is that the new fission spectrum matrix for the n + ^{235}U system will be somewhat softer in the tail region of the matrix than that contained in ENDF/B-VI (which is a 1983 calculation using the Los Alamos model). The two measured thermal spectra (Wang et al and Starostov et al) are in disagreement. Only one parameter of the Los Alamos model is unknown for the n + ^{235}U system, namely, the lumped nuclear level density parameter. The incident neutron energy dependence of this parameter is important for constructing the matrix and this dependence was presented for the work to date.

Mannhart reported on his analysis of the integral cross section measurements performed in the n + ^{235}U field for thermal (or near thermal) neutrons. He selected 38 experiments (15 post 1976) having a total of 200 data points with 4 absolute measurements and 196 ratio measurements. These data span 30 different reactions with thresholds ranging from 0.0 MeV to 12.43 MeV which are sensitive to the energy range between 0.2 and 18 MeV of the neutron field. The 30 evaluated integral cross sections were compared with a similar evaluation performed in the neutron field of spontaneous fission of ^{252}Cf. The ratio of both evaluations plotted against the mean response energy of each of the individual reactions showed a smooth trend within the combined uncertainties valid for all reactions with the exception of ^{63}Cu(n,2n). In addition, recommendations were presented for appropriate sets of sigma(E) data to be used in future calculations of integral cross sections. The selection was based upon calculations for the ^{252}Cf(sf) neutron field performed with sigma(E) data taken from the various existing evaluations. C/E values were obtained with complete error propagation of the individual contributions from the differential data, the neutron field, and the integral data. His current conclusion is that only a careful selection of differential data from the various sources guarantees a bias-free set of calculated integral responses.

Madland reported on the comments of Kornilov. These are:

a. His analysis of the Univ. Mass. - Lowell data (Staples et al) reduce the average emitted neutron energy (first moment) of the spectrum. Thus, the tail of the spectrum is softer.
b. A re-analysis of the Knitter et al data on ^{252}Cf(sf) and a recent anaylsis by Samant et al demonstrate that ~ 10% of the emitted neutrons cannot be from fully accelerated fragments. This implies a nubar(scission) $\approx 0.25 \pm 0.05$
c. Therefore, new experimental and theoretical work should be dedicated to scission neutrons.
d. Therefore, evaluation of the n + ^{235}U fission spectrum matrix must take into account scission neutron emission.

Hambsch reported on the re-analyzing of the ^{252}Cf(sf) experiment of Knitter and Budtz-Jorgensen (in collaboration with Kornilov and Kagalenko).

It was concluded that a (30 ± 5)% neutron excess exists at ~ 90 degrees which cannot be accounted for with the assumption that all neutrons are emitted from fully accelerated fragments. These neutrons are emitted either at (or just prior) to scission or from accelerating fragments. The re-analysis indicates that emission at (or just prior) to scission is preferred over emission during fragment acceleration. The integral over angle yields ~ 10% total scission neutrons and there exists some evidence that the energy spectrum of the scission neutrons consists of two components.

Work Summary and Plan for the n + ^{235}U Prompt Fission Neutron Spectrum Matrix:

1. Madland has two more differential spectra to analyze using the Los Alamos model (and will analyze others that may be located in the interim). At this point seven have been analyzed.
2. Mannhart has finished Phase 1 of his work on the integral cross sections.
3. Kornilov has provided the results of the differential measurements available to him and continues to analyze these and other differential data.
4. Staples has provided the differential data from the four Lowell measurements.
5. Second- and third-chance fission spectra for the n + ^{235}U matrix have not been addressed by the subgroup. The Los Alamos model calculates such spectra and includes the neutrons emitted prior to fission as a portion of the spectra. Note that these are evaporated neutrons and not so-called scission neutrons. The subgroup will include multiple-chance fission in the agenda for the next meeting.
6. Scission neutrons for the n + ^{235}U matrix have not been an explicit agenda item for the subgroup. This subject will be added to the agenda of the subgroup for the next meeting.
7. Madland will calculate integral cross sections for the thermal field using the two calculations of that field from the Los Alamos model based upon two differential measurements (Wang et al and Starostov et al).

ANNEX 2

List of Participants in the WPMA Meeting

S. Andriamonje	CERN, Switzerland
B. Block	USA
A.D. Carlson	USA
R. Haight	USA
F.-J. Hambsch	IRMM Geel, Belgium
D. Madland	USA
W. Mannhart	Germany
D.W. Muir	IAEA
N. Olsson	Sweden
Y. Popov	Russia
D.L. Smith	USA
S. Tagesen	Austria
Liu Tingjin	China
H.Vonach	Austria
H. Weigmann	IRMM Geel, Belgium (Chairman)

plus most of the participants in the WPEC meeting.

Appendix VI

For Official Use **NEA/SEN/NSC/WPEC(99)2**

OECD
OCDE
PARIS

Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development

OLIS : 10-May-1999
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NUCLEAR ENERGY AGENCY
NUCLEAR SCIENCE COMMITTEE

Working Party on International Evaluation Co-operation

SUMMARY RECORD OF THE ELEVENTH MEETING

Held at Brookhaven National Laboratory, USA, 19-21 April 1999

77842

NEA/SEN/NSC/WPEC(99)2

NUCLEAR SCIENCE COMMITTEE

Working Party on International Evaluation Co-operation

Summary Record of the Eleventh Meeting

Brookhaven National Laboratory, USA, 19 to 21 April 1999

B. Bari, Associate Director of the Brookhaven National Laboratory, welcomed the participants and presented a brief outline of the activities of the laboratory.

The Chairman, A. Hasegawa, opened the meeting. The WPEC meeting was preceded by a joint meeting of this Working Party and the Working Party on International Nuclear Data Measurement Activities (WPMA). A summary of the joint meeting is given below.

Joint meeting of WPEC and WPMA

This part of the meeting was organised to discuss a proposal from the NEA Nuclear Science Committee (NSC) to merge the two Working Parties. The status of the High Priority Request List for Nuclear Data was also reviewed, as well as the status of three joint subgroups and the list of upcoming meetings and conferences of relevance to the nuclear data community.

Merging of the WPEC and WPMA

The Chairmen and Vice-Chairmen of the WPEC and WPMA met the evening before the meeting to discuss a proposal from the bureau of the NEA Nuclear Science Committee to merge the two Working Parties. A proposal was drawn up for discussion and decision by the joint WPEC/WPMA meeting.

It was noted that the driving force behind the NEA nuclear data activities was the need for more accurate data for nuclear energy applications, as provided in the evaluated data libraries. The role of the new Working Party would therefore be to co-operate on the development and improvement of such evaluated data libraries, including the co-ordination of the essential contributions from nuclear data measurement activities.

It was agreed that the new Working Party would need to have a limited membership in order to work efficiently. The following four regions, with evaluation and data measurement activities were identified: USA (ENDF project), Europe (JEFF project), Japan (JENDL project), and non-OECD countries (BROND (Russia) and CENDL (China)).

It was proposed that the new Working Party would consist of four (4) representatives from each region, under the leadership of the head of the respective evaluation projects, or someone designated by him/her. At least one of the four members from each region would represent the measurement community. A staff member of the IAEA Nuclear Data Section would be the head of the representatives from non-OECD countries. The NEA would provide the Secretariat of the Working Party. A limited number of experts would be allowed to participate in Working Party meetings, following approval by the heads of the evaluation projects.

The Working Party would set up Expert Groups to perform the agreed upon work. Only well-prepared proposals would be considered, containing information about the goal of the project, a confirmed participation list and a time-schedule for completion of the work. The number of active Expert Groups at one time should be limited, depending on the available resources.

The Working Party would meet at least annually to review progress in the Expert Groups and to discuss new co-operative projects. It would also organise workshops or specialists meetings as needed.

The new Working Party would continue the work started by WPEC/WPMA to identify common problems or deficiencies in the evaluated data libraries and to establish Expert Groups, involving the best experts in the world, to tackle these problems. The goal would be to improve the quality and completeness of the evaluated data libraries of the participating projects and to gradually eliminate the most important discrepancies.

One of the first actions of the Working Party would be to review the existing WPEC/WPMA subgroups and to progressively reduce the number of active Groups, to make the most efficient use of the available international resources.

The joint WPEC/WPMA meeting approved the proposal with the comment that the new Working Party should have an adequate representation of the nuclear data measurement community.

Preparation of an in-depth nuclear data discussion at the next NSC meeting

The NSC had decided to hold an in-depth discussion of all NEA nuclear data activities at its meeting on 2-4 June 1999. The WPEC, WPMA, as well as the JEFF project had been asked to present their activities and plans for future work.

It was agreed that the WPEC/WPMA presentation would be made by the Chairman, supplemented by other members of the WPEC and WPMA bureaux. The main item to present was the above mentioned proposal to merge the WPEC and WPMA. The representatives should also be prepared to reply to the question posed by the NSC Bureau concerning the creation of a unique evaluated world file.

Review of the High Priority Request List

At the last Working Party meeting, it had been stressed that the request list needed to be shortened. Each request in the list should have a priority assigned, should give the name of the person responsible for the request and have a clear motivation for the request.

R. McKnight had co-ordinated the assignment of priorities for the US entries in the list. A. Hasegawa presented a revised version of the Japanese list. A. Ignatyuk was asked to provide the priorities for the Russian list before the end of May 1999 and communicate it to R. McKnight. A new request list would then be issued.

F. Storrer presented two methods to review the requests in the high priority request list, the rigorous and the pragmatic approach. The rigorous method was based on the propagation of integral uncertainties to the basic nuclear data. The pragmatic approach was based on the collection of systematic trends from data validation studies, complemented by a circulation of the list for comments by reactor physicists, data users and evaluators.

It was considered that the most important task was to collect the information about priorities, the originator and a justification of each request, and to make a clear presentation of the list before any review would be undertaken.

The NEA was asked to develop an on-line Internet system where the list would be available and where feedback and complementary information could be entered.

It was pointed out that in many instances the most difficult part of a nuclear data measurement was to obtain a suitable sample. It would be very convenient if a central list could be maintained on the NEA Web page, giving information about the existence and availability of such samples. The NEA agreed to host such a list, if the update and maintenance were performed by someone with a good overview of the field.

Review of joint subgroup activities

Subgroup 7: Standards data

It was decided that the following cross sections will be evaluated in the standards evaluation: H(n,n), ^{6}Li(n,t), ^{10}B(n,a0), ^{10}B(n,a1), Au(n,g), ^{235}U(n,f), ^{238}U(n,f), ^{238}U(n,g), and ^{239}Pu(n,f). All of these cross sections except H(n,n) will be evaluated by combining the results of a simultaneous evaluation and R-matrix analyses using a procedure similar to that used for the ENDF/B-VI standards evaluation. An R-matrix analysis of the H(n,n) cross section will be made which extends to 150 MeV. The simultaneous evaluation will also be extended to ~150 MeV. The ^{3}He(n,p) and C(n,n) standards will not be evaluated since the few recent measurements, which have been made, agree with the ENDF/B-VI evaluations.

Concerns were expressed about the relatively small uncertainties present in the ENDF/B-VI standards evaluation. This led to plans to compare the output uncertainties of the R-matrix (EDA) and simultaneous (GMA) evaluations used in the ENDF/B-VI evaluation, for part of the standards database, with that obtained using similar programs. Two programs, which could replace the combining program used in the ENDF/B-VI standards evaluation, are being considered. Work has been done investigating many standards experiments completed since the cut-off date for the ENDF/B-VI standards evaluation. It was decided that the deadline for including experimental results in the evaluations would be April 2001.

The subgroup welcomed an initiative by D. Muir consisting of a proposal to the forthcoming INDC meeting to establish a CRP to assist in the evaluation of the neutron reaction standards. The main task would be to develop a procedure to combine, in an optimum way, the results of the R-matrix evaluations with the directly evaluated experimental results. An important goal would be to build confidence in the final uncertainty assignments.

Experimental Activities in Intermediate Energy Data

On-going and planned experimental activities to measure intermediate energy nuclear data were reviewed. A Concerted Action on nuclear data "Lead for Transmutation Applications" has been started within the EU and additional proposals are expected for the 5th framework programme. The project involves 13 institutions performing measurements at five European laboratories (GSI, Jülich, KVI, Louvain-la-Neuve, TSL). Similar experiments are in progress in Japan at the TIARA cyclotron of JAERI Takasaki and at KEK with researchers from Tohoku University, JAERI and Kyushu University. A few experimental groups from St. Petersburg, employing neutron beams abroad, study various fission cross sections. In the US, measurements have been carried out at LANSCE on total cross sections for 37 targets in the 5-500 MeV region, on gamma production spectra up to 200 MeV using GEANIE, light charged particle production spectra up to 50 MeV, and capture cross sections on radioactive targets. Proton reaction cross sections on nuclei from Be to Pb are measured in the range 580 MeV - 10 GeV at BNL.

D. Madland (Los Alamos) presented the theoretical and evaluation development at LANL. A new evaluated file up to 150 MeV for selected nuclei has recently been released. It has been produced using the GNASH code system, which includes HF, FKK and direct reaction mechanisms.

The subgroup also discussed the future, considering the proposed merging of the WPEC and WPMA. If there were a continued interest in transmutation development, a subgroup on Intermediate Energy Data would be useful. It was noted that such a subgroup already exists within the WPEC (SG22), and it seems adequate to incorporate the measurement activities into this subgroup.

Subgroup 9: Prompt Fission Neutron Spectrum

Seven of nine differential measurements have been analysed using the Los Alamos model. The conclusion at this time is that the new fission spectrum matrix will be somewhat softer than that in ENDF/B-VI.

Thirty integral cross sections together with uncertainties have been determined from the experimental database and these will be used to test the new thermal neutron field(s). A re-analysis of the Knitter et al experiment on ^{252}Cf(sf) concludes that a ~10% scission neutron component exists. Therefore, the scission neutron question for the n + ^{235}U system should be addressed by the subgroup. The multiple-chance fission portion of the fission spectrum matrix has yet to be addressed by the subgroup.

Thus, the next meeting of the subgroup will include:

(a) integral cross section calculations in the new thermal field(s) and comparisons with the new set of 30 evaluated experimental values;
(b) multiple-chance fission calculations and measurements (if any) and
(c) scission neutrons.

Conferences and meetings of interest to the nuclear data community

The following meetings, conferences and lectures were mentioned:

- European Summer School on Nuclear Fission, Geel, Belgium, 17 - 21 May 1999

- Workshop on Pion-nucleon Coupling Constant, Uppsala, Sweden, 7 - 8 June 1999
- Third International Conference on Accelerator Driven Transmutation Technology Application, Prague, Czech Republic, 7 - 11 June 1999
- Tenth International Symposium on Capture-ray Spectroscopy and Related Topics, Santa Fe, USA, 30 Aug. - 3 Sept. 1999
- International Conference on Nuclear Criticality Safety, Versailles, France, 19 - 22 Sept. 1999
- IAEA Workshop on Nuclear Data for Medical Application, Trieste, Italy, 27 - 30 Sept. 1999
- Ninth International Conference on Radiation Shielding, Tsukuba, Japan, 17 - 22 Oct. 1999
- International Nuclear Data Conference, Japan, Sept. - Oct. 2001

Time and place of next meeting

In the event that the new Working Party is approved, it is proposed to hold a first organisational meeting of the Working Party in Paris in early autumn 1999. The first regular meeting would then be held in Japan in June 2000, in conjunction with the first meeting of the International Programme Committee for the International Nuclear Data Conference, scheduled for September or October 2001.

Adoption of the Agenda

The proposed agenda was adopted without modifications.

Approval of the Summary Record of the Tenth WPEC Meeting

The summary record (NEA/SEN/NSC/WPEC(98)2) of the tenth meeting of the Working Party was approved without corrections.

Membership

H. Gruppelaar had recently resigned as chairman of the JEFF project due to health problems. He was replaced by Robert Jacqmin, CEA, France.

Short status reports from the evaluation projects

ENDF

C. Dunford presented the highlights from the CSEWG meeting that was held at BNL in October 1998. Release 6 of the ENDF/B-VI library will be made in the summer 1999. The release will contain 35 neutron and 35 proton evaluations that have been extended from 20 to 150 MeV, updates to the standard cross sections for H(n,n) and ^{235}U(n,f) and possibly a revision of the six group delayed neutron constants.

Five US laboratories (ANL, BNL, LANL, NIST, and ORNL) have submitted a joint 3-year proposal to the Nuclear Energy Research Initiative for the development of an ENDF/B-VII library. The decision on this proposal will be taken in spring 1999.

JEFF

R. Jacqmin reported that the official documentation of the JEF-2.2 and EFF-2.4 libraries, containing results from the extensive benchmark testing of the files, would be published in early autumn 1999. The JEFF-3.0 library was being compiled and checked at the NEA Data Bank. The major modifications, compared to JEF-2.2, concerned the light elements, structural materials and the major actinides.

The long-term time-schedule for the JEFF-3 project coincided well with the recently approved 4-year programme of work for the EC sponsored EFF project. The general-purpose library would undergo first benchmark testing during 1999, followed by improvements and further detailed benchmark testing in 2000-2001. The general release of the JEFF-3 file was scheduled for early 2002.

JENDL

A. Hasegawa announced that a new revision of the complete JENDL-3 library would be released in spring 2001. The main features were the following: Covariance information for the major elements, new evaluations such as Er, and adoption of isotopic evaluations rather than elemental ones. A number of special purpose files, such as fusion, actinide, dosimetry, activation, high energy, pka/kerma, and photo-nuclear data files would be released at the same time.

The Working Party was also informed of the different completed and on-going ISTC projects in the field of nuclear data that have been initiated by Japan. The main emphasis had been given to evaluation of minor actinides and to intermediate-energy nuclear data for transmutation applications.

BROND

A. Ignatyuk informed the Working Party of a 5-year programme to create a BROND-3 library. The new library would benefit from the experience gained in the adjustment of the BROND-2 based group constant library ABBN-93. New evaluations for the Th fuel cycle, as well as re-evaluations of ^{240}Pu and ^{242}Pu and new evaluations for ^{237}Np, ^{241}Am and ^{243}Am would be included. New gamma-ray production cross-sections and spectra would also be developed.

Evaluations of neutron and proton induced reaction cross sections for ^{232}Th, up to 150 MeV, had been performed, and a new version of the Russian Reactor Dosimetry File (RRDF-98) had recently been prepared.

CENDL

Liu Tingjin presented the progress in the development of the CENDL-3 library. The general-purpose library, containing evaluations for 200 nuclides, would be released in 2000. Development of special purpose libraries is being done in parallel. The fission yield library presently contains evaluations for 15 fission products from ^{235}U and 25 from ^{238}U. In addition, there are ongoing evaluation efforts on activation cross-sections and on photo-nuclear reaction data.

The validation of CENDL-2.1, using 18 thermal and 9 fast assemblies, had shown that the ^{235}U and ^{238}U evaluations performed well, whereas the data for Pu needed to be improved. Calculations of tritium production from ^{6,7}Li showed reasonable good agreement with experimental results.

FENDL

D. Muir informed the Working Party that the IAEA Nuclear Data Section (NDS) planned to set up mirror sites of their on-line data base services at Sao Paulo in Brazil and perhaps also in India.

Following the release of the FENDL-2 library in 1997, the NDS has continued to validate and to maintain the library. A consultants' meeting had been held in Vienna in October 1998 to review the recent testing of the basic and derived transport-data sub-libraries. The latest version of the FENDL-2.0 library was released in January 1999 and can be obtained on CD-ROM.

Creation of a unique world evaluated library

The Working Party discussed the question raised at the NSC Bureau meeting in December 1998 concerning the feasibility of creating a unique world evaluated data library.

It was generally felt that it was an attractive long-term goal, towards which the different files evolved naturally. However, the resources needed to create this unique library would be orders of magnitude larger than was presently available to maintain and improve the existing files. The FENDL library, which contains only a subset of a complete multipurpose evaluated data library, was mentioned as an example of the huge resources needed. It had taken about 10 years to complete the FENDL-2.0 library. Another factor that would make it difficult to create a unique evaluated data library was that the priorities of the different evaluation projects were somewhat different from each other.

One risk, associated with the idea to create a unique file under the auspices of NEA, would be that resources allocated to regional or national evaluation efforts would be reduced. This would be counterproductive, as the NEA activity, which is one of co-ordination, is dependent on viable regional and national efforts.

It was also noted that although the integral results from the evaluated libraries indicate that they are of comparable quality, the individual differences in the libraries are still too large to consider the creation of a unique file. The role of the WPEC is to eliminate the large discrepancies in the most cost efficient way through international co-operation.

Review of Subgroup Activities

Subgroup 4 (Capture and Inelastic Scattering Cross-Sections of ^{238}U)

A. Hasegawa reported that M. Baba had recently taken over the co-ordination of the subgroup, following the retirement of Y. Kanda. The subgroup had been waiting for the finalisation of the new ^{238}U evaluation by Maslov and new measurements at Tohoku University. The group would produce a final report to the planned meeting of the new Working Party in September/October 1999.

Action by M. Baba: To produce a final report of subgroup 4 by September 1999.

Subgroup 6 (Delayed Neutron Data)

A. D'Angelo presented the outline and three draft chapters of the final report of the subgroup. E. Fort complemented the presentation by giving more details concerning the chapter on total delayed neutron yields, for which he was in charge. A number of activities, of direct relevance to the work of the subgroup, were in progress at Obninsk. The co-ordinator proposed to await these results, which would delay the final report by a few months. The Working Party felt that the final report should be written with the presently available information and be presented at the September/October meeting of the new Working Party. The possibility to include additional results in an Annex would then be reviewed.

Action by A. D'Angelo: To produce a final report of subgroup 6 by September 1999.

Subgroup 8 (Minor Actinide Data)

A. Hasegawa informed the Working Party that T. Nakagawa had returned again to JAERI after a few years of work in another field. The graphical intercomparison of the minor actinide data had been restarted and would be completed in the summer 1999. H. Takano had performed burnup calculations for spent fuel using different evaluated libraries. He would complete these calculations for the final report, but would also like to include results obtained at CEA, France and Obninsk, Russia.

Action by C. Nordborg: To send a JEF/DOC to H. Takano with results from French benchmark calculations relevant to the minor actinides.
Action by A. Ignatyuk: To send information to H. Takano on results from benchmark calculations relevant to the minor actinides.
Action by H. Takano: To produce a final report of subgroup 8 by September 1999.

Subgroup 10 (Fission Product Inelastic Scattering)

The co-ordinator, M. Kawai, informed the Working Party in an E-mail that he was confident with the recommendations on the calculation methods to be used for direct inelastic cross sections. However, he felt that there was no consensus about the true reasons for the reactivity discrepancy, which had triggered the setting up of the subgroup. The co-ordinator would like to perform sensitivity studies in order to solve this discrepancy, which would delay the finalisation of the report by about 6 months.

The Working Party felt that the additional delay would not be acceptable and that a final report should be sent to the NEA Secretariat by mid September 1999.

Action by M. Kawai: To produce a final report of subgroup 10 by September 1999.

Subgroup 11 (Resonance Region of ^{52}Cr, ^{56}Fe, ^{58}Ni and ^{60}Ni)

The co-ordinator, F. Fröhner, had recently spent a couple of months at CEA Cadarache, where he had worked part of the time on the resonance parameters of 52Cr. He was now back in Germany and had indicated that he would finalise the subgroup report in May 1999. The report would be circulated to WPEC before printing.

Action by F. Fröhner: To produce a final report of subgroup 11 by June 1999.

Subgroup 14 (Thorium Cycle)

A. Ignatyuk had investigated the interest in starting up a subgroup on nuclear data for the Th fuel cycle, but had not been able to muster enough participation. It was thus decided to abandon the subgroup.

Subgroup 19 (Data Validation Methods)

E. Fort was preparing the benchmark specifications to be sent out in early autumn 1999. The plan was that the benchmark results should be collected in early 2000. The analysis of the results would follow in spring 2000, with the possibility of having a final report at the next Working Party meeting.

There was a strong interest in the subgroup, and considering the ongoing reorganisation of the Working Party, it was decided to postpone the official start of the subgroup until the time when the benchmark specifications were available. The status would be reviewed at the planned autumn 1999 meeting of the new Working Party.

Action by E. Fort: To prepare the benchmark specifications for distribution in early autumn 1999.

Subgroup 21 (Fission Product Cross-Sections for Thermal Reactors)

It was noted that it had not been possible to find adequate funding for the potential co-ordinator of the subgroup. As there were no other potential candidates to take responsibility for the work, it was decided to close the subgroup.

Subgroup 18 (^{235}U Epithermal Capture)

C. Lubitz gave an overview of the main achievements of the subgroup and outlined topics for future investigations. A draft final report had been written and was being reviewed by the subgroup participants. It was foreseen that all comments would be collected in May and that the final report could be published in June or July 1999.

The work of the subgroup has led to a new evaluation of ^{235}U, which has been adopted in ENDF/B-VI.5 and in JEFF-3.0. Most of the evaluation work was performed at ORNL and KAPL in USA, with significant contributions also from European laboratories in UK and France. Topics remaining to be addressed include an improved unresolved resonance region and a better understanding of the energy dependence of nu-bar.

Action by C. Lubitz: To prepare the final report for publication in June-July 1999.

Subgroup B (Formats and Processing)

R. Roussin presented a proposed charter for the subgroup covering evaluated data formats and procedures, processing of evaluated libraries, testing of evaluated and processed data for format and physics content, and validation of commonly-adopted processing systems. The Working Party felt that the scope should be limited to the collection and preparation of proposals for changes to the ENDF format and procedures. As this would be an on-going part of the work programme, it was decided to integrate it directly into the tasks of the Working Party and not create a separate subgroup.

Action by project chairmen: To communicate to R. Roussin the contact point within each evaluation project for matters concerning formats and procedures.

Review of Proposed New Subgroups

Testing and Validation of Nuclear Modelling Codes

C. Dunford presented a short proposal from M. Chadwick for a subgroup on "Testing and Validation of Nuclear Modelling Codes". The subgroup would focus on identifying test cases for checking the predictions of different codes. The Working Party expressed interest in the subject, but would like to review a more elaborate proposal at its planned meeting in early autumn 1999.

Action by M. Chadwick: To prepare a more elaborate proposal for discussion in early autumn 1999.

^{235}U unresolved energy range

L. Leal presented a follow-up proposal to the subgroup on ^{235}U epithermal capture. It concerned a recommendation from the former subgroup to improve the unresolved resonance region of ^{235}U and to validate the new evaluation in highly enriched benchmarks. ORNL had initiated some work in this field and would like to co-operate with the other evaluation projects on this subject. The Working Party accepted the proposal to start this new subgroup, but would like to see a more detailed proposal and work-plan at its planned meeting in early autumn 1999.

Action by L. Leal: To prepare a more elaborate proposal for discussion in early autumn 1999.

Intermediate energy data

Action by NEA: To contact N. Olsson and clarify if he had a proposal for an activity in the area of intermediate energy data.

Any other business

The NEA was asked to develop a specific Web page for the Working Party, including a list of subgroups (active and completed), published reports, links to the high priority request list and its feedback system, documents presented at the Working Party meetings, contact points, etc.

Action by NEA: To develop a specific Web page for the Working Party.

ANNEX 1

Status of subgroups

	Topic	Co-ordinator	Status
1	***^{52}Cr, ^{56}Fe & ^{58}Ni data***	***C.Y. Fu, USA***	***Published***
2	***Covariance files for Fe***	***H. Vonach, Austria***	***Published***
3	***Thermal actinide data***	***H. Tellier, France H. Weigmann, Geel***	***Published***
4	^{238}U capture and inelastic data	M. Baba, Japan	Final report in mid September 1999
5	***^{239}Pu fission cross-section***	***E. Fort, France***	***Published***
6	Delayed Neutron Data	A. d'Angelo, Italy	Final report in mid September 1999
7	Nuclear Data Standards	A. Carlson, USA	Ongoing jointly with WPMA
8	Minor Actinide Data	T. Nakagawa, H. Takano, Japan	Final report in mid September 1999
9	Fission Neutron Spectra	D. Madland, USA	Ongoing jointly with WPMA
10	Fission Product Inelastic Scattering	M. Kawai, Japan	Final report in mid September 1999
11	Resonance Region of ^{52}Cr, ^{56}Fe, and ^{58}Ni	F. Fröhner, Germany	Final report in May 1999.
12	***Nuclear Model Validation***	***M. Chadwick, USA***	***Published***
13	***Intermediate Energy Nuclear Data Evaluation***	***A. Koning, Holland, T. Fukahori, Japan***	***Published***
14	***Thorium benchmarks***		***Closed***
15	***Self-shielding treatment in the unresolved resonance region***	***F. Fröhner, Germany***	***Published***
16	***Nuclear Level Densities for ^{52}Cr, ^{56}Fe and ^{58}Ni***	***M. Chadwick, USA***	***Published.***
17	***Fission Product Cross -Sections for Fast Reactors***	***H. Gruppelaar, Holland***	***Published***
18	Epithermal capture of ^{235}U	C. Lubitz, USA	Final report in July 1999
19	Data validation methods	E. Fort, France	Benchmark specs. in preparation.
20	Doppler Effects	P. Ribon, IRMM	Ongoing jointly with WPMA
21	***Fission Product Cross-Sections for Thermal Reactors***		***Closed***
22	Processing & validation of intermediate energy evaluated data files	A. Koning, Holland	New subgroup
B	Formats and Processing	R. Roussin, USA	To be managed directly by the Working Party
C.	High Priority Request List	R. McKnight, USA, F. Storrer, France	Next version to be issued in June 1999.

ANNEX 2

List of Participants at the Eleventh WPEC meeting
Brookhaven National Laboratory, USA, 19 - 21 April 1999

WPEC Members:

A. Hasegawa	Japan	(Chairman)
C. Nordborg	NEA	(Secretary)
C. Dunford	USA	
Ph. Finck	USA	
A. Ignatyuk	Russia	
R. Jacqmin	France	
R. McKnight	USA	
E. Menapace	Italy	
D. Muir	IAEA	
R. Roussin	USA	
K. Shibata	Japan	
D. Smith	USA	
Liu Tingjin	China	

WPEC subgroup co-ordinators:

A. D'Angelo	Italy
E. Fort	France
C. Lubitz	USA
F. Storrer	France

WPEC Observer:

T. Kawano	Japan
J. Kopecky	Netherlands
L. Leal	USA
S. Tagesen	Austria

Annex 3

Documents presented at the Eleventh Working Group Meeting

Brookhaven National Laboratory, USA, 19 - 21 April 1999

IEC-192	Activity on the HPRL; F. Storrer
IEC-193	Japanese Revisions and Comments for the High Priority Request List of Revised Version in May, 1998; T. Fukahori and A. Hasegawa
IEC-194	Japanese High Priority Request List (Revised Version in April, 1999); T. Fukahori and A. Hasegawa
IEC-195	CSEWG Status Report to the Working Party on Nuclear Data Evaluation Co-operation
IEC-196	The Status of the JEFF-3 Project
IEC-197	Present Status of JENDL Project; A. Hasegawa
IEC-198	Status of the BROND Project; A. Ignatyuk
IEC-199	Progress on CENDL-3; Liu Tingjin
IEC-200	Progress Report on the Fusion Evaluated Nuclear Data Library (FENDL); M. Herman and D.W. Muir
IEC-201	SG-4: U-238 Inelastic cross-sections; A. Hasegawa
IEC-202	Status Report of the WPEC Subgroup 6 activities; A. D'Angelo
IEC-203	Status Report of Subgroup 8 on Minor Actinides; T. Nakagawa and Hideki Takano
IEC-204	WPEC Subgroup 10 (E-mail from M. Kawai to C. Nordborg)
IEC-205	Epithermal Capture Cross-section of ^{235}U; C. Lubitz
IEC-206	Subgroup B: Formats and Processing, Proposed Charter; R. Roussin
IEC-207	Proposal for a subgroup to address remaining issues on ^{235}U evaluation; L. Leal
IEC-208	Proposal for a subgroup on Testing and Validation of Nuclear Modelling Codes; M. Chadwick