Heliyon 10 (2024) e24160

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Experimental evaluation of transition rate of sapphire crystal for thermal and fast neutrons using MNSR vertical neutron beam line

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ABSTRACT

Using a perfect single crystal as a neutron filter allows us to have a thermal neutron beam with almost no background of fast neutrons. Single crystals of Al2O3 (sapphire) have proven to be effective filters for fast neutrons and are incorporated into neutron instruments. The present work would experimentally investigate c-axis neutron transmission rate by using different crystal thicknesses. In fact, the optimal thickness for sapphire filter is the one that maximizes the transmission of low energy neutrons and minimizes the transmission of fast neutrons, if there is no significant decrease in thermal neutron flux. In addition, neutron-filtering power of a-axis and c-axis sapphire crystals were compared with each other using different tests on a 2.5 cm slab of the sapphire crystals. The experimental tests were carried out by means of the available neutron flux top of the vertical neutron beam line of the Isfahan Miniature Neutron Source Reactor (MNSR) in two methods of foil activation and flux monitoring. In addition, the thermal and fast neutron dose rate reduction was discussed by using different thicknesses of the c-axis crystal.

1. Introduction

Using perfect single crystals as filters can produce beams of thermal neutrons with a relatively low background of fast neutrons. These crystals significantly reduce the background at the sample location in neutron analysis experiments. Material of filter and also its dimensions have an important role on the performance of a neutron scattering system [1].

Several materials have been proposed as the most successful neutron filters, including quartz (SiO2), bismuth, silicon, germanium, lead, and sapphire (Al_2O_3) [2]. Among the crystals mentioned, Al_2O_3 sapphire single crystals have proven to be effective filters for fast neutrons and are incorporated into many neutron instruments [1].

Sapphire is an effective filter for fast neutrons. 100 mm thickness of this crystal transmits only 3 % of neutrons at wavelengths below 0.04 nm (500 meV). Sapphire is also a good filter for thermal neutrons with wavelengths less than about 0.1 nm. One of the advantages of sapphire crystals over other neutron filters is that it can work well at room temperature [3].

Various studies have been performed regarding characteristics of sapphire crystals in neutron fields. Those interested can referrer to Refs. [4–12].

The neutron transmission spectra of various single crystal filters with Miller index (111) were measured using a DN-6 diffractometer in an IBR-2 pulse reactor. A cylindrical crystal of $5 \times 10\ cm^2$ was selected to test the transmittance. For single-crystal sapphire filters, a sharp increase in the neutron transmission curve from 53 % to 80 % is observed in the (0.8–2 Å) neutron wavelength range. In the cold neutron range (3.2 Å to 8 Å), the transmittance curve of sapphire is observed to decrease monotonically from 78 % to 58 % [7].

The MTEST diffractometer of the Budapest Research Reactor with a wavelength of 0.144 nm uses a sapphire single crystal to filter out epithermal neutrons at this facility. In addition, the thermal neutron three-axis spectrometer (TAST) of the Budapest Research

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https://doi.org/10.1016/j.heliyon.2024.e24160
Received 14 September 2023; Received in revised form 16 December 2023; Accepted 4 January 2024

Reactor uses 15 cm long sapphire single crystal in order to suppress the intensity of fast neutrons [8].

Because of the wide application of such crystals in radial channels of the research reactors, the present work has been carried out based on 001 and 1120 sapphire crystal transmission tests using the vertical channel of Isfahan Miniature Neutron Source Reactor (MNSR).

2. Material and methods

The Isfahan Miniature Neutron Source Reactor (MNSR) is a tank-in-pool low temperature reactor. It is a small, safe nuclear facility whose core design includes highly enriched uranium (90.2 % U235) as fuel, light water as moderator, coolant and biological shielding. Its reflector Contains metal beryllium. It is primarily designed for use in universities, hospitals, and research institutes for neutron activation analysis, production of short-lived radioisotopes, and education and training. There are five interior and five exterior illumination locations in and around the annular beryllium reflector. MNSR uses only one control rod for reactivity control and reactor shutdown under normal and accident conditions. The core, which is cooled by natural convection, is located inside and near the bottom of a cylindrical water-filled vessel that floats in a large pool of water [14].

The main characteristics of the MNSR are shown in Table 1 and the cross-sectional view of the reactor is shown in Fig. 1. The reactor is equipped with multiple vertical beamlines for performing tests such as neutron radiography and PGNA [13–18].

To determine the crystal transmutation rate for thermal and fast neutrons, 7.5 cm of c-axis sapphire crystal with 16 cm diameter was placed top of the vertical beam line of MNSR and 2 bare indium and cadmium-covered indium foils were located on its surface. The crystal was irradiated for 2.5 h at a thermal neutron flux of 5×10^5 n/s.cm^2 (Fig. 2). In addition, to compare the transmission rates of a-axis and c-axis crystals two 2.5 cm thick sapphire crystals were irradiated top of the vertical beam line for 0.5 h respectively while the mentioned foils were located on their surface to monitor the thermal and fast neutron transmission rate by the crystals via foil activation method.

At next step, a BF3 detector was used to monitor the received neutron flux by using different thicknesses of the sapphire crystal (2.5, 5, and 7.5 cm). The setup is represented in Fig. 3.

NM2 neutron dosimeter was used to determine total neutron dose rate reduction by using different thicknesses of the sapphire crystal (2.5, 5 and 7.5 cm) top of the vertical beam line of MNSR reactor according to Fig. 4.

Moreover, the dosimeter was used to determine fast neutron dose rate reduction by using different thicknesses of the sapphire crystal (2.5, 5 and 7.5 cm) top of the vertical beam line of MNSR reactor when a 0.5 mm cadmium sheet was used to remove the thermal region of the neutron spectra according to Fig. 5.

3. Result and discussion

Foil activation measurements showed that about 60 % of fast neutrons were filtered using c-axis (001) sapphire crystal with 7.5 cm thickness while about 37 % of the thermal neutrons ($E_n < 0.5$ eV; cadmium cut off) were removed also. A comparison between c-axis (001) and a-axis (1120) crystal with 2.5 cm thickness (Ø16cm) showed that the a-axis filtering power is better for fast neutrons with about 12 % higher value, moreover transmission of thermal neutrons is better too with about 5 % superiority (Table 2).

The c-axis transmission tests using BF3 detector (which its data could be referred to thermal neutrons) showed that about 41 % of thermal neutrons were filtered by the sapphire crystal with 7.5 cm thickness (Fig. 6). It should be taken in attention the obtained data by BF3 counter is in good agreement with the foil activation tests.

Thermal neutron transmission was also investigated in two other cases using BF3 detector. The case where 7.5 cm (2.5 cm a-axis and then 5 cm c-axis) were irradiated in MNSR vertical beam and the other case was vice versa; i. e 7.5 cm (5 cm c-axis and then 2.5 cm a-axis) were irradiated. The results showed that in the first case, 41.5 % of thermal neutrons were filtered while in second case 43 % of thermal neutrons were removed. These results show that this combination is not much different from the case where we placed 7.5 cm of c-axis which 41 % of thermal neutrons were filtered.

At another step, the crystal filtering power on neutron dose rate was investigated. The obtained results showed that the total neutron dose rate falls down to 1/4th using 7.5 cm c-axis sapphire crystal (Fig. 7).

A 0.5 mm thick cadmium sheet was used between the beam outlet and the crystal to remove thermal neutrons rising from the vertical beam line of MNSR. The c-axis crystal neutron dose rate resulted from fast neutrons were measured by means of different

Table 1
Main specifications of Isfahan MNSR.

Parameters	Description
Reactor type	Tank-in-pool
Nominal power	30 kW
Fuel	UAl_4 dispersed in Al
U-235 enrichment	90.2 %
Fuel density (g/cm^3)	3.456
Number of fuel elements	343
Core diameter	23 cm
Core height	23 cm
Moderator and coolant	Light water

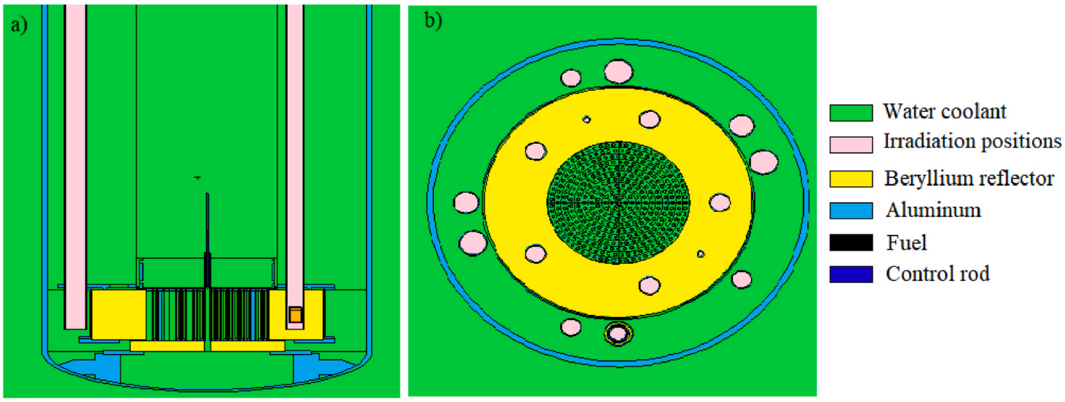

Fig. 1. xz view of the Isfahan MNSR.

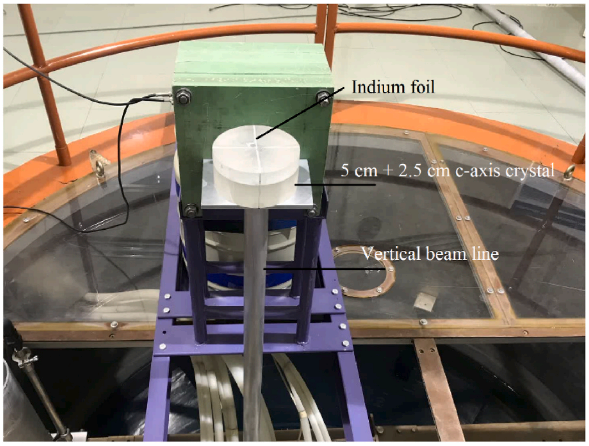

Fig. 2. Setup of indium foil activation experiment to measure fast and thermal neutron transmission rate through 7.5 cm c-axis sapphire crystal.

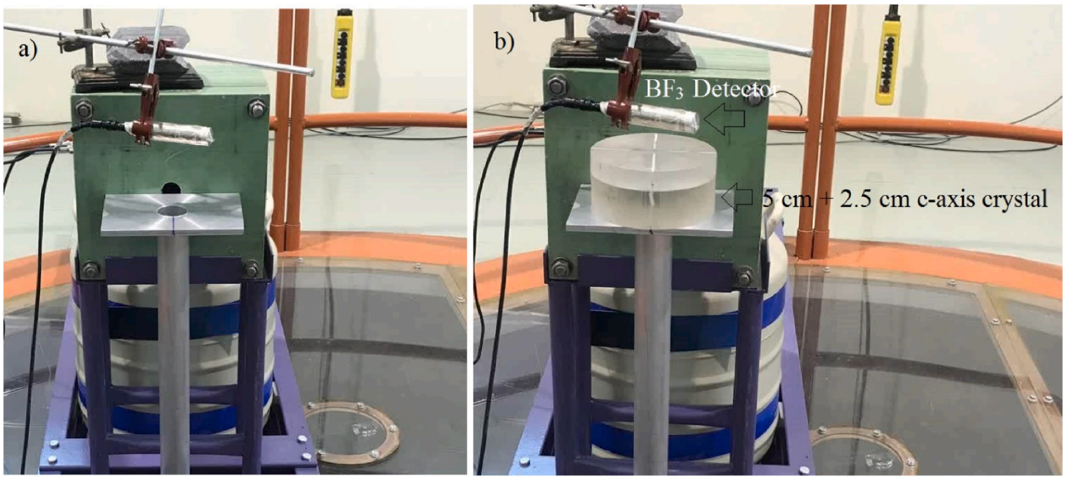

Fig. 3. Setup of BF3 experiment to measure neutron transmission rate a) background b) trough 7.5 cm c-axis sapphire crystal.

thicknesses of the crystal positioned on the cadmium sheet. The obtained results showed 7.5 cm c-axis crystal could effectively reduce the fast neutron dose rate up to 7.5 times (Fig. 8).

Another step that was irradiation of 7.5 cm) 2.5 cm of a-axis and then 5 cm of c-axis (of sapphire crystal in front of the vertical beam

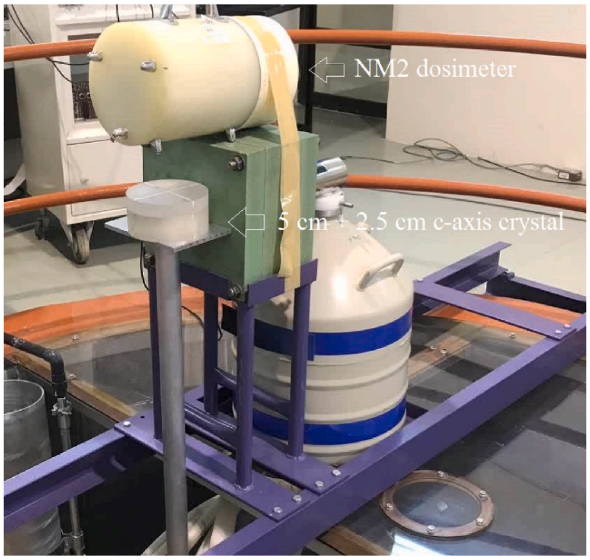

Fig. 4. Setup of NM2 experiment to measure neutron dose rate through 7.5 cm c-axis sapphire crystal.

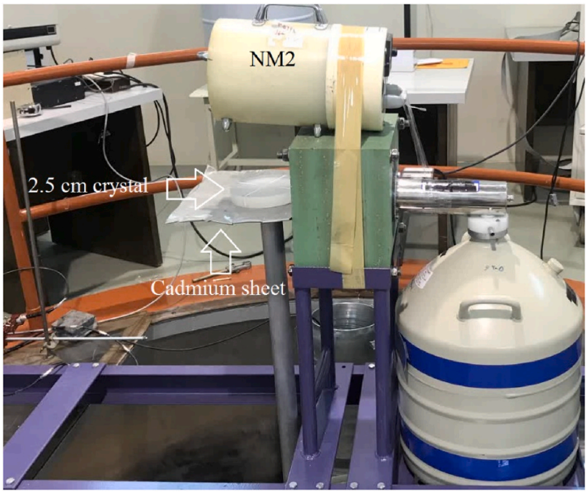

Fig. 5. Setup of NM2 experiment to measure fast neutron dose rate trough 7.5 cm c-axis sapphire crystal by placing 0.5 mm cadmium thermal neutron filter.

Table 2
Sapphire crystal transmission tests for thermal and fast neutrons using Isfahan MNSR neutron beam line.

Number	Test arrangement	Foil activity without cadmium cover (Bq)	Foil activity with cadmium cover (Bq)	Cadmium ratio	Thermal neutron attenuation (%)	Fast neutron attenuation (%)
1	c-axis, 7.5 cm	3478.72	235.10	13.96	36.42	59.36
2	a-axis, 2.5 cm	4073.53	368.34	10.40	17.04	38.90
3	c-axis, 2.5 cm	3872.43	435.96	8.35	23.19	27.68
4	Original beam	5079.29	578.50	7.92		

to investigate the transmission tests using BF3 detector.

A comparison between our experimental data and the simulated ones by Zahar et al. (2016) shows the theoretical transmission is 1/4th the measured data in the present work for sapphire crystal with 7.5 cm thickness (Fig. 9) [11] It should be mentioned that in this work neutrons above 0.5 eV have been considered as fast neutrons.

The difference between our experimental data and Zahar et al. (2016) can be due to neutron beam and also crystal simulation condition. Usually in simulations a perfect crystal is considered while in fact some factors such as its real mosaic factor effects on the

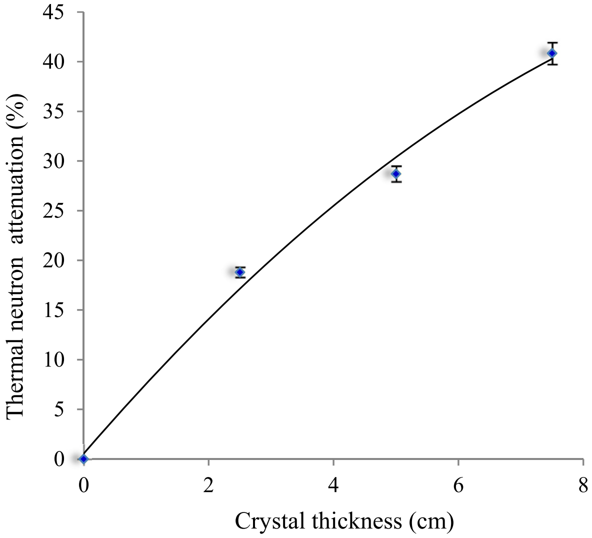

Fig. 6. Thermal neutron attenuation measured by BF3 detector using different thicknesses of c-axis sapphire crystal.

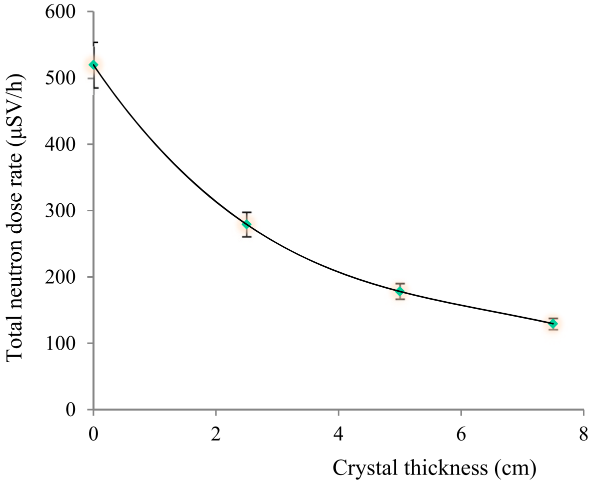

Fig. 7. Total neutron dose rate measured by NM2 detector using different thicknesses of c-axis sapphire crystal.

crystal operation.

Emanoella et al. (2013) conducted several experiments at BOA test beamline at PSI. A total of 12 c-axis crystals were used, all with the same dimensions 26 mm × 26 mm × 10 mm; The 10 mm edge is parallel to the beam direction. Crystals were provided from three different providers. They measured dependencies of fast neutrons (>∼0.1eV) and cold neutrons (∼1-10 Å) into the thickness of the crystal. They also tested performance differences, including inherent contaminants (quality control) of these 3 types of sapphire crystals. Their experimental results showed 7 cm sapphire crystal could filter the fast neutrons approximately 71 % according to Fig. 10.

Adib et al. (2004) has theoretically studied a-axis sapphire crystals and found that a sapphire crystal with a thickness of 7.5 cm can filter out neutrons with energies above 1 eV (Transmittance <8 %) whereas ensuring high transmittance (more than 85 %) for neutron energies below 0.02 eV. The variation due to Bragg reflection is less than 5 % around the examined crystal [4].

4. Conclusion

Neutron transmission measurement at different thickness of the c-axis (001) sapphire crystal (2.5, 5 and 7.5 cm) have been performed in order to determine the c-axis sapphire crystal filter efficiency against fast neutrons (En > 0.5 eV). Measurements showed 2.5 and 7.5 cm c-axis sapphire crystal filters about, 28 % and 60 % of fast neutrons respectively and 2.5 cm a-axis sapphire crystal also filters about 39 % of fast neutrons. It was also observed that about 37 % of the thermal neutrons (En < 0.5 eV; cadmium cut off) were removed with 7.5 cm thickness of c-axis sapphire.

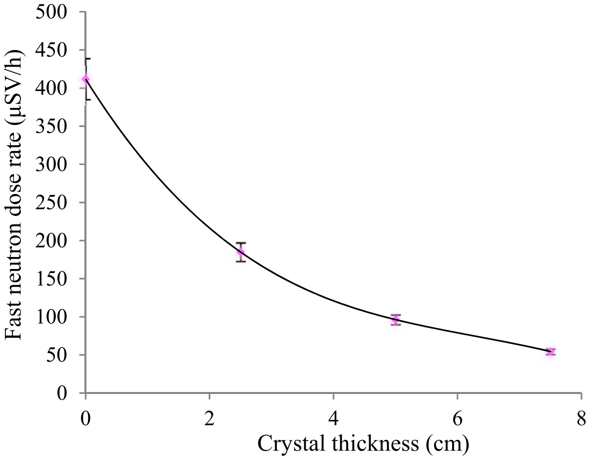

Fig. 8. Fast neutron dose rate measured by NM2 detector rate using different thicknesses of c-axis sapphire crystal.

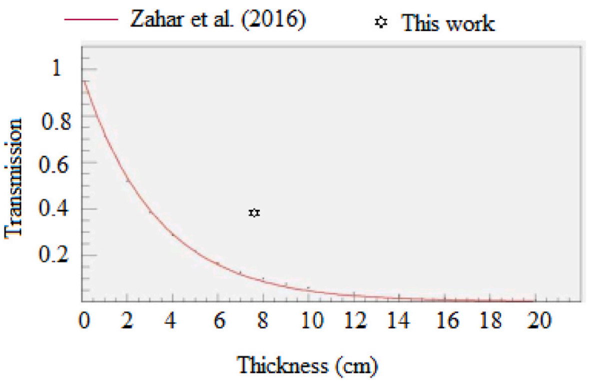

Fig. 9. Fast neutron transmission on the different thicknesses of c-axis sapphire crystal [11].

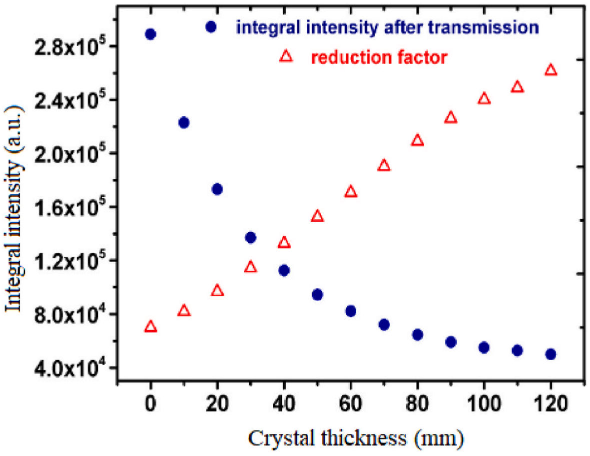

Fig. 10. Integral intensity and fast neutron reduction factor versus sapphire crystals' thickness [19].

Dose rate measurements also showed total neutron dose rate falls down to a quarter of its former value using 7.5 cm c-axis sapphire crystal.

In addition, there was a comparison between c-axis (001) and a-axis (1120) sapphire crystal with 2.5 cm thickness (Ø16cm) that showed the a-axis filtering power is better for fast neutrons with about 12 % higher value, moreover transmission of thermal neutrons is better too with about 5 %. In future activities, the neutron attenuation in these crystals will be simulated and calculated with neutron optical codes and will be compared with the experimental results.

Data availability statement

No data was used for the research described in the article.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Z. Gholazadeh: Writing – original draft, Methodology, Data curation, conceptualaization. **E. Bavarnegin:** Writing, review and editing, Methodology, Data curation, conceptualaization. **R. Ebrahimzadeh:** Writing – review & editing, Data curation. **J. Mokhtari:** Setting up the test setup, Data curation. **M. Jafari:** Setting up the test setup, Data curation. **M.H. Choopan Dastjerdi:**Setting up the test setup, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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