FAST NEUTRON CROSS SECTION MEASUREMENTS

Final Technical Report

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Final Report on DOE Cross Section Project (DRDA 023493)

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Introduction

The fast neutron cross section project at the University of Michigan has now been terminated with the completion of the final two Ph.D. dissertations by Nestor Tsirliganis and Emmanuel Christodoulou. We have completed measurements on the differential cross sections for elastic and inelastic scattering of 14 MeV neutrons in natural chromium, iron, nickel, and niobium. These measurements are described in detail in the report that follows. A condensed version of these descriptions and results is under preparation for submission to the journal *Nuclear Science and Engineering*.

The data that have been generated over the course of the project represent a valuable contribution to the very sparse existing data on differential scattering cross sections in this energy region. In addition to their value in basic nuclear analysis, the data are of importance in the design of fusion-based reactors or conceptual fast neutron breeding systems. The quality of the data generated in our laboratory is enhanced because of the great attention that was given to minimizing the interfering effects of external scattering on these measurements. Despite the relatively low intensity of our neutron source, we have been able to carry out these measurements in a "clean" environment that helps to add to the reliability and accuracy of the results.

The Cockcroft-Walton accelerator and beam bunching system that were employed in this project have now been transferred to the University of Texas where the equipment will be used for additional 14 MeV neutron studies. The large-volume laboratory in which the measurements were conducted is in the process of conversion to other uses.

We are grateful for the financial support that has been provided by the U.S. Department of Energy that has allowed this work to be completed. It has not only led to useful contributions to nuclear data, but also served as an excellent educational experience for a series of students at the undergraduate, Masters, and Ph.D. levels.

Measurements of the Differential Cross Sections for Elastic and Inelastic Scattering of 14 MeV Neutrons in Natural Chromium, Iron, Nickel, and Niobium

Abstract

The time-of-flight technique was used with the 'ring' scattering geometry in a laboratory with low neutron scattering background to measure the angular distributions of the cross sections for elastic and inelastic scattering of 14 MeV neutrons in natural chromium, iron, nickel, and niobium. Specifically for inelastic scattering included were: the 1.43 MeV and 4.56 MeV levels of ^{52}Cr , the 0.85 MeV level, and (2.94-3.12) MeV and (4.46-4.51) MeV level groups of ^{56}Fe , the 1.33 MeV level of ^{60}Ni combined with the 1.45 MeV level of ^{58}Ni , and the 4.48 MeV level of ^{58}Ni . Pulses of neutrons with time width of 0.9-1.1 ns were produced via the $^3\text{H}(\text{d},\text{n})^4\text{He}$ reaction in a 150 keV Cockcroft-Walton linear accelerator, with average intensities of 9×10^8 n/s. The energy of the incident neutrons was between 14.75 MeV (at 16°) and 13.48 MeV (at 160°). High purity scattering ring samples were used. The scattering angles ranged from $\sim 16^\circ$ to $\sim 150^\circ$, for iron, chromium, and nickel, and from $\sim 16^\circ$ to $\sim 160^\circ$ for niobium, with a typical step of $\sim 10^\circ$. High purity ring samples were used. Scattered neutrons were detected by a heavily shielded, high resolution, large volume liquid scintillator (NE 213). The operational characteristics of the various components of the time-of-flight system were determined in a series of independent tests and preliminary time-of-flight measurements with direct source neutrons and neutrons scattered by a carbon ring sample. The relative efficiency of the detector as a function of energy was measured using a time-of-flight technique with a ^{252}Cf source, while absolute values were provided by Monte Carlo calculations. The neutron pulse width and current were monitored by a secondary time-of-flight system and a BF_3 long counter. Aluminum activation disks were used to determine the integrated neutron flux. The activity of the disks was measured with a standard gamma spectroscopy system based on a high purity germanium detector. The differential cross sections were calculated from the area of the scattering peaks in the time-of-flight spectra after the necessary corrections (background, multiple scattering etc.) were applied. The overall uncertainty for the elastic scattering cross section was in the range of 7-10% for all four materials, with some higher values observed around the minima of the angular distribution for niobium. The uncertainties for the inelastic scattering cross sections were estimated to be between 8 and 24%. The measured angular distributions were compared with the evaluations in the ENDF/B-VI, JENDL-3,

CENDL-2, BROND-2, and JEF-2 nuclear data libraries. For elastic scattering, there are no significant discrepancies in general, neither among the evaluations nor between the present data and the evaluations. For the inelastic scattering there are significant discrepancies both in shape and magnitude among the evaluations (when available) as well as between the present data and the evaluations. These data provide a valuable contribution to the scarce inelastic scattering data available in the literature. With an uncertainty of approximately 10%, the elastic scattering data also provide a valuable supplement to the currently available data.

Introduction

Cross sections of nuclear reactions induced by fast neutrons are important for many applications: nuclear theory, fission and fusion reactor technology, fast-reactor design and control calculations, radiation damage, neutron fluence monitoring, safeguards, neutron therapy, medical physics, activation and prompt radiation analysis, radionuclide production, radiobiology, nuclear geophysics, dosimetry and space sciences [1]. With the use of generators which produce intense monoenergetic neutron beams based on the D-D and D-T reactions, much effort has been put into measuring the cross sections of the various neutron interactions, for different materials and a broad range of neutron energies. In the energy region between 1 eV and 20 MeV the most common of the neutron interactions is the scattering of neutrons with the atomic nuclei.

Large compilations of nuclear data (evaluated nuclear data libraries) which have been developed throughout the world; ENDF/B of the USA, JENDL of Japan, CENDL of China and others, are being continuously revised or re-evaluated. These libraries attempt to recommend the true value of a particular physical quantity, such as a cross section, based on theoretical calculations and experimental nuclear data. The various parameters, such as optical model parameters, level density parameters, and information on nuclear level scheme, which are required as input to the theoretical calculations are adjusted based on the experimental data so that the agreement between the calculated and experimental data becomes as good as possible.

Cross sections with 14 MeV neutrons from D-T reactions, besides being standard reference data, have become of primary importance with the increased interest in fusion reactor design. The neutron field in a fusion reactor will be much more anisotropic than that in a fission reactor, and its spatial and spectral change will be large. As a result, the formation of neutron field (spatial and energy-spectral distribution of flux) becomes sensitive to secondary neutron distributions of 14 MeV neutron reactions with reactor materials [2,3]. Neutron scattering cross sections and secondary emission differential data are therefore essential in fusion reactor neutronics (radiation damage of metals and alloys; tritium breeding ratio; neutron multiplication and nuclear heating in the components; neutron spectrum and reaction rate in the blanket). The need for such data was highlighted in the report "National Nuclear Data Needs of the 1990s" prepared in 1992 by the Subcommittee on Nuclear Data Needs of the Nuclear Science Advisory

Committee: "The data required for predicting nuclear responses includes all neutron induced reaction cross sections for neutron energy up to 20 MeV, energy and angular distributions of secondary neutrons, gamma ray production cross sections, energy distributions of emitted charged particles, and decay data for radioactive isotopes." Very few data are available at small and large angles. For the most important structures in future fusion reactor systems (breeder/multiplier, component shield, and magnet), the data requirements for candidate elements are deemed either unmet or only partially fulfilled.

The potential structural materials of a fusion power reactor and those employed in fusion reactor components including first wall/divertor/limiter, blanket, magnet, magnet shield and biological shield system, have been established by several studies. A summary of potential fusion materials for which total and secondary neutron emission data are required, is given in table 1.

As it can be seen from table 1., iron, chromium, and nickel, the basic elements in most alloy steels, are essential in the majority of the components of a fusion reactor. In the sixth issue of Communication of Nuclear Data Progress published in 1991 by the Chinese Nuclear Data Center, it is pointed out that for natural iron although there are substantial experimental data for elastic scattering cross sections in the energy region 0.4-16.1 MeV, the angular distributions for inelastic scattering to discrete levels are deficient in experimental data [4]. In the INDC/NEANDC Joint Discrepancy File of 1990, it is suggested that for natural chromium and nickel the differential data for inelastic scattering suffer from disagreements larger than the quoted uncertainties [5]. Niobium is used as an alloying agent in carbon and alloy steels and in nonferrous metals, mainly to stabilize and increase the strength of the alloy. It also has superconductive properties; Among the A-15 class superconductors Nb_3Sn is of primary importance for the development of large, high field magnets (such as toroidal coils) for fusion applications. There are large discrepancies in the current data on angular distributions of elastically scattered 14 MeV neutrons, for niobium [6,7]. The most reliable are due only to a single laboratory, the Octavian Facility at Osaka University. Niobium is available in pure bulk metallic form and has the additional advantage of being almost monoisotopic (~100% Nb-93) that makes it preferable from a theoretical standpoint. One minor drawback is the existence of a low-lying excited state at 30 keV that is practically impossible to separate

from the ground state, but the corresponding inelastic yield should be very small because of the large angular momentum change ($DI=4$) that is involved in the transition to the ground state.

Materials and Methods

The method of energy measurement by means of velocity determination is widely known as time-of-flight (TOF) and was used in neutron energy measurements since the earliest studies. The method [8] is based on measuring the elapsed time t_n for a neutron originating at a source point to reach a detection point after traveling a fixed distance l . If l is given in meters and E_n is the kinetic energy of the neutron in MeV, with rest mass $E_0 = 939.565$ MeV, then the neutron travel time t_n in ns is given by [9]:

$$t_n = \frac{33356404 \cdot l}{\left[1 - \left(\frac{939.565}{E_n + 939.565} \right)^2 \right]^{1/2}} \quad (1)$$

The time of origin of a neutron must be determined by producing the neutrons in pulses of a certain time duration. A specific neutron can be considered then to have originated at the production site at a time with uncertainty equal to the pulse duration. If the neutrons are produced by a nuclear reaction bombarding a target with ion pulses, then the neutron pulse duration can be considered equal to the ion pulse duration. The maximization of the energy resolution of the particular experiment (minimization of ΔE_n) is practically achieved by maximizing the neutron flight path and minimizing the neutron pulse duration. For the measurement of the elastic and inelastic scattering cross sections the neutron pulse duration must be in the order of 1 ns and the neutron flight path in the order of a few meters.

The measurements were carried out using 'ring geometry' in which a relatively massive target could be employed. The sample ring was placed around the axis of the ion beam line at the end of which the neutron producing target, via the D-T reaction, was located. Scattered neutrons were detected by a large-volume fast liquid scintillator after a flight path of 9 meters. By varying the position of the ring relative to the neutron producing target, a range of scattering angles between 16 and 160 degrees were covered. This approach has certain advantages over the alternative fixed sample methods utilizing

detectors mounted on goniometers [10, 11], multiple detector for simultaneous multi-angle measurements [12,13], or some beam rotating system [14,15]. These are highlighted below: a) Sufficient shield for the neutron detector is possible, since the detector is fixed. b) The volume of the ring sample can be quite large, so that counting statistics become much better and consequently relatively long flight paths can be adopted to gain energy resolution. c) Good angular resolution can be attained even for relatively large samples. d) Wide range of scattering angles can be covered.

Measurements for forward angles are much easier since the background of the direct source neutrons can be sufficiently attenuated by using an appropriate shadow bar.

However, some shortcomings also exist: a) The incident neutron energy varies from 14.7 to 13.4 MeV corresponding to the change of scattering angle from 0 to 180°. b) In the case of very forward ($<10^\circ$) or backward ($>160^\circ$) angles, the position of the sample is too far from the target to obtain sufficient counting statistics in a reasonable time. c) The effect of multiple scattering is significant.

The 14 MeV neutron laboratory where the experiments took place was located in a building which originally facilitated the 83-inch cyclotron operated by the Physics Department at the University of Michigan. The large internal volume of the former cyclotron vault room which is approximately 38,720 ft^3 allowed us to set up a measurement geometry, 3.5 m above the floor and approximately midway between the floor and the ceiling, in which effects due to neutron scattering from nearby structures were minimal. The control room was located in a well shielded area adjacent to the main laboratory room.

A. Pulsed Neutron Generator System

The 14 MeV neutron generator used in this project was a Texas Nuclear Corporation Model 9400 with beam line components custom made in their majority by our Nuclear Data Project group.

The ion source used in the neutron generator was a 52 MHz radio-frequency (RF) type source capable of producing an ion beam consisting of approximately 90% singly ionized atomic ions from 99.999% pure deuterium gas. The ion beam current produced by this source was in excess of 1 mA. The accelerator was a 150 kV Cockcroft-Walton type accelerator. The output voltage was variable from 0 to 150 kV with a rated current output of 5 mA.

Figure 1 shows a schematic diagram of the neutron generator, with the accelerator and the associated beam line components. The DC beam from the accelerator drifts down a length of beam line where it is focused by the electrostatic quadrupole doublet. After the quadrupole lens it is deflected by the pulser across an aperture located near the entrance of the mass analysis magnet. The pulsed beam after passing the mass analysis magnet is bunched and enters next the quadrupole triplet that focuses the beam at the position of the target. Finally, the pulsed, and bunched deuteron beam is passed through the capacitive pick-off and bombards the tritium target producing a nearly uniform disk source of neutrons.

The pulsing of the DC ion beam was achieved in two stages: the pulsing stage and the bunching stage. Beam pulsing was accomplished by applying a 1 MHz sinusoidal voltage within the range of 500–2000 V to a set of 20 cm long and 3.5 cm wide deflector plates which periodically swept the steady state deuterium beam across an aperture forming pulses 30–40 ns long. Two pulses were obtained per cycle. In order to further compress the 30–40 ns long pulses after the first stage of pulsing, the klystron bunching technique was employed. The velocity of the ions was modulated, applying an axial 6 MHz sinusoidal voltage to a buncher system consisting of three electrodes made of 3.2 cm diameter copper tube. The frequency of this voltage was phase-locked to the 1 MHz frequency of the pulser unit. The time-varying electric field retards the leading particles and accelerates those at the end thus compressing the pulse to about 1 ns at the neutron-producing target. The power to the pulser and buncher circuits was supplied by two identical solid state power amplifiers capable of delivering up to 140 W in the frequency range of 1.6–200 MHz. Wide-band hybrid linear amplifier modules with excellent gain stability and very good linearity were used as driver amplifiers. A Master Oscillator and Phase Lock unit was used to set the base frequency and the relative phase of the driving signals for both the pulser and buncher circuits. Constant-k low-pass Chebeshev filters are used in the input and output stages of each main amplifier to convert the square wave output of the master oscillator into a sinusoidal voltage and suppress the harmonics produced by the amplifier itself. Tank circuits, enclosed in aluminum containers which provided more than 350 dB attenuation of the RF radiation, generated the sinusoidal high voltages in the pulser and buncher assemblies. Proper impedance matching check between the amplifiers and their loads was achieved with power meters positioned

between each amplifier and its load. The same meters were used during tuning of the pulsing and bunching systems.

Pre-acceleration beam focusing was performed by a 0–10 kV potential across a gap lens. An electrostatic quadrupole doublet positioned near the exit of the acceleration column focuses the DC ion beam, forming a crossover near the aperture that forms the pulsed beam. A quadrupole triplet was used to focus the pulsed beam coming out of the buncher onto the target with a beam spot diameter of approximately 2.5 cm, matching the active diameter of the target.

A mass analysis magnet was used for two purposes. First by bending the beam 90°, the magnet allows orientation of the beam line toward the open volume of the laboratory where extended flight paths are possible. Second, the molecular component from the beam was eliminated so that the target life could be prolonged [16,17]. The magnet was double-focusing with a bending radius of 30 cm.

The timing pick-off unit was positioned approximately 18 cm away from the target to shorten deuterium ion drift time and it was of very low mass (less than 10 gm) in order to minimize scattering. It consisted of a 2.54 cm diameter capacitive pick-off copper ring, supported between two aperture forming metallic foils. As the ion pulses passed through the copper ring, they induced a bipolar signal which was amplified with the use of a wide bandwidth, high gain W1G2H Trontech amplifier. This amplifier was located 127 cm away from the pick-off ring and connected to it via a 50 ohm electrical feed-through with a section of RG174 cable shielded from the beam by 0.08 mm stainless steel tubing. A schematic diagram of the pick-off unit is shown in figure 2, and a typical signal from this unit is shown in figure 3. The primary purpose of the timing pick-off unit was to provide the “stop” signals for our time-of-flight measurements. The unit was also used for: a) beam intensity monitoring since the amplitude of the pick-off signals was proportional to the beam intensity, b) beam positioning on the target since low intensity unstable signal was indication of beam misalignment with respect to the target, and c) buncher phasing monitoring since minimization of the time width of the signal was indication of proper buncher phasing.

An ultra low mass target chamber was used to minimize the distortion of the neutron energy spectrum and angular yield distribution caused by scattering and absorption of neutrons in the structural materials that surround the neutron-producing

target. This chamber was 15.25 cm long, 5.2 cm in diameter, and had a wall thickness of 0.63 mm. It was made of a single piece of aluminum alloy 7075-T651 with small neutron cross section and high yield strength. The pressure difference across the chamber under vacuum was enough to couple the chamber to the beam line with the help of a 1.8 mm thick O-ring, avoiding any bulky coupling flanges. The section of the beam line that was directly coupled to the target chamber was 122 cm long and made of 0.9 mm thick stainless steel pipe with an ultra-low-mass flange on one end that was not much larger in diameter than the diameter of the target chamber. A normal CF flange was located on the other end. This section of the beam line kept heavy beam line components away from the target area.

The neutron-producing target was a 25.4 mm diameter tritium impregnated Ti lattice on 0.254 mm thick copper backing, which was mounted on the 0.38 mm thick end of the target chamber with a very thin layer of conducting epoxy.

Most of the beam line components were made of stainless steel and were joined together with copper gaskets. The system included one turbo-molecular pump with a 210 l/s volume flow rate and $1.5 \cdot 10^3$ compression ratio for hydrogen. This pump, together with its associated forepump were located near the exit of the accelerating column. A 120 l/s ion pump was used closer to the hot activity area of the target to maintain a good vacuum and avoid degradation of the pulsed deuterium beam. The ultimate pressure of the system was $5 \cdot 10^{-7}$ Torr while during normal operation the pressure was $2\text{--}3 \cdot 10^{-6}$ Torr.

B. Neutron Detector

Because of the relatively large distance needed to obtain a good time-of-flight separation, as well as the indirect method of neutron detection, large detecting volumes are required to obtain an adequate solid angle and detection efficiency. The NE 213 liquid organic scintillator supplied by Nuclear Enterprises Ltd. was chosen as the detector medium in the present work, for its physical, scintillation, and excellent pulse shape discrimination properties [18]. The detector is encapsulated in a cylindrical aluminum cell 20 cm in diameter and 8.2 cm in height, with a 3 mm thick quartz window at one end. The inner dimensions (sensitive volume) of the container are 18.8 cm diameter and 7.6 cm height. The cylindrical geometry is the most convenient for measurements, while aluminum has a low cross section for neutron reactions. The container is virtually leakproof since it was made from a solid block of aluminum and the quartz window was

attached using an epoxy glue (M51 Hysol Epoxy Patch) which is both resistant to the scintillator solution and does not poison it. The interior walls and front surface of the cylinder are covered with a TiO_2 coating (NE 561) in order to improve timing resolution and pulse height uniformity. The above size was adopted as a compromise between contradicting demands. The efficiency of the detector increases with its thickness; however, increasing the thickness of the detector negatively affects its time resolution, since it introduces an uncertainty in the neutron flight path. In addition, increasing the size of the detector results in a reduction in scintillation photon intensity reaching the photomultiplier and a parallel increase of spread in photon collection time. This affects both the time resolution of the detector and its pulse shape discrimination properties. The 7.6 cm thickness yields a total intrinsic efficiency of approximately 25% for 14 MeV neutrons incident parallel to the detector axis, while introducing an uncertainty in the flight path of approximately 1% for a path of 7 meters. The diameter of 18.8 cm, results in an overall size big enough to provide a sufficient counting rate, a reasonable time resolution (order of 1 ns) and good pulse shape discrimination. A tapered light guide made from Lucite is used to match the cell diameter to the diameter of a Hamamatsu R1250-03 photomultiplier tube. The exterior surface of the light guide is also covered with several coatings of TiO_2 reflector paint. The guide is optically coupled to the window of the cell and the photomultiplier tube by NE 586 clear viscous silicone fluid. The Hamamatsu R1250-03 photomultiplier tube was chosen in this application because of its large window (127 mm), spectral response range (300–650 nm), timing characteristics (rise time 3.0 ns, transit time spread 1.2 ns), quantum efficiency (22%) high gain ($1.4 \cdot 10^7$), long and short term stability (both approximately 1%), and low afterpulse rate [19]. The photomultiplier is fitted with a m-metal magnetic shield and a base suitable for fast time response and good linearity that is essential for good pulse shape discrimination.

The main characteristics of the neutron detector, response to neutrons and g-rays, time resolution, pulse shape discrimination properties, and neutron detection efficiency, were determined by carrying out measurements with various neutron and g-ray sources. In most cases, the general performance of the detector was evaluated under normal operating conditions without an attempt to establish any operating limits.

The timing and amplitude characteristics of the detector output signal were measured using gamma (^{137}Cs , ^{22}Na) and neutron (Pu-Be) sources. The signals from the anode and the last dynode were recorded with a Tektronix 11402 fast digital oscilloscope for an operating voltage of -2000 V. The light yield of the scintillator as a function of energy of the detected particles is needed to compute the pulse height spectrum for the specific particles and determine the absolute efficiency of a specific detector for a given bias level.

The relative pulse height (light output) response of the present NE 213 detector as a function of the neutron energy was determined using a time-of-flight technique. A polyethylene ring with 20 cm outer diameter and 1 x 1 cm square cross section was used to provide variable neutron energies by elastic scattering from hydrogen at different angles. The pulse amplitude from the detector was then determined by measuring the count rate for the corresponding peak in the time spectrum as a function of the fast discriminator threshold and recording the threshold level where this peak disappeared. A plot of these results is given in figure 4 together with the values suggested by Verbinski *et al.* [20]. Since the present data are in very good agreement with those from Verbinski *et al.*, the latter curve was used in subsequent measurements to estimate the effective neutron energy threshold.

The relative pulse height resolution DL/L of the detector can be fitted by the empirical estimate; $DL/L = (\alpha^2 + \beta^2/L + \gamma^2/L^2)^{1/2}$ [21,22]. This includes independent contributions due to; a) the position-dependent light transmission from the scintillator to the photocathode, α , which limits the resolution of the detector system particularly at large pulse heights, b) the statistical behavior of the light production, attenuation, photon-to-electron conversion, and electron amplification, β , and c) all noise contributions due to the photomultiplier and electronic circuits, γ , which are usually small and can be neglected.

The pulse height response to neutrons for the present NE 213 detector was computed using the Monte Carlo code NRESP7 [23] accepting the light output data of Verbinski *et al.*, and realistic values for the pulse height resolution parameters; $\alpha=10\%$, $\beta=10\%$, and $\gamma=0.5\%$. The code is a realistic simulation of the detector that takes into account the scintillation detector geometry, the neutron source specifications, the neutron cross sections for the materials of the scintillator and its surrounding, the neutron transport

effects including relativistic kinematics and the influence of the scintillator surrounding, the production of secondary charged particles, the light production from charged particles including wall effects, and the pulse height resolution of the detector system. The predicted response for 2.5 and 14 MeV neutrons is shown in figure 5. The measured pulse height spectra for neutrons with the same energies are shown in figure 6.

A common problem with large volume detectors is the potential for non-uniform response from the entire volume of the detector. The uniformity of the present detector was examined by scanning a collimated ^{137}Cs g-ray source across a diameter of its front face. The count rate was recorded as a function of the distance from the center of the detector using the experimental setup that is described later for the time resolution measurements. The relatively large variation (-15%) towards the side walls of the detector (points at -86 and 86 mm from the center) can be attributed to edge effects. Since the detector is always operated at a certain bias, some events that shift to a lower pulse height due to edge effects will be lost. Since edge effects for protons are not significant for a scintillator of this size (the range of 14 MeV protons in NE 213 is approximately 2.4 mm), the uniformity of the response to neutrons is expected to be superior.

The optical behavior of the present detector was modeled using the program DETECT (version 3) [24]. The program is a Monte Carlo model of the optical behavior of scintillation detectors. The program was used to calculate the response characteristics of the specific detector design under various photon generation conditions (localized, entire detector volume, etc.). The time resolution of a scintillation detector depends on the time spread of the flight times of scintillation photons from the position of their creation to the photocathode of the photomultiplier, the transit time spread of the photomultiplier, and the 'walk' of the timing electronics.

The time resolution of the detector was tested by detecting g-rays from a 4 MBq ^{22}Na source in coincidence with a 2.54 x 2.54 cm fast BC 404 plastic scintillator mounted on the center of the window of a fast 5.08 cm EMI 9887B photomultiplier (figure 7). In order to examine the uniformity of the response from its entire volume, the NE 213 detector was mounted on a X-Y-Z precision turntable and a mapping of its surface was attempted. The source was placed inside a lead collimator that provided a g-ray beam with small divergence (approximately 4°) and enabled a detailed 61-point mapping. Constant fraction discriminators (CFDs) were used in the timing circuitry to avoid 'walk'

problems due to amplitude and rise time. The shaping delay time and the triggering fraction of the CFDs were optimized to minimize the timing errors due to 'jitter'. After the adjustments, the time resolution of the electronics was less than 300 ps which is much smaller than the detector resolution. An example of the time spectra acquired during these measurements is shown in figure 8. The results from the mapping of the detector surface are plotted in figure 9. The variation of the full-width-at-half-maximum (FWHM) of the coincidence peak (time resolution) as well as the full-width-at-tenth-maximum (FWTM) and the full-width-at-hundredth-maximum (FW.01M) of the same peak, across a diameter of the detector are shown in figure 10. The behavior shown in these plots is typical for detectors of comparable size. The time resolution around the center of the detector is the best overall, 0.96 ns, and degrades slightly towards the edge. The rather large discrepancy of the FWHM (~42%) observed at both end-points (-86 mm and +86 mm from the center of the detector) is partly because of the fact that these points lie very close to the side wall of the container and the divergence of the g-beam has a greater effect on these measurements. Even at these points however, the time resolution of the system is 1.36–1.42 ns. Measurements were also carried out with a slender collimator forming a 'pencil' beam of γ -rays incident at the center of the detector at various angles. The FWHM, FWTM, and FW.01M were recorded as a function of the angle of incidence to examine any effects of the latter to the timing performance of the system. For angles of incidence $>30^\circ$ from the surface normal, the effects of the angle of incidence are rather appreciable. However, for time-of-flight measurements with relatively long flight paths, this is not a problem since the detected particles enter the scintillator almost parallel to its axis, with an angle less than 2° . It should be noted, that these results reflect only geometrical effects (position of creation of scintillation photons, edge effects etc.) since the response of the scintillator itself is isotropic. The above observations were verified from measurements taken with un-collimated γ -rays for different solid angles subtended by the detector. This type of measurement gives an overall time resolution of the system under more realistic experimental conditions. For large solid angles (large angles of incidence) the overall time resolution was approximately 1.4 ns while for small solid angles (almost parallel beam) it was only 1.17 ns. As can be seen from table 2, these values are in very good agreement with the predicted time resolution from the program DETECT, taking also into account that the measured time resolution includes the resolution of the second detector

used in the tests. All measurements quoted above were obtained using the predominant 0.511 MeV photons from the ^{22}Na source. The timing performance of the detector is expected to improve with greater light yield. However, two additional factors affect the timing performance when neutrons are used. The lower light output of NE 213 per unit energy loss for recoil protons compared to that of fast electrons, results in a 2 MeV recoil proton giving about the same light yield as a 0.5 MeV electron. Since the timing resolution is expected to improve with greater light yield, the figures quoted above should be attainable with neutrons with energies of about 2 MeV and above. The second factor is the transit time of the neutron from the face of the scintillator to the point of scintillation plus the photon transit time from the scintillation to the phototube. This factor is not appreciable for γ -rays, but becomes significant for neutrons. It represents the dominant source of time dispersion especially at lower energies. Overall the time resolution of the present NE 213 scintillator was shown to be in the order of 1 ns. This is less than the time spread of the neutron source or that of the neutron passing through the detector for typical neutron time-of-flight measurements.

Large scintillators have g-ray detection efficiencies comparable to their neutron efficiencies. As a result, the ability to differentiate between γ -rays and neutrons is essential for successful neutron measurements in order to suppress excessive backgrounds. The two most common methods of pulse shape discrimination are those of zero crossing and charge comparison [25]. The latter is the most direct. With this technique, particle identification is achieved by comparing the charge produced by the fast scintillation component with the total charge released by the scintillation. A device (PSD 5010 manufactured by Link Systems Ltd.) based on a design described by Adams *et al.* [26], using the charge comparison technique was chosen for n- γ discrimination in the present measurements. This instrument was developed to be used in conjunction with neutron detectors employing NE 213 as the detection medium. The unit can be operated over a dynamic range (ratio between the maximum and minimum amplitude pulses acceptable by the system) of 400 to 1 providing useful separation down to very low neutron energies. In addition to the particle identification signals, it provides a fast timing signal and an integrated output pulse which can be used for pulse height analysis. A pile-up rejector is also included in this device. The principle of operation is very straightforward; the anode current of the photomultiplier is integrated in a pure integrator

for a time T_1 (25 ns) and then held, a second integrator opens coincidentally with the first but continues integrating for time T_2 (400 ns). The outputs of the integrators are weighted so that when they are compared, the output of the comparator indicates a neutron, if the output of integrator 2 exceeds that of integrator 1, and a γ -ray if the reverse is true. The pulse shape discrimination properties of the detection system were investigated using a 37 GBq Pu-Be neutron source. The neutron spectrum from this source spans the energy range $0 < E_n < 10.5$ MeV with maxima at 1.4, 3.1, 4.8, 6.6, 7.7, and 9.8 MeV [27], while the associated γ -ray spectrum extends over the range $0 < E_\gamma < 4.8$ MeV. The gamma-to-neutron ratio is approximately 0.7:1. The use of this type of white spectrum source constitutes a demanding test of the pulse shape discrimination system over a wide dynamic range. The anode signal from the photomultiplier of the neutron detector was fed directly into the input of the pulse shape discriminator. The total charge $K_2 \cdot (Q_1 + Q_2)$ (X) and difference $K_1 \cdot Q_1 - K_2 \cdot (Q_1 + Q_2)$ (Y) signals, where Q_1 is the charge collected in the time T_1 and $Q_1 + Q_2$ is the charge collected in the time T_2 , and K_1 and K_2 are normalizing weights, were displayed on an oscilloscope operated in X-Y mode. All the parameters of the PSD unit were optimized with the aid of the oscilloscope display. A single channel analyzer (SCA), which is incorporated in the PSD unit, was used to select a very narrow energy band by setting a narrow window for the output of the integrated total charge. The amplified difference signal, gated by the signal from the SCA, was fed to a multichannel analyzer through an analog-to-digital converter. A representative spectrum, for a bias level corresponding to a recoil proton energy of approximately 5 MeV is shown in figure 11. The performance of a pulse shape discrimination circuit may be characterized by two criteria: a figure of merit, M , which is defined as $M = S / (W_n + W_\gamma)$, where W_n and W_γ are the FWHM of the γ -ray and neutron distributions respectively and S is the separation of their peaks in the charge distribution spectrum; and the neutron peak-to-valley counting rate. A figure of merit of $M \geq 1.5$ is usually required to achieve a nearly 100% rejection and acceptance ratios [28]. As can be seen from figure 11, for 5 MeV protons, with the present system the figure of merit is $M = 2.1$ and the neutron peak-to-valley ratio is 92. The figure of merit depends on the particle energy and the bias level set for the measurements. In general, it is increasing for higher energies and higher bias levels. The demonstrated value of 2.1 for 5 MeV protons indicates a sufficient operation of the PSD

unit for 14 MeV neutron scattering cross section measurements where much higher energies are involved and the usual neutron cut-off energy (bias level) is above 2.5 MeV.

Quantitative time-of-flight measurements require the knowledge of the energy dependence of the efficiency of the neutron detector. The efficiency of organic scintillators as a function of energy depends on the properties of the scintillator, the size of the scintillator, the mechanical configuration of the detector (in scattering), and the energy threshold (bias level). Various analytical expressions exist [29,30], that estimate the efficiency taking into account most of the above parameters but generally more detailed and accurate computations can be done using Monte Carlo methods. However, because of possible influences of the pulse height resolution and the n- γ discrimination on the efficiency, the relative efficiency of the detector used should be verified experimentally when possible. Various experimental techniques are available to determine the relative detector efficiency. It is often determined by observing neutrons scattered from a hydrogen sample at a number of angles with the consequent large changes in scattered neutron energy [12,29,31]. Another technique is the associated particle method [30]. There are several problems though associated with the above technique. An alternative method, is the measurement of a standard continuum neutron spectrum from a suitable source and a subsequent comparison of the measured spectrum and the assumed standard. In this case a detailed relative detector response can be obtained free of many of the problems associated with the previous methods [32]. The neutrons from the spontaneous fission of ^{252}Cf have a continuous energy distribution that has been carefully investigated experimentally [33-37] and theoretically [38] and the evaluated shape can be regarded as a reference. These neutrons are emitted in a time interval smaller than 10^{-14} s following a fission event [36], allowing the time-of-flight technique to be applied for the recording of their energy spectrum [32]. The ^{252}Cf fission source used was a 5 mm diameter spot of electro-deposited californium oxide centered on a 12.7 mm diameter x 0.13 mm thick platinum foil. It was covered with $50 \mu\text{g}/\text{cm}^2$ of gold to prevent loss of ^{252}Cf by recoil. The nominal activity of the source at the time of its production was 1.85 Mbq. The source was mounted on one base of a 6 cm diameter by 6 cm height cylindrical chamber that functioned as a gas scintillation detector for the emitted fission fragments. Since the californium neutron spectrum should be influenced as little as possible by scattering in the constructing material, the chamber was made from

1.6 mm thick aluminum that has a small cross section for fast neutrons. In order to discriminate against the α -particles emitted by the californium source, the height of the chamber was chosen to be less than the range of 6.1 MeV alphas. The efficiency of the chamber for the detection of fission events was estimated to be 77–81% based on the nominal activity of the source. Both the low mass fission chamber and the NE 213 detector were mounted approximately 3.5 m above the floor level in the experimental hall of the time-of-flight facility, in order to reduce the fraction of wall-scattered neutrons. The separation distance (flight path) was measured to be 258.8 ± 0.2 cm using a precision steel tape. The PSD unit was included in order to separate the few neutron events from the approximately one order of magnitude higher γ -ray background of the unshielded neutron detector. The neutron triggered time-of-flight spectrum was recorded with a ND76 multichannel analyzer. After recording the original spectrum, a background spectrum was measured by inserting a 1 m long copper shadow bar with an additional 50 cm long paraffin segment. This combination of shadow bars is long enough to attenuate neutrons up to 15 MeV by a factor larger than 10^7 . A schematic diagram of the experimental setup is shown in figure 12. Figure 13 shows the TOF spectrum along with the background components; a) The background spectrum which was acquired by placing the combination of shadow bars between the Cf-252 source and the neutron detector. This background is shown as curve “A” in figure 13. b) A background caused by valid neutron ‘start’ signals with an uncorrelated ‘stop’ signal [35,39]. This background has to be calculated, and consists of the accidental coincidence gains and the associated coincidence losses in each channel. The gains predominate in the lower energy part of the spectrum while the losses predominate in the higher energy part. Curves “G” and “L” in figure 13 show the accidental coincidence gains and losses respectively. c) Random background such as γ events for which the $n-\gamma$ discrimination has failed. This background is fitted to the measured distribution between the γ peak and the end of the TAC range and is shown as curve “B” in figure 13. Additional corrections due to the time resolution of the system were not applied since they are significant only for short flight paths (~ 1 m) [40]. Corrections for air scattering were not considered either since they are important only for longer flight paths (~ 5 m) [33]. The net TOF spectrum was converted to energy spectrum, and was compared to a recently evaluated ^{252}Cf fission neutron spectrum by Mannhart [41], which for all practical purposes can be approximated by a

Watt distribution. The relative neutron detection efficiency was computed by dividing the measured energy spectrum by this Watt distribution. The resulting efficiency is shown in figure 14 as point data. The absolute detector efficiency was calculated using the widely used Monte Carlo program NEFF7 by G. Dietze and H. Klein [23]. This program calculates the detection efficiency for NE 213 scintillation detectors as a function of the neutron energy in the energy range from 10 keV to 20 MeV for a given neutron energy bin width and various bias values. The program uses relativistic kinematics and takes into account the geometry, the pulse height resolution, and the light response properties of the scintillator. The calculated efficiency as a function of energy is also shown in figure 14. Finally, the dashed line in figure 14 shows the result of an analytical estimation of the efficiency as a function of the neutron energy, suggested by Fowler et al. [30]. As can be seen from figure 14, the shape of the calculated efficiency with the NEFF7 code is in good agreement with the measured relative efficiency data for energies up to approximately 10 MeV. The very low emission rate of ^{252}Cf neutrons in the energy range above 10 MeV results in rather large uncertainties in this range although the overall trend of the experimental data closely follows the calculated shape. The method proposed by Fowler et al. does not take into account the light output characteristics and the pulse height resolution of the scintillator and as a result overestimates the efficiency of the detector in the energy range of 5–13 MeV. However, the general trend with energy is similar to the other two curves in figure 14.

C. Detector Shield

Measurements of elastic and inelastic differential cross sections of fast neutrons present severe shielding problems. At the detector position without shielding, the total scattering background (air-scattering and wall-scattering) rapidly overwhelms the value of the direct flux as the source-detector separation increases. In scattering experiments, the background flux can be several orders of magnitude larger than the flux scattered from the sample (sample neutrons). In addition, the flux density of neutrons from the source can be higher by a factor of about 10^4 than the flux density of sample neutrons [42]. Finally, especially with large volume detectors, the natural background of γ -rays and cosmic rays can become severe. With measurements using the time-of-flight technique coupled with some kind of pulse shape discrimination it is possible to reduce this background, although a large portion of it may be strongly time correlated to the

source neutron pulse. However, a properly shielded detector provides much better results than an unshielded detector regardless of the nature of the surrounding laboratory [43]. To shield the detector against the background neutrons and photons it is usually surrounded by a massive shield with an opening (collimator) towards the scattering sample. A 'shadow' shield between the neutron source and the detector capable of attenuating the direct flux by a factor of 10^6 – 10^7 is typically used to suppress this flux. In principle, the purpose of the collimator is to provide a nonperturbing access channel to the shielded detector for the neutron flux of interest. However, in practice the access channel perturbs this flux since beam associated, time correlated and uncorrelated background neutrons are scattered into the detector by the entrance port and walls of the collimator and the bulk shielding in the vicinity of the collimator. The time correlated neutron background is especially serious because it cannot be estimated by any background measurements. Sample neutrons may hit the walls of a collimator channel and reach the detector by small angle scattering. This effect changes the efficiency of the detector system and leads to an uncertainty of the scattering angle depending on the differential cross section of the sample and on the shape and material of the collimator channel. However, these perturbing effects can be minimized by a properly designed collimator and shadow shield system. The background from the entrance part of the collimator can be reduced by tapering the walls in this area [10,43].

Figure 15a, shows a schematic diagram of a lateral cut of the primary neutron detector shield assembly. The entire shielding is adequately thick for 14 MeV neutrons (attenuation more than 10^3). It consists of a massive ($\sim 4,000$ kg) $3,725 \text{ cm}^3$ cube with a double truncated cone collimator placed symmetrically around the central axis. The outer layer is made of paraffin blocks ($\sim 8 \times 10^{22}$ at./ cm^3 hydrogen content) which thermalize the neutrons scattered by the laboratory structures. The inner layer is made of 5 wt.% borated polyethylene used to thermalize and absorb these neutrons. The 3840 b neutron capture cross section of ^{10}B produces 0.48 MeV γ -rays which can be shielded more easily than the 2.2 MeV γ -rays produced by neutron capture in hydrogen. The 112 cm long double truncated cone collimator was made of 10 wt.% lithiated polyethylene in order to take advantage of the nonradiative absorption of thermal neutrons in ^6Li . Considering the direction of neutron travel (from the source toward the detector), the geometry of the collimator is such that the first cone has a taper angle of 18.5° such that the detector does

not "see" any of its surface. The other cone has a grow angle of 5.4° such that the neutrons that scatter from the ring sample do not "see" its surface directly for sample to detector distances greater than 3 m. A lead shield 5 cm thick positioned behind the collimator and around the detector shields the detector from background and capture photons. The entire shielding assembly was seated on four leveling jacks supported by a steel structure that could move along the beam line on rails permanently bolted on the laboratory floor. A maximum separation distance of 9 m between the neutron source and the detector could be achieved.

The detector was shielded from the direct 14 MeV source neutrons by a 1 m long double cone shadow bar (figure 15b). It was made of copper and provided attenuation by a factor of $\sim 10^7$. 2.5 mm diameter wire cables were used to suspend the shadow bar from a carriage attached to a structural ceiling beam. This carriage could move along the beam direction accommodating continuously variable positions of the shadow bar. Positioned 40 cm away from the neutron source, the shadow bar with a grow angle of 1.72° and a taper angle of 2.06° not only shielded the detector from the primary neutron flux, but it also shielded the collimator throat from direct source neutrons and neutrons scattered by its edges, preventing it from becoming a source of scattered neutrons. At the same time, it avoided shadowing the detector from neutrons scattered in the ring sample.

D. Alignment

It is important for time-of-flight measurements that the neutron producing target, the scattering ring sample, the shadow bar, and the neutron detector with the surrounding shield are geometrically aligned on the same symmetry axis. For this purpose a rotating alignment laser along with plumb lines in fixed reference positions were used for an optical alignment of ± 2 mm over the 9 m flight path. In order to change the scattering angle by moving the ring sample along the beam axis without disturbing the alignment, the ring samples were suspended by 0.1 mm diameter music wires from a precision linear motion system attached to the same structural beam with the carriage that supported the shadow bar. A very low speed 3.1 rpm servo motor was used to remotely position the ring sample with accuracy.

E. System Performance

The performance of the components related to the beam line and the neutron source was investigated using neutrons from the D-D and D-T reactions. The energy of

the neutrons are 2.45 MeV and 14.1 MeV for the D-D and D-T reactions respectively. The majority of the measurements for the characterization of the 150 keV deuterium beam were made using an aluminum blank in place of the neutron producing target, and D-D neutrons were generated from the self-implanted deuterium in the blank. A time-of-flight technique was used to tune the pulsing system and measure the width of the neutron pulse. In order to minimize the contribution of the detector to the overall timing resolution, the 3 mm thick Pilot U plastic scintillator was used to detect the neutrons after a flight path of 50 cm at 0°.

The ion source is capable of providing a maximum DC current of approximately 1.5 mA as measured at the exit of the accelerator. Under typical operating conditions the intensity of the dc deuterium beam at the target position, measured directly by means of a Faraday cage and a digital ammeter, is 200–250 μ A. Assuming a utilization factor of 0.08, this yields an average pulsed beam current of about 16–20 μ A. The size of the pulsed beam at the target position is 2–2.5 cm as measured by viewing the beam striking a quartz target. The dissipated power at the target is approximately 2.5–3 W. This power is sufficiently low so that no cooling is required for the target during measurements.

Pulses of 40 ns length are produced from the primary dc beam by operating the pulser at a rf frequency of 1 MHz and a peak-to-peak voltage of approximately 2 kV. This pulse width is the optimum for maximum beam utilization. The best time focusing for 150 keV deuterons after a drift length of 4.4 m was obtained by operating the buncher at a rf frequency of 6 MHz and a peak-to-peak voltage of approximately 10 kV. Under these conditions the full width at half maximum (fwhm) of the peak in the time spectrum for both D-D and D-T neutrons is 1.3 ns (figure 16). Considering the finite resolution of the detector itself, the time width of the beam pulse alone is estimated to be approximately 0.9–1.1 ns.

This beam pulsing performance is more than adequate for neutron energy measurements in view of the additional time spread that is introduced by finite neutron flight time through the larger NE 213 detector that is used in the actual time-of-flight experiments. The fwhm of the peak in the time spectrum of D-D neutrons taken with this detector is 3.8 ns (insert in figure 17) which is almost three times longer than the width obtained with the thin scintillator and is clearly dominated by the spread in neutron flight

time in the detector (approximately 3.5 ns). The overall resolution achieved for 14 MeV neutrons with the NE 213 neutron detector is 2.4 ns (figure 17).

The distribution of the energy of the neutrons emitted from a 'thick' tritium target, as a function of the emission angle, is well known [1] and plotted in figure 18a. Since the structure of the target assembly and non-uniformity of the deuteron beam can greatly affect and alter the angular distribution of the neutron yield, the latter was measured for the present configuration by the $^{93}\text{Nb}(n,2n)^{92m}\text{Nb}$ reaction using the activation method. The angular distributions relative to 0° , both measured and calculated [1] are shown in figure 18b. The dip of the measured neutron yield around 80° can be attributed to neutron scattering in the target assembly.

In order to demonstrate the performance of the present facility, time-of-flight spectra for 14 MeV neutrons scattered by a carbon sample were recorded at various angles between 20° and 160° over a flight path of 5.74 m. A ring sample was used with a 20 cm outer diameter and a 2×2 cm square cross section. A background spectrum was taken by removing the sample and was subtracted later from the original spectra. An example of these spectra before and after the subtraction of the background is shown in figures 19 and 20 respectively. The peaks due to elastic (0^+) and first inelastic (2^+) scattering from the 4.438 MeV level can be resolved in all spectra. The inelastic peak (0_2^+) from the second level at 7.654 MeV is not visible due to its small differential cross section (less than 2 mb/sr) except at the 20° angle where the cross section is 6.1 mb/sr. This peak can still be seen at 45° , although its differential cross section is only 0.5 mb/sr at this angle, due to the finite dimension of the scattering sample that leads to contributions from other angles and multiple scattering. The third inelastic scattering (3^-) peak from the 9.641 MeV level can not be seen at 140° where its differential cross section drops to 1.9 mb/sr. The magnitude of the differential cross sections corresponding to the observed peaks ranges from 15.1 mb/sr at 140° to 560 mb/sr at 20° for the elastic peak, from 7.9 mb/sr at 90° to 37.1 mb/sr at 20° for the first inelastic, and from 5.6 mb/sr at 90° to 10.4 mb/sr at 20° for the third inelastic peak. Even though gamma rays were suppressed using pulse shape discrimination, peaks (γ) from prompt g-rays originating from the target assembly and the scattering sample appear in all spectra. These peaks can be used to obtain absolute flight times. The data in these spectra have not been corrected for multiple scattering and are shown only to indicate the capabilities of the time-of-flight

facility for neutron scattering measurements. The main characteristics of the facility are summarized in table 3.

F. Scattering Samples

The scattering samples were of the highest purity compatible with machining in the desired ring form with dimensions 20 cm OD and 2 cm $\times$ 2 cm cross section. The elemental concentrations were: for natural chromium 99.8%, for natural iron 99.9%, for natural nickel 99.64%, and for niobium 99.85%.

Experimental Procedure

A. Geometric Arrangement

Figure 21 shows a schematic diagram of the geometric arrangement of the TOF experiments, with the relative positions of the neutron producing target, shadow bar, neutron detector and detector shield. These positions were fixed during all angular distribution measurements. The position of the ring sample of the material under investigation was changed to choose the desired scattering angle. For each material, the scattering angles covered the range from 16° to 160° with steps of approximately 10° . If θ is the average scattering angle from a distribution of angles within a particular range, which corresponds to a specific position of the ring sample relative to the target position, C the number of neutrons detected after scattering within that angle range, $\Delta\Omega$ the solid angle of the ring sample subtended by the detector, N the atom density of the sample material, V the volume of the ring sample, Φ the neutron fluence at the position of the ring, $\epsilon(E_n)$ the energy dependent detector efficiency, and f a correction factor that accounts for the multiple scattering and attenuation of the neutrons, then the differential microscopic scattering cross section is given by:

$$\sigma(\theta) = \frac{C \cdot f}{\Delta\Omega \cdot \Phi \cdot N \cdot V \cdot \epsilon(E_n)} \quad (2)$$

B. Neutron Source

The production of the high energy neutrons used in the present experiments was achieved via the reaction:

The large positive Q -value and the low atomic numbers of the D-T fusion reaction make it a prime candidate for the production of 14 MeV neutrons. The excitation function of this reaction with the broad resonance at deuteron energy $E_d = 109 \text{ keV}$ permits high yields of fast neutrons at $E_n = 150\text{-}200 \text{ keV}$ using 'thick' targets [44]. The energy of the incident neutrons varies between 14.75 MeV (at 16°) and 13.48 MeV (at 160°).

C. Data Acquisition System

Figure 22 shows a block diagram of the data acquisition system used in the TOF measurements. There are two distinct branches in this system: the 'main' branch that records the spectrum of the neutrons that scatter from the ring sample under investigation,

and the 'flux monitoring' branch that is used for the neutron fluence determination in each experimental run. In the 'main' branch each scattering event is characterized by the time difference between neutron production in the tritium target and neutron detection in the primary NE-213 detector. This time difference is converted to pulse amplitude in a time-to-amplitude converter (TAC) with 1000 ns range and is then recorded in a multichannel analyzer (MCA) with 2048 channels and 0.391 ns per channel bin width. Since the event recording rate at the NE-213 detector is approximately only 1 event every 10^5 neutron pulses, 'inverse timing' was employed in order to avoid occupying the TAC with 'START' signals for which there are no corresponding 'STOP' signals. In the 'inverse timing' the 'START' signal originates in the primary neutron detector, while the corresponding 'STOP' signal is provided by the timing pick-off unit delayed by 162 ns using 32.07 m of RG-58/U cable. The constant fraction discriminator unit (CFD), which is used to provide good signal timing characteristics, has a threshold of ~ 2.5 MeV neutron energy. The 'neutron' output of a pulse shape discriminator unit (PSD) is used as 'GATE' in the analog-to-digital converter (ADC) of the MCA for the TAC output signal, in order to discriminate against photon events. The 'flux monitoring' branch consists of two TOF sub-branches with fast plastic scintillator detectors located 2.5 m from the tritium target. One of the detectors is a $2'' \times 1''$ cylinder with its axis forming a 45° angle with respect to the beam direction and the other is a $2'' \times 2''$ cylinder with its axis forming a 175° angle with respect to the beam direction. They are used for two purposes. One is to record using the TOF technique the 14 MeV source neutron events that register in a single TOF spectrum peak for each experimental run. The area of the peak is proportional to the neutron fluence and is used in conjunction with the neutron fluence normalization measurement (see section D) to determine the neutron fluence at the position of the ring sample, at the end of each measurement. The other purpose of this branch is to monitor the average neutron pulse width by observing the width of the 14 MeV TOF peak, in order to optimally tune the system before each experimental run and also to detect any resolution deterioration during the measurement. A BF_3 counter was also used to monitor the relative beam intensity in real time during the measurements by continuously recording the neutron events every 10 s.

In order to estimate the number of neutrons that were misidentified as photons, by the PSD in the data acquisition system, TOF spectra of the 14 MeV source neutrons gated

separately by the neutron and gamma outputs of the PSD unit were acquired. Figure 23 shows a set of such spectra normalized for the same number of total events recorded by the BF_3 flux monitor. It is evident that there is a peak in the gamma gated spectrum at the same location as the 14 MeV neutron peak in the neutron gated spectrum. This peak is not a 'real' gamma peak because its location in the TOF spectrum does not correspond to the flight time of any possible time dependent γ -rays. The ratio of the areas of the two peaks that appear at the same location in the neutron and gamma gated spectra is an estimate of the relative amount of the 'leak-through' of neutrons in the gamma channel of the PSD unit. Five such sets of spectra were acquired at different neutron count rates. They yielded 16.52 % neutron 'leak-through'. The relative uncertainty, in the short term (within a few days), due to instabilities in the electronics, temperature changes, etc. was approximately 0.5 %. Figure 24 shows the relative amount of the gamma background reduction achieved with the use of the PSD unit. It is more than 90 %.

D. Neutron Fluence Measurement

The calculation of the microscopic scattering cross section from equation 2 requires the knowledge of the neutron fluence at the position of the scattering sample. For each run, the area of the 14 MeV neutron peak in the TOF spectra acquired by the monitors in the 'flux monitoring' branch of the data acquisition system (section B) is a relative measure of the neutron fluence for that run. The absolute measure of the neutron fluence is obtained by comparing the area of the 14 MeV neutron peak with the corresponding area measured during the fluence normalization run, during which an absolute measurement of the neutron fluence is made using the neutron activation reaction $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$.

Results and Discussion

In each TOF spectrum, besides the peak which corresponds to elastic scattering, additional main peaks are observed. For natural chromium, these peaks correspond to inelastic scattering from the 1.43 and 4.56 MeV levels of Cr-52. For natural iron, the spectra indicate three distinct inelastic scattering peaks. These correspond to the 0.85 MeV energy level, and the 2.94-3.12 MeV and 4.46-4.51 MeV energy level groups of Fe-56. For natural nickel, there are two prominent inelastic scattering peaks. One corresponds to the 1.45 MeV level of Ni-58 and the 1.33 MeV level of Ni-60 which are unresolvable and the other to the 4.48 MeV level of Ni-58.

A. Peak Area Determination

The estimation of the TOF peak areas, requires first the determination of the background upon which these peaks are superimposed. There are two possible types of background which must be subtracted from the TOF spectra; a) the 'sample-out' background which is measured by removing the sample under investigation from the neutron flux. This background is due to neutrons that register in the detector after they have been scattered in the air that surrounds the neutron producing target and in other laboratory structures within the detector field of view. Other background events include cosmic rays and any gamma rays that may have not been discriminated by the PSD unit. b) the 'sample-in' background which is measured with the sample under study in place and consists mainly of the neutron continuum and (n, xn') neutron interactions in the sample.

Figure 25 shows a typical spectrum of a 'sample-out' background. The peak in the 800-950 channel range is due to the small angle air scattering in the vicinity of the target. Before this background type could be subtracted from each TOF spectrum, it had to be re-scaled and possibly re-binned in order to match the background during the particular measurement as accurately as possible. It is noticeable in figure 25 that the background in the 650-900 channel range, is particularly featureless in this experimental arrangement. This is especially useful for the accuracy of the peak area analysis since the elastically and inelastically scattered neutron peaks appear in the 650-900 channel range in the 'sample-in' TOF spectra. Figures 26-28 show three selected TOF spectra, a) with the 'sample-out' background superimposed and b) with the 'sample-out' background subtracted.

Since the 'sample-in' background cannot be measured separately, this had to be estimated in cases where subtraction from the spectrum was necessary for the correct peak area determination. An example case is the peak which corresponds to inelastic scattering to the 4.563 MeV energy level of Cr-52. The procedure for the estimation of this background has as follows; The shape of the peak baseline was approximated with a straight line. This approximation is deemed reasonable since the width of the peaks at their bases is less than 20 channels. The approximation was carried out by selecting 2-3 points on each side of the peak, in the vicinity of its base. Then two points from the opposite sides of the peak were connected with a straight line and the background was estimated. This was performed for all the possible combinations of points. The average of the results was the best estimate of the 'sample-in' background for the particular peak. Figure 29 shows the above procedure graphically.

The peak areas were estimated, where possible, by direct summing of the counts in the channels of the peak. In cases where this was not possible because of overlapping peaks (as in most cases for the elastic and first inelastic level peaks), the areas were determined after fitting the peaks with properly selected functions. D. Schmidt et al. [45] have noticed that the TOF neutron scattering peaks which usually have 'tails' toward the longer flight paths, can be most successfully fit by folding an exponential function with a Heavyside distribution:

$$F(x) = \frac{N \cdot e^{\left(\frac{\sqrt{2}\sigma}{\lambda} y - \frac{\sigma^2}{2\lambda^2}\right)}}{\lambda \cdot \left[1 + e^{(2.252 y + 0.2022 y^3)}\right]} \quad (4)$$

where N is the peak area, and

$$y = \frac{x - x_0}{\sqrt{2} \cdot \sigma} + \frac{\sigma}{\sqrt{2} \cdot \lambda} \quad (5)$$

The parameters x_0 , σ and λ correspond to the position, FWHM and asymmetry of the peak but are not identical to them. Figure 30 shows an example of fitting with this function a doublet obtained experimentally. The nonlinear fitting procedure NLIN in the SAS/STAT® software module of the SAS System® was used for the fitting. Attempts to fit peaks with relatively small areas fail to converge because of overparametrization of this function. In these cases, a Gaussian function was successfully used.

B. Data Corrections and Uncertainties

The corrections to the experimental data that were applied before the microscopic scattering cross sections were calculated, include the multiple scattering correction, the air scattering correction, the correction for neutron misidentification from the PSD unit and the self-absorption correction of the activation foil, that was used during the fluence normalization procedure.

For the multiple scattering correction, a Monte Carlo code by A. B. Smith of the Argonne National Laboratory [46] was used which simulates a ring scattering experiment assuming a point neutron source. Originally the calculation provided multiple scattering corrections for elastically scattered neutrons. The code was modified to also provide multiple scattering corrections for inelastically scattered neutrons. The interactions taken into account for each inelastic level include besides the specific reaction, elastic scattering and any inelastic scattering to a shallower level under investigation. A best estimate of scattering cross section values that approximate the 'true' cross sections had to be used in an input data file for this calculation. The JENDL-3 evaluated nuclear data library was chosen as the source for the required neutron cross sections. The angular distribution of each cross section that can be represented as a Legendre polynomial series, was introduced in the input data file as the coefficients of the polynomials in this series. In certain cases the angular distribution of the cross section of an energy group was needed. Then the cross section weighted average of the angular distributions of the individual energies within the group was fitted with a Legendre polynomial series and the coefficients that resulted from the fitting procedure were used. The correction to the peak area due to multiple scattering is in an extreme case up to 55%. The precision of the correction is on the average less than 10%, with an extreme case of 26%. The accuracy of the correction is governed mainly by the accuracy of the selected 'true' cross sections.

In order to correct for air scattering, the scattering experiment was simulated using the MCNP transport code. In the simulation, source neutrons with energies of interest follow flight paths that intersect the detector. For each ring sample position two runs were executed: one in which the space between the detector and the scattering ring was filled with air, and the other in which this space was under vacuum. The air composition was assumed to be 78% nitrogen 21% oxygen and 1% argon. The correction factors range

between 5 and 7%. The precision of this correction as determined by the tallying statistics of MCNP is within 0.1%.

The correction due to the neutron 'leak-through' in the γ channel of the PSD was 16.52% with an uncertainty of 0.5%.

The self absorption of the activation foil used to measure the neutron fluence, in the fluence normalization run, was estimated to be 2.3% [47].

The most significant uncertainties in the determination of the neutron detector efficiency as a function of neutron energy, using the Monte Carlo code NEFF7, are the uncertainties associated with the cross sections of the neutron interactions. Based on these uncertainties, an overall uncertainty of 5% was assigned to the efficiency values.

The neutron fluence, Φ , at each sample position is proportional to the neutron fluence, Φ_{nm} , during the fluence normalization run, and to the neutron yield at the position of the sample normalized at the position of the activation foil, Y . The relative uncertainty in Φ_{nm} was calculated to be 1.68 %. The neutron yield for each sample position was estimated from the fit of the experimental data (figure 20), to a nine node spline. The maximum deviation of the experimental data from the fitting curve was 4.5%. This was estimated to be the relative uncertainty in Y . The relative uncertainty in Φ is then calculated to be 4.8%.

C. Differential Scattering Cross Sections

Tables 4-7 show the measured angular distributions of neutron scattering cross sections at 14 MeV, for natural chromium, iron, nickel, and niobium.

Figures 31-40 show plots of the measured angular distributions for chromium, iron, and nickel, along with all the available corresponding angular distributions from the existing evaluated nuclear data libraries: a) ENDF/B-VI of the USA, b) JENDL-3 of Japan, c) CENDL-2 of the PR China, d) BROND-2 of the former USSR and e) JEF-2 of Europe. ENDF/B-VI and JEF-2 offer only isotopic evaluations while CENDL-2 offers evaluations only for natural elements.

For natural chromium, the measured angular distribution for the elastic scattering is forward peaked with two local minima, one around 70° and the other around 120° . The overall uncertainty range is 7-8%. The measured distribution agrees particularly well in shape and magnitude with the ENDF/B-VI evaluation in the angle range $110^\circ - 150^\circ$. The

measured angular distribution for the inelastic scattering to the 1.43 MeV level is also forward peaked. The overall uncertainty is in the range of 9-13%. It agrees in general shape and magnitude with the JENDL-3 evaluation and the ENDF/B-VI evaluation for 14.5 MeV neutrons. The CENDL-2 evaluation differs significantly in shape and the cross section values are on the average lower by almost an order of magnitude. There are no evaluations for the angular distribution in BROND-2 or JEF-2. However the integrated cross section value in BROND-2 is similar to the present data while in JEF-2 it is two orders of magnitude smaller. The measured angular distribution for the inelastic scattering to the 4.56 MeV indicates a peak around 45° with a minimum around 110° . The range of the overall uncertainty is 12-19%. The only available evaluation for the angular distribution is in JENDL-3. It agrees fairly well both in shape and magnitude with the present data in the range 70° - 150° . The integrated cross section value in BROND-2 is similar to the present data while the one in JEF-2 is about an order of magnitude smaller.

For natural iron, the angular distribution for the elastic scattering was measured with an overall uncertainty of 7-8%. There are two local minima: one around 70° and the other around 110° . The shape of the distribution matches well the evaluations. The ENDF/B-VI and BROND-2 evaluations refer to incident neutron energy of 13.57 MeV. The magnitude of the cross section around 110° confirms the evaluation in JENDL-3. The measured angular distribution for the inelastic scattering to the 0.85 MeV level is in remarkable agreement, both in shape and magnitude, with the JENDL-3 evaluation. The overall uncertainty in this measurement is in the range of 8-14%. The distribution in CENDL-2 is roughly isotropic with integrated cross section value about an order of magnitude smaller. JEF-2 does not include an evaluation for this energy level. The measured angular distribution for the inelastic scattering to the 2.94 - 3.12 MeV level group matches closely the BROND-2 evaluation in all but three angles: 51° , 61° and 90° . The overall uncertainty is in the range of 12-24%. ENDF/B-VI and JEF-2 do not include evaluations for the particular energy group. The measured angular distribution for the inelastic scattering to the 4.46 - 4.51 MeV level group indicates a peak around 43° . The overall uncertainty range is 11-22%. JENDL-3 and BROND-2 evaluations indicate a peak just above 50° . Nevertheless the magnitude of the cross section in these evaluations is different by a factor of about 3. For angles up to $\sim 50^{\circ}$ and for 140° and 150° , the present cross section values are closer to the BROND-2 evaluation, while for the range 50° - 140° ,

are between the two library values. The distribution in CENDL-2 is approximately isotropic and the cross section is significantly lower in magnitude. ENDF/B-VI and JEF-2 do not include evaluations for this energy group.

For natural nickel, there are two local minima in the measured angular distribution for the elastic scattering: one around 63° and the other around 106° . The range of the overall uncertainty is 7-8%. The CENDL-2 evaluation refers to incident neutron energy of 14.1 MeV. Above 100° the present data follow closely the evaluated distribution in BROND-2. The evaluations in ENDF/B-VI and JEF-2 are identical. The measured angular distribution for the inelastic scattering to the 1.33 - 1.45 MeV level group matches distinctly the JENDL-3 evaluation in all angles except 25° and 45° . The measurement has an overall uncertainty of 9-14%. For those two angles the measured cross sections agree better with the ENDF/B-VI and JEF-2 evaluations which are identical and refer to incident neutron energy of 14.5 MeV. The CENDL-2 evaluation refers to incident neutron energy of 14.1 MeV. The distribution in the BROND-2 evaluation is isotropic. The angular distribution for the inelastic scattering to the 4.48 MeV level was measured with an overall uncertainty of 12-20%. It has a peak around 53° and a local minimum around 100° . The only available evaluation which is in JENDL-3 indicates a peak around the same angle, with cross section values which match closely the measured values in the vicinity of the peak. In this evaluation one local minimum is indicated around 80° , and another just before 150° which could not be confirmed from the present measurements.

The present measurements underestimate the elastic scattering cross section for angles smaller than 35° , in all of the above three materials. This underestimation can be attributed partially to the variable energy of the incident neutrons in the present measurements. This variation is due to the dependence of the neutron energy from the D-T source to the emission angle in the laboratory system. The energy is higher than 14 MeV at the forward ($<90^\circ$) angles, and lower at the backward ($>90^\circ$) angles.

The angular distribution of the elastic scattering cross section, for niobium, is compared in figures 41-43 with the values reported in the ENDF/B-VI and JENDL-3 in the range of 13-15 MeV, and in JEF-2 in the range of 12-16 MeV, since this range covers the energy variation in the present measurements. The effects of the incident energy variation can also be seen in figure 41. For the forward angles there is an overall better agreement with the angular distribution at 15 MeV while this agreement seems to be

shifted towards the 14–13 MeV distributions for the backward angles. Overall, the present measurements appear to be in very good agreement with the data from the ENDF/B-VI library. One exception is the areas of local minima in the distribution where the ENDF/B-VI values seems to significantly underestimate the minimum values. The JEF-2 library, although in general agreement for angles less than 60° , seems to significantly overestimate the cross section values at the local maxima above 60° (figure 42). In addition the local minima above 45° , especially for its 14 MeV distribution, appear to be shifted to different angles than those indicated by the ENDF/B-VI library and supported by the present measurements. As can be seen in figure 43, the JENDL-3 library has a tendency to overestimate the values of the differential cross sections although the general shape of the angular distributions is similar to the shape indicated by the present measurements.

Conclusion

With the present work we have met our goals which were: a) to measure the angular distributions of the inelastic scattering cross sections to the most prominent energy levels of natural chromium, iron and nickel, and b) to contribute to the determination of the angular distribution of the elastic scattering cross section of 14 MeV neutrons for natural chromium, iron, nickel, and niobium with an accuracy better than 10%. For inelastic scattering, the evaluations for the differential cross sections are scarce, and the discrepancies among them, both in shape and magnitude, are significant. These data will serve as an important addition to the available experimental data sets. The particular strengths of these experimental data are: the low background of the scattered neutrons from the laboratory environment, and the especially small time width of the neutron pulses (0.9–1.1 ns), compared to the 1.5–2.0 ns pulse widths commonly employed in similar measurements. The low background results in a more accurate subtraction from the composite TOF spectra. The narrow neutron pulses increase the energy resolution of the system, improving or even making possible at small scattering angles the separation of the shallow energy levels from the ground level. The present results also suggest that even higher accuracy could be achieved in the future with some improvements of the experimental facility and techniques.

A significant improvement would be the addition of a pre-collimator between the sample and the main shield structure in order to reduce the view field of the detector, and

greatly reduce the 'air scattering' peak. A rather 'featureless' background diminishes the effects of possible variation of the time profile of the pulsed deuteron beam between measurements and allows a much more accurate subtraction of the background. An increase of the intensity of the beam, either by increasing the beam utilization factor or replacing the RF ion source with a duo-plasmatron source, could allow the use of smaller scattering samples where multiple scattering effects are not as serious, thus diminishing one of the major contributors to the uncertainty of the measured cross sections. Additional benefit would be the capability to make measurements over shorter times, decreasing the possibility of 'drifts' during a measurement. An accurate, absolute calibration of the energy dependence of the efficiency of the primary neutron detector under the same experimental conditions as in the time-of-flight measurements would also be desirable. It could decrease the uncertainty associated with the efficiency of the detector which is one of the dominant uncertainties in the calculation of the cross sections.

Table 1. Potential fusion materials [3].

Component	Major Element
Structure	Fe, Cr, Ni, Mn, V, Ti, Al, Si, C
Breeder/Coolant	Li, H, O, Pb, F, He, Be, Al
Neutron Multiplier	Be, Pb
Magnet	Cu, Sn, Nb, Al, N, He + structure
Magnet Shield	C, B, W, Pb, H, O + structure
First wall/Divertor/Limiter	C, Cu, W, Be + structure
Hybrid Blanket	Th, U, Pu
Biological Shield	Ca, Si, Ba, O + structure

Table 2. Measured and predicted time resolutions of the NE 213 detector. The predicted values are from the Monte Carlo code DETECT (version 3).

	DETECT	Measured
Pencil beam incident at the center of the detector, parallel to its axis	0.83 ns	0.96 ns
Parallel beam incident on the entire detector surface, parallel to its axis	1.07 ns	1.17 ns

Table 3. Operational parameters of the neutron time-of-flight facility at the Nuclear Data Laboratory.

Ion beam	D ⁺
Beam energy	150 keV (max.)
Beam current at target position	200–250 μ A (dc)
	16–20 μ A (pulsed)
Beam spot size at the target	20–25 mm
Neutron producing target	TiT, 25.4 mm diameter
Tritium loading of the target	185 GBq
Neutron yield	$9 \cdot 10^8$ n/s
Pulse width	<1.3 ns (estimated 0.9–1.1 ns)
Pulse repetition frequency	2 MHz

Table 4. Angular distributions in the laboratory system of 14 MeV neutron scattering cross sections for natural Cr.

Average Angle [degrees]	Elastic		Q = -1.43 MeV		Q = -4.56 MeV	
	Cross Section [barn/sr.]	Error [+]	Cross Section [barn/sr.]	Error [+]	Cross Section [barn/sr.]	Error [+]
16.6	7.1173E-1	4.9776E-2	--	--	--	--
25.4	2.3700E-1	1.6690E-2	1.2379E-2	1.4085E-3	--	--
35.0	4.7494E-2	3.3352E-3	6.0551E-3	5.9187E-4	1.5760E-3	2.9403E-4
42.6	4.5616E-2	3.2439E-3	7.8590E-3	9.2417E-4	3.1460E-3	4.3319E-4
51.2	2.3532E-2	1.6589E-3	2.9393E-3	3.8242E-4	1.5434E-3	1.8873E-4
58.5	1.3715E-2	9.7545E-4	2.2610E-3	2.9051E-4	2.3995E-3	2.8990E-4
68.1	5.9989E-3	4.4749E-4	1.8067E-3	1.6310E-4	1.4980E-3	2.1291E-4
77.5	1.2644E-2	9.0656E-4	2.5576E-3	2.8565E-4	1.0626E-3	1.3987E-4
87.3	1.4275E-2	1.0181E-3	1.8519E-3	2.3963E-4	8.0051E-4	1.1814E-4
97.7	1.1393E-2	8.1583E-4	2.1968E-3	2.1880E-4	8.6448E-4	1.3316E-4
107.8	6.1148E-3	4.4501E-4	2.2414E-3	1.9475E-4	4.1101E-4	5.9569E-5
118.0	4.1740E-3	3.0671E-4	1.7209E-3	1.5162E-4	6.5993E-4	1.0359E-4
128.4	4.8160E-3	3.5072E-4	1.9737E-3	1.7117E-4	7.0094E-4	1.0351E-4
139.1	6.4560E-3	4.7410E-4	2.3549E-3	2.1971E-4	8.9335E-4	1.4843E-4
149.6	7.1091E-3	5.3714E-4	2.7179E-3	2.8679E-4	7.4068E-4	1.3494E-4

Table 5. Angular distributions in the laboratory system of 14 MeV neutron scattering cross sections for natural Fe.

Average Angle [degrees]	Elastic			Q = -0.85 MeV			Q = -(2.94 - 3.12) MeV			Q = -(4.46 - 4.51) MeV		
	Cross Section [barn/sr.]	Error [±]		Cross Section [barn/sr.]	Error [±]		Cross Section [barn/sr.]	Error [±]		Cross Section [barn/sr.]	Error [±]	
17.0	7.5790E-1	5.3483E-2		--	--		--	--		--	--	
24.7	3.1407E-1	2.2134E-2		--	--		--	--		--	--	
33.3	6.9535E-2	4.8418E-3		1.2100E-2	9.8928E-4		2.3755E-3	5.4144E-4		1.3800E-3	3.0588E-4	
42.9	4.0444E-2	2.8958E-3		1.1747E-2	1.1086E-3		2.5339E-3	6.1118E-4		2.7086E-3	3.9435E-4	
50.9	2.8791E-2	2.0297E-3		6.2268E-3	6.4341E-4		1.0592E-3	2.3516E-4		2.5314E-3	2.8618E-4	
60.8	1.1396E-2	8.0324E-4		3.2560E-3	2.5070E-4		5.1411E-4	8.8416E-5		1.9085E-3	2.6380E-4	
70.5	5.6517E-3	4.0804E-4		3.1193E-3	2.4232E-4		1.5602E-3	2.1435E-4		1.6456E-3	1.8018E-4	
80.5	1.1991E-2	8.4770E-4		3.8742E-3	3.0314E-4		9.3258E-4	1.6662E-4		7.7609E-4	1.2739E-4	
90.0	1.5167E-2	1.0585E-3		2.7968E-3	2.1152E-4		3.3867E-4	6.8511E-5		9.3307E-4	1.3015E-4	
98.5	1.0641E-2	7.5143E-4		2.0254E-3	1.7016E-4		8.9740E-4	1.7635E-4		9.3679E-4	1.5426E-4	
110.5	4.1013E-3	3.0207E-4		2.2758E-3	2.0366E-4		5.7969E-4	8.8545E-5		8.6883E-4	1.0759E-4	
120.5	4.5873E-3	3.3252E-4		1.6805E-3	1.3878E-4		7.6252E-4	1.3016E-4		8.4799E-4	1.1883E-4	
128.8	6.0255E-3	4.4159E-4		1.7249E-3	1.7215E-4		9.1853E-4	1.0966E-4		9.3563E-4	1.1606E-4	
139.1	5.6343E-3	4.0986E-4		2.1174E-3	2.2946E-4		--	--		1.1476E-3	1.6239E-4	
149.5	6.8104E-3	5.1485E-4		2.4984E-3	3.3861E-4		--	--		9.2155E-4	1.3426E-4	

Table 6. Angular distributions in the laboratory system of 14 MeV neutron scattering cross sections for natural Ni.

Average Angle [degrees]	Elastic		Q = -(1.33 - 1.45) MeV		Q = -4.48 MeV	
	Cross Section [barn/sr.]	Error [±]	Cross Section [barn/sr.]	Error [±]	Cross Section [barn/sr.]	Error [±]
16.5	8.3914E-1	5.8588E-2	--	--	--	--
25.1	2.9001E-1	2.0246E-2	1.3341E-2	1.8018E-3	--	--
34.5	5.8265E-2	4.0850E-3	8.2017E-3	7.2311E-4	6.7332E-4	1.2332E-4
43.8	3.6252E-2	2.5797E-3	1.0240E-2	9.0194E-4	1.3027E-3	2.2906E-4
53.1	1.2866E-2	9.4847E-4	4.1203E-3	4.1789E-4	1.5239E-3	1.8997E-4
62.5	3.0789E-3	2.2863E-4	1.9765E-3	1.7667E-4	8.6999E-4	1.2975E-4
71.9	9.5869E-3	7.0375E-4	2.2185E-3	2.2129E-4	5.1411E-4	7.9949E-5
86.0	1.3266E-2	9.3823E-4	2.5799E-3	3.2652E-4	3.4358E-4	6.3411E-5
93.3	8.8107E-3	6.2857E-4	2.1608E-3	2.1065E-4	3.6607E-4	4.2341E-5
103.3	3.6825E-3	2.7260E-4	1.2215E-3	1.1405E-4	2.8057E-4	3.8338E-5
111.6	3.7266E-3	2.7552E-4	8.3126E-4	7.7506E-5	3.1561E-4	3.9426E-5
122.3	5.3148E-3	4.0298E-4	1.0726E-3	1.2267E-4	3.7719E-4	5.2411E-5
132.9	5.9519E-3	4.4323E-4	1.1583E-3	1.6349E-4	7.3483E-4	1.4510E-4
143.6	5.0484E-3	3.8305E-4	1.5388E-3	2.1447E-4	--	--
149.0	5.1999E-3	4.0966E-4	2.0251E-3	2.1181E-4	--	--

Table 7. Angular distribution in the laboratory system of 14 MeV neutron elastic scattering cross section for Nb.

Average Angle [degrees]	$d\sigma/d\Omega$ [barn/sr]	Error [$\pm$]
16.6	2.35E+00	1.70E-01
23.6	8.53E-01	6.28E-02
30.5	2.14E-01	1.69E-02
37.6	2.97E-02	3.53E-03
45.5	9.63E-03	4.77E-03
52.4	1.66E-02	2.07E-03
60.3	2.22E-02	2.03E-03
70.4	2.40E-02	1.90E-03
79.2	1.41E-02	1.22E-03
90.3	7.84E-03	6.82E-04
100.7	1.43E-02	1.26E-03
110.6	1.38E-02	1.37E-03
120.4	9.60E-03	1.26E-03
135.7	8.00E-03	6.31E-04
145.0	5.72E-03	6.09E-04
160.6	1.74E-02	1.83E-03

Figure 1. Schematic diagram of the 14 MeV neutron generator. (not in scale)

Figure 2. Schematic diagram of the capacitive beam pick-off.

Figure 3. Signal from the capacitive beam pick-off. Printout from digital oscilloscope ('normal' mode).

Figure 4. Relative pulse height response as a function of proton energy for the NE 213 neutron detector. The error bars correspond to 10% uncertainty.

Figure 5. Calculated response spectrum for the NE 213 detector with a neutron energy (a) 2.5 MeV and (b) 14 MeV.

Figure 6. Measured pulse height spectra of (a) 2.5 MeV (D-D) and (b) 14 MeV (D-T) neutrons with the NE 213 neutron detector.

Figure 7. Block diagram of the experimental setup used to examine the time resolution of the primary neutron detector. HV: high voltage supply, PMT: photomultiplier tube, CFD: constant fraction discriminator, TAC: time-to-amplitude converter, ADC: analog-to-digital converter, MCA: multichannel analyzer, PC: personal computer, DOSC: digital oscilloscope.

Figure 8. Coincidence time spectrum for a ^{22}Na source (0.31 ns/ch).

a.

b.

Figure 9. Time resolution of the NE 213 detector, a. surface mapping, b. contour plot.

Figure 10. Width of the prompt coincidence peak at half-, tenth-, and hundredth- maximum as a function of the distance from the center of the surface of the NE 213 detector.

Figure 11. Neutron and γ -ray 'difference charge' pulse height spectrum.

Figure 12. Block diagram of the experimental setup used to determine the relative efficiency of the primary neutron detector as a function of energy. HV: high voltage supply, PMT: photomultiplier tube, CFD: constant fraction discriminator, TAC: time-to-amplitude converter, PSD: pulse shape discriminator, ADC: analog-to-digital converter, MCA: multichannel analyzer, PC: personal computer.

Figure 13. The TOF spectrum recorded with the primary neutron detector NE-213 during the relative detector efficiency determination (a), and the background components (A, B, G, L), of the TOF spectrum (dotted line) recorded during the relative efficiency determination of the NE-213 neutron detector (b).

Figure 14. Energy dependence of the neutron efficiency for the NE 213 detector from NEFF7 (histogram), measured (point data), analytical calculation (dashed line).

(a)

(b)

Figure 15. Schematic diagrams of the primary neutron detector shield assembly (a) and the primary neutron beam stop (copper shadow bar) (b). (not in scale)

Figure 16. Time-of-flight spectrum showing 2.45 MeV neutrons detected by the thin Pilot U plastic scintillator over a flight path of 50 cm. The channel width is 78 ps. The fwhm of the peak is 1.25 ns.

Figure 17. Time-of-flight spectra showing D-T and D-D (insert) neutrons detected by the NE 213 detector. The channel width is 0.39 ns for the D-T and 0.19 ns for the D-D spectrum. The fwhm of the peak is 2.4 ns and 3.8 ns respectively.

(a)

(b)

Figure 18. Thick target neutron energy (a) and relative yield (b) distribution as a function of the emission angle in the laboratory system. In figure (b) the solid line shows the measured distribution while the dashed line shows the expected distribution [1]. The dotted lines indicate the $\pm 3\%$ uncertainty levels for the measured distribution.

Figure 19. Time-of-flight spectra of 14 MeV neutrons scattered by carbon at various average laboratory angles before the subtraction of the background.

Figure 20. Time-of-flight spectra of 14 MeV neutrons scattered by carbon at various average laboratory angles after the subtraction of the background.

Figure 21. Schematic diagram of the geometric arrangement of the tritium target, ring sample, copper shadow bar, neutron detector and neutron shield used in the time-of-flight experiments. (not in scale)

Figure 22. Experimental arrangement for the neutron time-of-flight measurements.

Figure 23. Neutron and γ gated TOF spectra of the 14 MeV source neutrons showing the relative amount of neutron misidentification or 'leak-through' of neutrons in they channel of the PSD unit.

Figure 24. Detail of neutron and γ gated TOF spectra of the 14 MeV source neutrons showing the relative amount of the γ background reduction achieved with the use of the PSD unit.

Figure 25. Typical time-of-flight 'sample-out' background spectrum.

(a)

(b)

Figure 26. Neutron TOF spectrum of natural Cr at 42.6 deg. with the 'sample-out' background showing separately (a) and with the 'sample-out' background subtracted (b).

(a)

(b)

Figure 27. Neutron TOF spectrum of natural Fe at 42.9 deg. with the 'sample-out' background showing separately (a) and with the 'sample-out' background subtracted (b).

(a)

(b)

Figure 28. Neutron TOF spectrum of natural Ni at 43.8 deg. with the 'sample-out' background showing separately (a) and with the 'sample-out' background subtracted (b).

Figure 29. Neutron TOF spectrum detail showing possible baselines for the 4.48 MeV peak of natural Ni at an average scattering angle of 62.5 degrees.

Figure 30. Experimental data of the elastic and first inelastic ($Q=0.85$ MeV) neutron scattering peaks of natural Fe, at 80.5 degrees, fitted with the function given by equations 4 and 5.

Figure 31. Angular distribution in the CM system of the elastic scattering cross section of natural Cr for 14 MeV neutrons.

Figure 32. Angular distribution in the CM system of the inelastic scattering cross section to the 1.43 MeV level of natural Cr for 14 MeV neutrons.

Figure 33. Angular distribution in the CM system of the inelastic scattering cross section to the 4.56 MeV level of natural Cr for 14 MeV neutrons.

Figure 34. Angular distribution in the CM system of the elastic scattering cross section of natural Fe for 14 MeV neutrons.

Figure 35. Angular distribution in the CM system of the inelastic scattering cross section to the 0.85 MeV level of natural Fe for 14 MeV neutrons.

Figure 36. Angular distribution in the CM system of the inelastic scattering cross section to the 2.94 - 3.12 MeV level group of natural Fe for ¹⁴ MeV neutrons.

Figure 37. Angular distribution in the CM system of the inelastic scattering cross section to the 4.46 - 4.51 MeV level group of natural Fe for 14 MeV neutrons.

Figure 38. Angular distribution in the CM system of the elastic scattering cross section of natural Ni for 14 MeV neutrons.

Figure 39. Angular distribution in the CM system of the inelastic scattering cross section to the 1.33 - 1.45 MeV level group of natural Ni for ¹⁴ MeV neutrons.

Figure 40. Angular distribution in the CM system of the inelastic scattering cross section to the 4.48 MeV level of natural Ni for 14 MeV neutrons.

Figure 41. Angle-differential elastic scattering cross section for niobium in the center-of-mass system from the present measurements and values reported in the ENDF/B -VI database in the energy range 13–15 MeV.

Figure 42. Angle-differential elastic scattering cross section for niobium in the center-of-mass system from the present measurements and values reported in the JEF-2 database in the energy range 12–16 MeV.

Figure 43. Angle-differential elastic scattering cross section for niobium in the center-of-mass system from the present measurements and values reported in the JENDL-3 database in the energy range 13–15 MeV.

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