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# Measurement of the differential cross section of neutron scattering on deuterium in the neutron energy range from 400 keV to 2.5 MeV

E. Pirovano(1), R. Nolte(1), M. Nyman(2) and A. Plompen(2)

(1) *Physikalisch-Technische Bundesanstalt - Braunschweig, Germany*
(2) *European Commission, Joint Research Centre - Geel, Belgium*

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**Summary.** — The angular distribution of n-d scattering was investigated in the energy range from 400 keV to 2.5 MeV using the recoil detection method, irradiating a proportional counter filled with deuterated gases with monoenergetic neutrons. Several techniques were employed to minimise the contribution of photons to the pulse-height distributions. A dedicated Monte Carlo model was developed to determine the differential cross section that best reproduces the measurements. The results are compared with the theoretical calculation of Canton *et al.* and the ENDF/B-VII.1 evaluation.

## 1. – Introduction

Accurate experimental data describing elastic scattering of neutrons on deuterium are of interest for both fundamental research and nuclear applications. The differential cross section is an important observable in studies concerning quantum-mechanical few-body systems, especially those aimed at the understanding of three-body forces [1], but it is also a quantity of practical interest in fields like nuclear engineering, neutron metrology, and detector physics. Below 3 MeV of incident energy, however, the available measurements of neutron angular distributions are scarce and partially discrepant, especially at backward angles [2]. Issues were documented also about the evaluated nuclear data libraries, which were found to produce inconsistent results when modelling benchmark experiments for heavy-water moderated critical assemblies [3]. Moreover, the re-evaluation of the angular distribution of n-d scattering below 1 MeV is one of the high priority requests featuring on the High Priority Request List for nuclear data maintained by the OECD/NEA [4].

For these reasons, a new measurement of the differential cross section of n-d scattering was carried out, investigating the angular distributions over a large angular range. The experiment was performed at the PTB Ion Accelerator Facility (PIAF) [5], where quasi-monoenergetic neutrons in the energy range from 400 keV to 2.5 MeV were employed to

Table I. – *Summary of the measurement runs. For each neutron producing reaction, and each neutron producing target, a list with the nominal mean energy $E_n$ and energy spread $\Delta E_n$ of the neutron field at the counter position is provided. Each ($E_n \pm \Delta E_n/2$) combination refers to a separate run.*

| Reaction | Target | List of ($E_n \pm \Delta E_n/2$) |
|---|---|---|
| $^7$Li(p,n)$^7$Be | metallic Li, 100 µg/cm$^2$ | (385±8) keV; (495±7) keV; (620±7) keV;<br>(748±7) keV; (868±6) keV. |
| $^3$H(p,n)$^3$He | T/Ti, 500 µg/cm$^2$ | (864±31) keV; (1.00±0.03) MeV; (1.25±0.03) MeV;<br>(1.50±0.03) MeV. |
| $^3$H(p,n)$^3$He | T/Ti, 955 µg/cm$^2$ | (2.00±0.04) MeV; (2.50±0.04) MeV. |

irradiate a proportional counter filled with mixtures of deuterated gases, which served as target for the incident neutrons and detector for the recoil deuterons simultaneously.

This work is a continuation of the project initially presented in [6]; in the measurement reported here, the recoil detection method was extended to higher neutron energies by adopting different gas and pressure combinations, to reduce the range of recoil deuterons and limit their escape from the sensitive volume of the detector. Furthermore, a new analysis procedure was implemented for the determination of the n-d differential cross section from the comparison of simulations with the experimental data.

## 2. – Experimental techniques and data analysis

The measurements were carried out in the low scatter hall of PIAF, where quasi-monoenergetic neutron fields were produced in open geometry using the $^7$Li(p,n)$^7$Be and $^3$H(p,n)$^3$He reactions. A metallic lithium target was employed (instead of the more common LiF target) in order to minimise the photon contamination of the neutron field. The detector was placed at 1 m distance from the neutron producing target, at 0 degrees relative to the direction of the ion beam. At this position, the neutron energies ranged from about 400 keV to 2.5 MeV: the nominal mean neutron energy incident on the counter and the energy spread are listed in Table I.

The counter used for the experiment, P2, is a recoil proton proportional counter routinely used for neutron fluence measurements (details can be found in [6]). In this case, P2 was operated with: a $D_2$/$CD_4$ mixture at a pressure of 1000 hPa (96.5% in volume of $D_2$ and 3.5% of $CD_4$, for incident neutron energies from 400 keV to 620 keV), deuterated propane ($C_3D_8$) at 600 hPa (for energies between 500 keV and 1.25 MeV), and $C_3D_8$ at 1000 hPa (for energies above 1.5 MeV). Propane has a higher stopping power than $D_2$, which makes it more suitable for measurements at higher energies: the shorter range of the recoil deuterons reduces the probability of incomplete energy deposition events due to particle escaping the sensitive volume of the detector. This however comes with the disadvantage of having a higher carbon content.

The photon-induced events were subtracted using the rise-time discrimination technique, which is thoroughly described in [6]. To subtract the contribution of room-return neutrons, for each incident energy data were taken with and without a shadow cone (300 mm of polyethylene and 200 mm of iron). The resulting pulse-height distributions are shown for selected energies in Figure 1.

For neutron elastic scattering, the energy of the recoil nucleus in the laboratory system is related to the scattering angle in the centre-of-mass reference system, and the

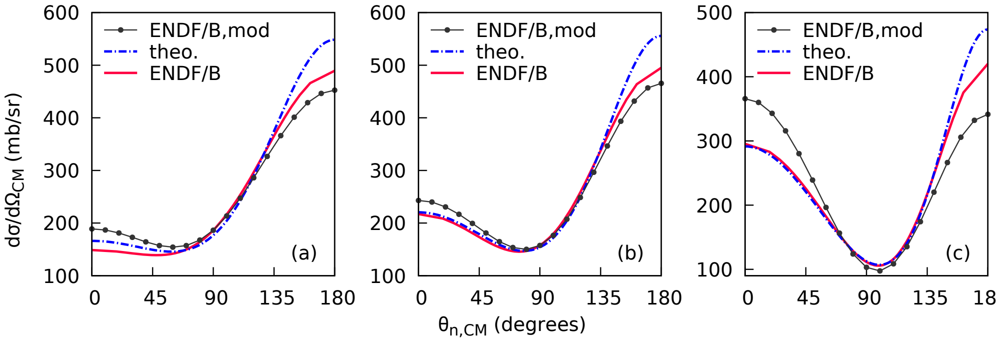

Fig. 1. – Recoil deuteron energy distribution for selected incident neutron energies $E_n$: (a) $E_n$ = 500 keV, (b) $E_n$ = 865 keV, (c) $E_n$ = 2.5 MeV. For the measurement at 500 keV, P2 was filled with $D_2/CD_4$, for the others with $C_3D_8$. The measurements ("meas.") are compared to the results of the Monte Carlo model using, for n-d scattering, the theoretical ("theo."), the ENDF/B-VII.1 ("ENDF/B", Fig. 1(a)) or the modified ENDF/B-VII.1 ("ENDF/B,mod", Fig. 1(b) and 1(c)) differential cross section.

recoil energy distribution is proportional to the differential cross section. The measured distributions therefore mainly reflect the shape of the angular distribution of n-d scattering. With $C_3D_8$, carbon also significantly contributes to the detector response: this results in a two-step distribution (Figures 1(b) and 1(c)), as compared to the one-step distribution obtained with $D_2/CD_4$ (Figure 1(a)), where carbon is negligible.

Real detectors, however, do not provide a direct measurement of the recoil energy distribution, but of the ionisation in the counting gas, which is related to the deposited energy. Therefore, instrumental effects such as incomplete energy deposition in the sensitive volume or an energy dependence of the mean energy $W$ required to produce an ion pair were included in a realistic Monte Carlo simulation of the pulse-height distributions produced by the proportional counter [6].

## 3. – Preliminary results

The results of simulations using two cross-section data-sets for n-d scattering are shown in Figure 1. The theoretical calculations of Canton *et al.* [1] (curve labelled as "theo.") predict a more pronounced peaking of the pulse-height distributions at large recoil energies than observed experimentally. At neutrons energies above 750 keV, the same but less pronounced trend is observed for the ENDF/B-VII.1 data [7]. At lower neutron energies, the pulse-height distributions simulated using the ENDF/B-VII data are consistent with the experimental data.

Above 750 keV, the ratio between the measured and simulated distributions was used to modify the ENDF/B-VII angular distribution, and the simulations were then updated. One iteration of this procedure was found to be enough for reaching a reasonable agreement, and the results are shown in Figures 1(b) and 1(c). Figure 2 shows the modified cross section data together with the evaluated data from ENDF/B-VII and the data of Canton *et al.*.

In general, the adjusted cross section data show a less pronounced backward-forward asymmetry than the theoretical calculations and the evaluated data. A smaller asymmetry leads to a less pronounced peaking of the recoil energy distribution at larger recoil

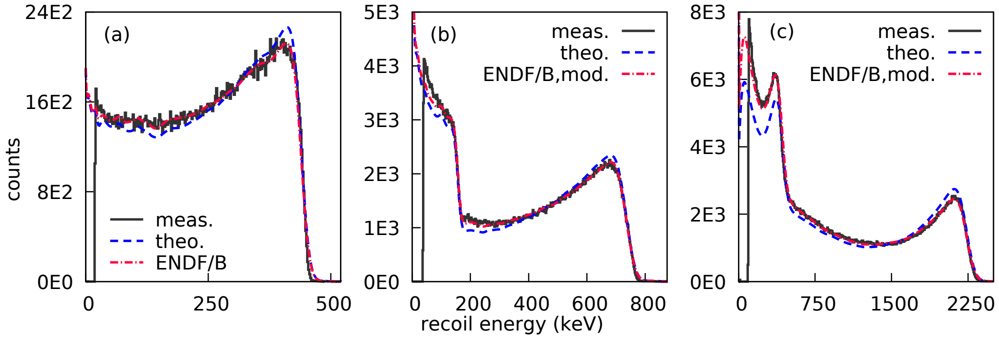

Fig. 2. – Differential cross section of n-d scattering $d\sigma/d\Omega_{CM}$ as a function of the neutron scattering angle in the centre-of-mass system $\theta_{n,CM}$ for selected incident neutron energies $E_n$: (a) $E_n = 865$ keV, (b) $E_n = 1.25$ MeV, (c) $E_n = 2.5$ MeV. The modified ENDF/B-VII.1 cross section obtained from the data analysis ("ENDF/B,mod") is compared with the original ENDF/B-VII.1 ("ENDF/B") and the theoretical cross section ("theo.").

energies, as observed experimentally. It is however important to notice that the uncertainty analysis is at this moment still missing. Without it, it is impossible to determine how significant these discrepancies are, and for this reason the main concern is now the determination of the uncertainties on the modified cross section.

## 4. – Conclusions

The neutron angular distribution of scattering on deuterium was measured irradiating a recoil proportional counter filled with deuterated gases with quasi-monoenergetic neutrons with energies from 400 keV to 2.5 MeV. Comparing simulations of the transport of neutrons and recoil nuclei to the experimental data, it was possible to determine, in an iterative procedure, the n-d scattering differential cross section that best reproduces the measurements. Discrepancies with both theory and the ENDF/B-VII.1 evaluated library were found, especially at backward angles, as also reported by other publications. Currently, the priority is completing the uncertainty analysis, in order to determine the significance of such discrepancies.

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