The $^{10}$B($n,\alpha_0$)$^7$Li and $^{10}$B($n,\alpha_1\gamma$)$^7$Li alpha-particle angular distributions, branching ratios and cross-sections measurements for $E_n < 3$ MeV

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Abstract. The $^{10}$B($n,\alpha$)$^7$Li and $^{10}$B($n,\alpha_1\gamma$)$^7$Li angular distributions have been measured at the GELINA time-of-flight spectrometer in the incident neutron energy range from 0.1 keV to 1 MeV by means of a twin Frisch-grid ionization chamber. With this type of detector it is possible to measure the angular distribution of the charged reaction fragments in a close to 2π solid angle with ~100% efficiency and a clear separation of both reaction channels: emission to the $^7$Li ground state ($\alpha_0$) or to its first excited state ($\alpha_1$). A strong angular anisotropy was observed at ~ 520 keV. In order to extend the energy range up to 2.5-3 MeV and to measure, also, the reaction cross sections, a double twin Frisch-grid ionization chamber was constructed. It is loaded with two very thin 94% $^{10}$B-enriched samples, mounted back-to-back with $^{235}$U samples on the common cathodes. New data acquisition, visualization and analysis software is used in a new set of long-term measurements, which are still going on.

1. Introduction

At the last standards evaluation of the IAEA [1], the $^{10}$B($n,\alpha$)$^7$Li ($^{10}$B($n,\alpha_0$) + $^{10}$B($n,\alpha_1\gamma$)) and $^{10}$B($n,\alpha_1\gamma$) standards got a large attention due to its improved ENDF/B-VII [2] database and its extension from 250 keV up to 1 MeV incident neutron kinetic energy.

For the ENDF/B-VII standards evaluation, a combined procedure similar to that used for the ENDF/B-VI was implemented. The $^{10}$B($n,\alpha$) standards were evaluated using, also, the GMAP code (GMA code [3], modified by adding the Chiba-Smith option [4] to handle Peelle’s Pertinent Puzzle problems), within a combining procedure, using input from the RAC [5] (Tsinghua Univ.) and EDA [6] (LANL) R-matrix analyses, and a thermal constants evaluation. The R-matrix analyses used all the available data, including total and scattering cross-section. The only boron data for direct use in the GMAP code were the ratio measurements. Because the $^{10}$B($n,\alpha$) and $^{10}$B($n,\alpha_1\gamma$) cross-sections obtained from the RAC and EDA analyses were not identical, the cross-sections from both analyses were averaged (without weights) and used as the R-matrix input to GMAP.

This way, the difficulties met in the previous evaluation were overcome via improvements of the evaluation procedure and using new experimental data sets, mainly those on the $\alpha$-particle angular distributions [7] and $^{10}$B($n,\alpha_0$) / $^{10}$B($n,\alpha_1\gamma$) branching ratios [8], obtained at the EC-JRC-IRMM, for incident neutron energies $E_n \leq 1$ MeV.
For the first time, also, the full angular distributions for both alpha-particle emission channels (\(\alpha_0\)-\(^7\)Li ground state transition and \(\alpha_1\)-\(^7\)Li* first excited state transition) were used in a multi-level, multi-channel R-matrix calculation [9].

The experimental setup, method and obtained results have been published in [7, 8] and in the literature cited therein. Here we focus our discussion on the improvements made on the existing experimental setup and measuring conditions. This was done in order to measure the \(\alpha\)-particle angular distributions and obtain the \(^{10}\text{B}(n,\alpha_0)\), \(^{10}\text{B}(n,\alpha_1\gamma)\) and \(^{10}\text{B}(n,\alpha)\) differential cross sections \(d\sigma_{n,\alpha_0}/d\Omega\), \(d\sigma_{n,\alpha_1\gamma}/d\Omega\), \(d\sigma_{n,\alpha}/d\Omega\), the angle integrated cross sections \(\sigma(\alpha_0), \sigma(\alpha_1), \sigma(\alpha)\) and their branching ratios \(\text{BR} \equiv \sigma(\alpha_0) / \sigma(\alpha_1)\) for \(E_n \leq 2.5\,\text{MeV}\).

Measurements of the differential cross-section \(d\sigma_{n,\alpha}/d\Omega\) in the fast neutron energy range \(E_n = 1.5\,\text{MeV}\) were made by Zhang et al. [10] and Giorginis and Khryatchkov [11] using Frisch-grid ionization chambers. A large discrepancy was observed between the two measurements. This deviation was attributed to the so-called particle leaking effect, a kinematic effect resulting from forward emission of both reaction products with respect to the direction of the incoming neutron [12]. If it is not taken into account in the analysis, the resulting cross section will not be accurate.

The shape of the \(^{10}\text{B}(n,\alpha_1\gamma)\) cross-section (relative to a “black” detector) for \(E_n = 0.2\,\text{MeV}\) was measured by Schrack et al. [13] in a NIST/ORNL collaboration. The cross-section obtained was normalized to the ENDF/B-VI evaluation over the region of \(E_n = 0.2\,\text{MeV}\), and agreed with this evaluation below 1.5 MeV. However, it differs from it by about 40% for \(E_n \geq 1.5\,\text{MeV}\). Additional shape measurements relative to \(H(n,n)\), in the neutron energy region \(E_n = 10\,\text{keV}\,\text{to}\,1\,\text{MeV}\) [14], led to a cross-section \(\sim 5\%\) lower than ENDF/B-VI for \(E_n = 120\,\text{keV}\,\text{to}\,1\,\text{MeV}\). In the same NIST/ORNL collaboration, the \(^{10}\text{B}\) total cross-section was measured for \(E_n = 20\,\text{keV}\,\text{to}\,20\,\text{MeV}\). The values agree with the ENDF/B-VI evaluation above \(E_n \sim 2\,\text{MeV}\), but are lower as much as 4% for \(E_n = 600\,\text{keV}\,\text{to}\,2\,\text{MeV}\) and higher as much as 5% for \(E_n < 600\,\text{keV}\).

At GELINA Märtén et al. [15] measured the \(^{10}\text{B}(n,\alpha_1\gamma)\) cross section relative to the \(^{235}\text{U}(n,f)\) and carbon standard cross sections in the incident neutron energy interval from 320 keV to 2.8 MeV. Their data are in reasonable agreement with those of Schrack et al.

With the present experiment we will try to extend the incident neutron energy range, so far reported in [7] and [8], up to about 2.5 - 3 MeV and, additionally, to measure the reaction cross section, relative to the \(^{235}\text{U}(n,f)\) standard, in order to compare with the data of [15] and to have an overlap with the measurements performed at the Van de Graaff accelerator [11].

A brief description of the new experimental setup is given elsewhere [16]. Here more details about the measurements are given.

2. The experimental setup

The GELINA facility of JRC-IRMM [17] is utilised as a white spectrum pulsed neutron source at which the time-of-flight (TOF) method is used to determine the energy of the interacting neutrons. Among the pulsed white spectrum neutron sources available in the world, GELINA is the one with the best time resolution. It is a multuser facility serving 12 completely independent flight-paths with a length of up to 400 m.

The experimental setup is commissioned at the FP16 experimental station, situated at a distance of about 60 m from the GELINA neutron producing target (figure 1).

This distance was chosen by several reasons: to use the un-moderated neutron beam, obtain better time (energy) resolution and to reduce the intensity of the very strong \(\gamma\)-flash from the neutron producing target. The \(\gamma\)-flash was additionally attenuated by a number of in-beam filters (bismuth and lead), situated at a distance of \(\sim 1\,\text{m}\) in the front of the chamber (figure 1). The neutron resonance absorption in these filters is used for time-to-energy conversion of the recorded TOF spectra.

As charge particle detector a double twin Frisch-grid gas ionization chamber (IC) was used. With this type of detector-spectrometer it is possible to register with an efficiency of \(\sim 100\%\) the kinetic
energy and the direction of irradiation of the charged particles (α-particles and fission fragments in this case), covering nearly $2\pi \times 2\pi$ solid angle.

Some parameters of the IC are shown in table 1. It is constructed from 2 ionization chambers of the same type, as the one used in the previous measurements [7].

![Image](image1.png)

**Figure 1.** The ionization chamber loaded with the boron and uranium targets at FP16/60m, in-beam filters ~ 1 m in the front of it, signal collecting electronics and (n+γ) beam profile with a diameter ~ 115 mm, recorded remotely by a scintillation counter at ~ 1.5 m behind the chamber during the adjustment of the collimation system.

| component  | vessel | cathodes | grids | anodes/shields | separators |
|------------|--------|----------|-------|----------------|------------|
| type       | cylinder | annular disc | stainless wires ring | Al | ceramics |
| material   | stainless | steel | foil | | |
| thickness (mm) | 1 | 0.11 | 1 | 0.05 | 4 |
| pitch (mm)  | 1.00 | | | | |
| inner ø (mm) | 228 | 100 | 152 | | 6 |
| outer ø (mm) | 230 | 178 | | | 10 |
| length (mm) | 364 | | | | 6, 10, 30 |

The only difference here is the distance between the common cathode and grids, which was chosen to be 40 mm. This way all the α-particles with kinetic energies up to ~ 4.5 MeV (from spontaneous α-decay of $^{235}$U and from the $^{10}$B(n,α) reaction) will spend their kinetic energy for ionization of the atoms of the mixed 95% Ar + 5% CO$_2$ gas media at a pressure of ~ 86 kPa before reaching the grids. The gas is refreshing (~ 30 ml/min) via a continuous flow through the chamber.

The samples are mounted in a back-to-back geometry (uranium/boron, boron/uranium) on the cathodes, perpendicular to the up/down neutron stream (backward/forward direction). The main characteristics of the samples are listed in table 2.
Because of different diameters of the uranium and boron samples, the beam was collimated to a diameter of ~95 mm at the entrance window of the IC, to assure that all 4 samples are fully covered by the beam. In fixed target geometry the homogeneity of the beam is required. It was checked by exposing photo-plates and remote scanning by a fast (neutron+gamma) scintillation detector (figure 1).

Table 2. Physical characteristics of the boron and uranium samples.

| characteristics | boron | uranium |
|-----------------|-------|---------|
| twin chamber    | sample | density (µg/cm²) | weight (µg) | sample | density (µg/cm²) | weight (µg) |
|                 | N² 3   | 14.5±0.8  | 804±44 | N² 2   | 193.1±2.9  | 3071±46 |
|                 | N² 4   | 15.7±0.8  | 870±44 | N² 1   | 193.7±2.9  | 3081±46 |
| support         | stainless steel | 0.3 | 0.5 |
| thickness (mm)  | 100    | 70 |
| diameter (mm)   | B₄C    | 1.66530% 23⁵U, 97.6630% 23⁶U |
| chemical form   | 98%    | 0.14912% 2³⁶U, 0.5229% 2³⁸U |
| purity          | 94% ¹⁰B | Sp. α-activity: 3.913±0.016 (dps/µg) |
| isotope         | 6% ¹¹B | |
| composition     | 84     | 45 |

The block diagram of the electronic set-up is shown in figure 2. It is the same as that described in [7], except that the present set-up records twice the number of spectra (8 amplitudes + 2 time signals) requiring the use of multiplexer modules (MMPM) developed at JRC-IRMM. The signals from the Frisch-grids were used to trigger the timing information of the neutron interactions with the sample nuclei. By setting appropriate low-level thresholds in the analog-to-digital converters and constant-fraction discriminators, the number of events from the spontaneous alpha-decay of the uranium samples was significantly reduced.

All the 16 outputs of the 4 MMPM modules were fed to the first slot of the MPI8100 data acquisition system and stored via the LISA software [18] (running in PV-WAVE environment) in list-mode on the hard disk for further off-line analysis. Recently, new software for data acquisition and analysis, named GENDARC [19], has been developed at IRMM and is used in this ongoing experiment, too. Some typical 2-dimensional spectra are shown in figures 3, 4 and 5.

The 1- and 2-dimensional visualization capability of the program allows to control the data acquisition and to do some primary analysis on the collected events. The reaction events, from the boron/uranium chamber, as function of the anode amplitude (~ fragment kinetic energy) and sum (anode+grid) amplitude (~ fragment kinetic energy and its angle of irradiation) are shown as 2-dimensional distributions for ²³⁵U(n,f) (figure 3, left) and for ¹⁰B(n,α) (figure 3, right). In figure 4 the same distributions are shown for the uranium/boron chamber. In the case of the ¹⁰B(n,α) reaction, the incident neutron momentum transfer to the reaction fragments is very well seen.

3. Conclusions
A new double twin Frisch-grid gas-flow ionization chamber was constructed for measuring the ¹⁰B(n,α) reaction channel α-particle angular distributions, cross sections and branching ratios up to 2.5-3 MeV incident neutron energy, relative to the ²³⁵U(n,f) reaction. The chamber is loaded with very thin 94% ¹⁰B samples, mounted in a back-to-back geometry with the ²³⁵U reference samples on its cathodes. It is installed at the FP16/60m of the GELINA TOF facility, where an air-conditioning
system assures the long-term stability of the electronic modules. A new data acquisition, visualization and analysis software was tested and used in the new measurements, which are still going on.

Figure 2. The scheme of the twin ionization chamber and associated electronics. The anode signal is proportional to the energy of the ionizing charged particle, the (anode+grid) signal, in addition, contains the information about the angle of irradiation.

Figure 3. Fission fragment events (anode+grid pulse-height, anode pulse-height) spectra from $^{235}$U(n,f) (left) and $^{10}$B(n,$\alpha$) (right) reactions in the boron/uranium chamber.
Figure 4. Fission fragment events (anode+grid pulse-height, anode pulse-height) spectra from $^{235}\text{U}(n,f)$ (left) and $^{10}\text{B}(n,\alpha)$ (right) reactions in the uranium/boron chamber.

Figure 5. Fission fragment events (pulse-height, TOF) spectra from $^{235}\text{U}(n,f)$ (top raw) and $^{10}\text{B}(n,\alpha)$ (bottom raw) reactions in the uranium/boron chamber.

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