UU-NF 01#01
(January 2001)
Uppsala University Neutron Physics Report
ISSN 1401-6269

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Ph.L. Thesis

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Editor: Jan Källne

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THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

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Date presented: January 30th, 2001
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Abstract

The interest in neutrons of energies above 20 MeV is growing rapidly, since new applications are being developed or have been identified. Transmutation of nuclear waste and cancer therapy with neutron beams are two research fields that would benefit from new neutron scattering data at these energies.

A facility for detection of scattered neutrons in the energy interval 50–130 MeV, SCANDAL (SCAttered Nucleon Detection AssembLy), has been developed and installed at the neutron beam facility of the The Svedberg Laboratory in Uppsala. It can be used to study the (n,n), (n,p) and (n,d) reactions.

This thesis describes the layout of the setup, the experimental procedure, and data analysis principles. The performance of the spectrometer is illustrated with measurements of the (n,p) and (n,n) reactions on ^{1}H and ^{12}C. In addition, the neutron beam facility is described in some detail.

1 Introduction

Nuclear waste management and cancer therapy may seem to have little in common, but there are at least two aspects that concern both topics: great public interest, and neutron physics.

The recent development of high-intensity proton accelerators has resulted in ideas to use subcritical reactors, fed by externally produced neutrons, for transmutation of waste from nuclear power reactors or nuclear weapons material. This has the potential to simplify the requirements for long-term storage of such materials.

Conventional radiation treatment of tumours is carried out using photons or electrons. Some common types of tumours, however, cannot be treated successfully in this way. For some of these, very good treatment results have been reached with fast neutron therapy, making it the largest non-conventional therapy world-wide.

It has also become evident that electronics in aeroplanes suffer effects from cosmic-ray neutrons [1, 2]. These can induce nuclear reactions in the silicon substrate of a memory device, releasing free charges, which in turn can flip the memory content. This random re-programming is obviously not wanted.

Furthermore, neutrons at aircraft altitudes give a significant radiation dose to airplane personnel. This poses a relatively new dosimetry problem, which is currently under investigation [3].

All these applications involve neutrons at energies above 20 MeV. As there is very little data available in this region, the interest in new data is growing rapidly.

This thesis work has been part of the neutron scattering programme at the Department of Neutron Research at Uppsala University. A facility for detection of scattered neutrons – SCANDAL – at energies relevant for the applications described above has been installed at the The Svedberg Laboratory (TSL) in Uppsala. Since the equipment can be used to study the (n,p) and (n,d) reactions in addition to neutron elastic scattering, the acronym should be interpreted as SCAttered Nucleon Detection AssembLy. The focus of this work, and the subject of the paper presented here, has been to characterize the performance of the equipment, by analyzing measurements of elastic and inelastic neutron scattering from hydrogen and carbon.

2 Transmutation of nuclear waste

All elements heavier than tungsten are known to fission with a large energy release if irradiated by neutrons. Thus, all heavy elements are potential sources of enormous amounts of energy. In reality, however, only one reasonably abundant element in nature, ^{235}U, can be utilized today on a technical scale, using reactors based on a self-sustained chain reaction.

In a nuclear reactor, fission is not the only occurring process as there are also those building up elements heavier than uranium. These transuranic actinides constitute the bulk of the long-lived waste, with plutonium being the most abundant nuclide.

In the opinion of many people, a major drawback of nuclear power production lies in the fact that the radioactive waste has to be stored safely for many years. However, a concept for dealing with the waste problem, acting as a complement to storage in a deep geological repository, is being investigated. By irradiation of actinides and long-lived fission products in spent fuel with an intense neutron flux, transmutation into elements with shorter lifetimes could be attained [4].

Besides providing a means for the reduction of nuclear waste, the same techniques might be used to destroy nuclear weapons material, especially plutonium which is difficult to incinerate in standard reactors. On a very long time scale, the strong neutron sources we are considering here can also be used to drive reactors that can make use of natural uranium and thorium, which are immense energy sources.

A limiting factor in the self-sustaining fission reactors of today is the neutron economy. Fission is induced by neutrons, but neutrons are also released after fission, which makes a chain reaction possible. Some of the released neutrons, however, are lost in other reactions. In addition, for a self-sustaining reactor, it is important for safety reasons that a reasonable fraction of the neutrons are released later in time (beta-delayed neutrons), making reactivity changes sufficiently slow to be possible to control.

These problems are making self-sustaining reactors, that can incinerate the long-lived wastes from the reactors of today, very difficult (or even impossible) to build. Subcritical reactors, where some neutrons are produced externally and fed into the reactor, are not limited by these shortcomings. This has made hybrid solutions, where an external neutron source is coupled to a reactor, a field of intense research during the last few years.

Presently, there seems to be some consensus about the basic design of a possible future device. The extra neutrons are created in spallation processes, generated by a beam of protons or deuterons (1–2 GeV, 20–100 mA) that is stopped in a heavy target material, e. g. lead. The spallation neutron flux can be several orders of magnitude higher than that in a conventional reactor.

After creation in the spallation target, the neutrons enter a surrounding blanket containing long-lived transuranic elements from spent nuclear fuel. Due to the intense neutron irradiation, these elements can be transformed into stable or short-lived ones by fission processes. This lessens in principle the requirements on the geological repository. In addition, the transmutation facility has a potential of producing energy, not only for the ion accelerator, but for the electric power grid as well.

In order to construct the core and to predict its performance, simulations have to be done. These require knowledge of the underlying fundamental nuclear reactions, i. e., cross sections for production of neutrons and charged particles in the target, and for reactions that are relevant for neutron transport and moderation.

The spallation neutron spectrum is different from the neutron spectrum of standard nuclear reactors, especially in the high energy region. The nuclear data libraries developed for reactors of today go up to about 20 MeV, but in a transmutation facility, 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, say above 200 MeV, make data in this region not being as important as mid-range data. Direct reaction models assuming a single interaction also work reasonably well above 200 MeV. In other words, there is a significant need for neutron scattering data in the 20–200 MeV region. Existing theoretical models and computation codes, together with the parameters used therein, have to be reviewed thoroughly. Experimental measurements are essential in order to verify these models and parameters.

3 Fast neutron cancer therapy and dosimetry

Radiation treatment of tumours is, in most cases, carried out using electron beams and bremsstrahlung photon beams. Unfortunately, not all tumours respond positively to this kind of radiation. A large number of patients could benefit from therapy with more densely ionizing radiation [5, 6].

Cancer therapy with fast neutrons can provide such radiation to a reasonable cost. In this case, ionizing charged particles are produced by nuclear reactions in the tissue. To fully investigate the potential of this therapy, the dose delivery has to be known with the same precision as in common photon therapy. This requires determination of the fundamental cross sections for conversion of neutrons into charged particles. Another important quantity is elastic scattering, which through the heavy recoils is responsible for 10–15 % of the dose in cancer therapy.

Modern neutron therapy beams extend up to 70 MeV, while most evaluated data bases go up to 20 MeV, as mentioned above. This makes it difficult to correctly estimate the dose given, and to plan and optimize the therapy. Hence, the needs of data for cancer therapy coincide in energy with those for transmutation applications.

4 The optical model

For transmutation purposes, neutron elastic scattering is the single most important intermediate energy quantity that remains to be measured. It also plays a key role in describing reactions that are relevant for medical purposes. There are several reasons for this, the most important one being that elastic scattering allows determination of the optical potential, which plays a role in every microscopic calculation that involves neutrons in either the entrance or the exit channel. The optical model for protons is well known, while this is not the case for neutrons.

Coulomb repulsion of protons creates a neutron excess in all stable nuclei with mass number $A > 40$. Incident protons and neutrons interact differently with nuclei, depending on the neutron excess. To account for this, an isovector coupling term has been introduced in the optical model by Lane [7], giving the nuclear part of the potential the form

$$U_N(E) = U_0(E) + (4/A)U_1(E)\vec{t} \cdot \vec{T}$$

where $\vec{t}$ is the isospin of the projectile and $\vec{T}$ is the isospin of the target. The origin of this term may be traced to the $\vec{\tau_i} \cdot \vec{\tau_j}$ term in the nucleon-nucleon interaction. The diagonal elements of the $\vec{t} \cdot \vec{T}$ matrix display the differences between proton-nucleus and neutron-nucleus elastic scattering, i. e.,

$$U_N(E) = U_0(E) \pm \epsilon U_1(E) + \Delta U_c$$

where $\epsilon = (N - Z)/A$ and $\Delta U_c = 0$ for neutrons.

This expression shows that the proton-nucleus optical potential contains both an isovector term, U_1, and a Coulomb correction term, ΔU_c. This means that the proton kinetic energy is lower inside the nucleus, compared to that of a neutron. Once ΔU_c is known, the isovector potential U_1 can be deduced by a comparison of neutron and proton elastic scattering from the same $T \neq 0$ nucleus at the same energy.

Given the time and cost to carry out elastic scattering experiments, the first nuclei to study are those being interesting for developing theoretical models, i. e. magic or semi-magic ones like ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr and ^{208}Pb. Fortunately, these elements are also important in transmutation and therapy applications.

The optical model provides additional support for measuring elastic scattering; it follows from the model itself that the elastic cross section must constitute at least half the total cross section.

5 Elastic scattering data

The major part of neutron elastic scattering data above 20 MeV comes from the period 1950–1960. Due to difficulties at that time in extracting particle beams from cyclotrons, experiments were performed by placing a neutron production target inside a cyclotron, at a radius corresponding to the desired charged particle energy. For neutron production, the Be(d,n) and C(p,n) reactions were utilized. The extension of the neutron production target, and the small radial difference between consequtive beam turns inside the cyclotron, resulted in neutron beam energy resolutions of typically 20–35 % (FWHM), and energy uncertainties of several MeV. There are elastic neutron scattering data from 80 to 350 MeV from this period [8, 9, 10, 11, 12], but due to the characteristics mentioned, their quality is considered too low for today's requirements.

In 1994, neutron elastic scattering data from UC Davis at 65 MeV on a few nuclei were published [13]. The neutron beam was produced by the ^{7}Li(p,n) reaction, and had a resolution of 1.2 MeV (FWHM). Cross sections were measured for targets of C, Si, Cd, Fe, Sn and Pb, at laboratory angles from 6° to 45°. Besides this, there are unpublished data for a few nuclei, from Los Alamos [14].

The neutron beam facilities at UC Davis and Los Alamos serve as representatives for the two main means of producing neutrons using accelerated particle beams. At the Los Alamos Meson Production Facility (LAMPF), 800 MeV protons collide with a tungsten target, producing spallation neutrons with a continuous energy distribution (a white spectrum) up to the proton beam energy. Even if data can be recorded simultaneously over a wide range of energies, there is one obvious disadvantage in the fact that the flux per energy unit decreases like $1/E_n$ – measurements at high energies become very time consuming.

The ^{7}Li(p,n) reaction, employed at UC Davis as well as at TSL, yields a quasi-monoenergetic spectrum of neutrons having roughly the same energy as the incident protons. The advantage of using a monoenergetic beam when studying reactions at a specific energy is shown in figure 1. Here, a ^{12}C(n,n) excitation spectrum obtained at TSL is compared with a corresponding spectrum from Los Alamos [14]. It illustrates the difference in time needed to obtain the same amount of data – a few hours using a monoenergetic beam, compared to some months for a white source.

6 Neutron detection principles

When measuring neutron scattering at energies up to 20 or 30 MeV, time-of-flight (TOF) techniques are normally used to determine the neutron energies. In the low end of the interval, the flight paths can be kept to a length of a few metres to obtain the desired energy resolution. Thus, it is also possible to rotate the detector around the scattering sample, to measure angular distributions. At the high end, however, the required flight path must be increased, meaning that rotation becomes unpractical. The solution is to use a beam swinger with which the incident beam angle can be changed by rotating a set of magnets.

At still higher neutron energies, the TOF techniques become less favourable. For instance, 20 MeV neutrons can be measured with an energy resolution of 0.5 MeV, given a time resolution of 1 ns and a flight path of 5 m. In contrast, 100 MeV neutrons require a 60 m flight path for the same energy resolution. Even if a resolution of 2 MeV is accepted, the flight path will be 15 m. In addition, a large array of neutron detectors is needed to maintain a reasonable solid angle and count rate.

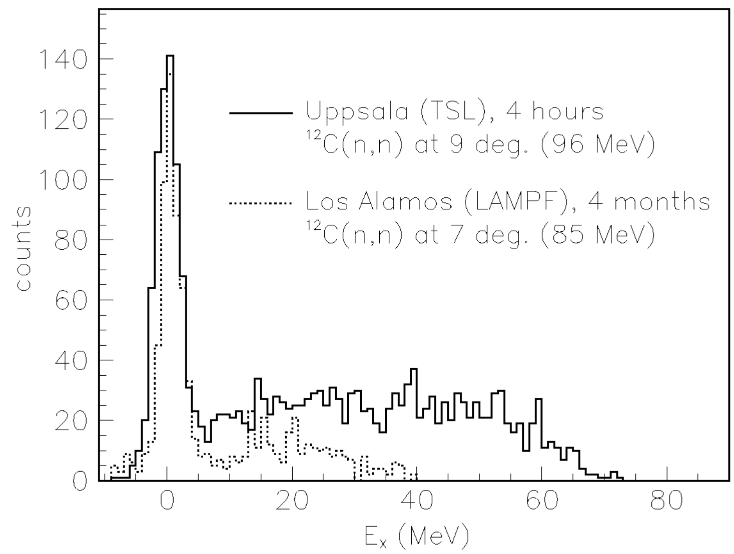

Figure 1: Comparison between a monoenergetic (Uppsala) and a white (Los Alamos) neutron source.

Another problem is related to the dumping of the charged particle beam. When a 100 MeV beam is stopped, a huge background of neutrons will be created. A solution is to bend the beam between the neutron production target and the scattering sample, and bring it far away to a well-shielded beam dump. Unfortunately, this leads to an increase in the neutron flight distance before they reach the target, resulting in reduced count rate.

A different approach is to increase the distance between the neutron production target and the scatterer, thereby enabling collimation of the neutrons into a well-defined, high-quality beam, as well as good shielding of the charged particle beam dump. By converting the neutrons to recoil protons in a hydrogenous converter near the scatterer (about 1 m), a large solid angle is guaranteed. The recoil protons can then be detected with a $\Delta E - E$ telescope.

This method has been employed for the SCANDAL setup at the TSL neutron beam facility. The assembly consists of two identical systems that can be rotated around the scattering target, normally covering a total angular range from 10 to 70 degrees. Neutrons are converted into protons in the H(n,p) reaction in a 10 mm thick plastic scintillator. Two additional scintillators act as ΔE detectors, while a stack of CsI detectors are used for energy determination. When measuring elastic neutron scattering, veto detectors in front of the converters are used for fast charged particle rejection. In addition to the ΔE and E detectors, drift chambers are used for tracking of the recoil protons and improvement of the angular resolution.

Measurements of the H(n,p), ^{12}C(n,p), and ^{12}C(n,n) reactions have been performed at a neutron beam energy of 96 MeV, using scattering targets of CH_2 and carbon, respectively. Principles of the experimental procedure and the analysis, as well as technical details on the equipment, are given in the paper presented.

The results of the analysis are illustrated in proton energy and excitation energy spectra. A response function for the SCANDAL setup, constructed from basic principles, describes the data very well; hence it is concluded that the performance of SCANDAL is under good control. The total energy resolution is 3.7 MeV.

Acknowledgements

I am very grateful for the support from my supervisor Jan Blomgren, who has always found time to share his knowledge and skills as a scientist with me.

I also wish to thank the staff of the The Svedberg Laboratory for their supportive participation in the SCANDAL project, especially Per-Ulf Renberg and Tore Sundqvist.

Last, but not least, I would like to thank the rest of the people at the Department of Neutron Research for the good atmosphere, especially Nils and our *controllers* Hélène and Susanne, who keep things running; as well as my room mates Somsak, Udomrat, Cecilia and Bel, who have made work funny or interesting in different ways.

This work was financially supported by Vattenfall AB, Swedish Nuclear Fuel and Waste Management Company, Swedish Nuclear Power Inspectorate, Barsebäck Power AB, Swedish Defense Research Establishment, Swedish Natural Science Research Council, and the European Commission.

References

[1] J.F. Ziegler, IBM J. Res. Develop. **40** (1996) 19.

[2] H.H.K. Tang, IBM J. Res. Develop. **40** (1996) 91.

[3] D. O'Sullivan, private communication. EU Cosmic Radiation and Dosimetry Group.

[4] Proceedings of the 3rd International Conference on Accelerator Driven Transmutation Technologies (ADTTA99), Prague, Czech Republic, June 7-11, 1999. www.fjfi.cvut.cz/con_adtt99/.

[5] A. Wambersie, P. Pihet, H.G. Menzel, Radiat. Prot. Dosim. **31** (1990) 421.

[6] M. Tubiana, J. Dutreix, A. Wambersie, Introduction to Radiobiology (Taylor & Francis, 1990).

[7] A.M. Lane, Nucl. Phys. **35** (1962) 676.

[8] A. Bratenahl, S. Fernbach, R.H. Hildebrand, C.E. Leith, B.J. Moyer, Phys. Rev. **77** (1950) 597.

[9] C.P. van Zyl, R.G.P. Voss, R. Wilson, Phil. Mag. **1** (1956) 1003.

[10] A. Ashmore, D.S. Mather, S.K. Sen, Proc. Phys. Soc. A **71** (1958) 552.

[11] R.S. Harding, Phys. Rev. **111** (1958) 1164.

[12] G.L. Salmon, Nucl. Phys. **21** (1960) 15.

[13] E.L. Hjort, F.P. Brady, J.L. Romero, J.R. Drummond, D.S. Sorenson, J.H. Osborne, B. McEachern, L.F. Hansen, Phys. Rev. C **50** (1994) 275.

[14] J. Rapaport, private communication. J. Osborne, thesis, unpublished.