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MEASUREMENTS OF CROSS SECTIONS FOR HIGH-ENERGY NEUTRON-INDUCED REACTIONS ON Co AND Bi

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Ндлову Н. и др. Е3-2020-36
Измерение сечений реакций, индуцированных нейтронами высоких энергий, на кобальте и висмуте

Существует не много экспериментальных данных для библиотек нейтронных сечений реакций (n, xn) на различных материалах для энергий выше 20 МэВ. Для высоких энергий (выше 20 МэВ) этот набор (n, xn) реакций важен для мониторинга флюенса нейтронов и развертывания спектров ядерных реакторов будущего IV поколения. Были попытки измерить поперечные сечения природного кобальта и висмута при энергии падения нейтронов до 90 и 140 МэВ. Эти измерения были выполнены с использованием квазимоноэнергетической нейтронной установки в iThemba LABS (ЮАР). Кроме того, аналогичные эксперименты с использованием нейтронов высокой энергии были выполнены с природным иттрием в Лаборатории Сведберга в Швеции. Измеренные сечения сравниваются с некоторыми доступными данными о сечениях нейтронно-индуцированных реакций при высоких энергиях. Данные, полученные в обеих лабораториях, потребовали внесения поправок на вклад низкоэнергетического хвоста (континуума) в спектр падающих нейтронов в этих измерениях.

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Ndlovu N. et al. E3-2020-36
Measurements of Cross Sections for High-Energy Neutron-Induced Reactions on Co and Bi

There are few experimental data for neutron cross-section libraries for (n, xn) reactions in various materials for energies above 20 MeV. For high energies (above 20 MeV), these sets of (n, xn) reactions are important for neutron fluence monitoring and spectra unfolding for future generation IV nuclear reactors. There were attempts to measure the cross sections on natural cobalt and bismuth at incident neutron energies of about 90 and 140 MeV. These measurements were made using the quasi-monoenergetic neutron facility at iThemba LABS, South Africa. In addition, using high energy neutrons at the Svedberg Laboratory in Sweden, similar experiments were performed on natural yttrium. The measured cross sections are compared with some of the few available cross-section measurements for neutron-induced reactions at high energies. The data obtained using facilities at both labs required corrections to be made for the contribution of the low-energy tail (continuum) in the incident neutron spectrum in these measurements.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

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1. INTRODUCTION AND MOTIVATION

Measurements of cross sections for the $(n, 3-6n)$ reactions of various target materials using quasi-monoenergetic neutron beams of 40 to 200 MeV at iThemba LABS (iTL) are ongoing. This campaign was initiated as a part of the IRDFF (International Reactor Dosimetry and Fusion File) library which consists of more than 70 reactions that are important for reactor dosimetry, fusion and fission studies. For example, the IRDF-2002 file that is available has experimental data for these dosimetry reactions which are insufficient, particularly at higher neutron energies, above the 20 MeV threshold [1]. In addition, the few existing data have large uncertainties (30–50%) and there is disagreement between model predictions at energies above 20 MeV [1].

Figures 1 and 2 show, respectively, some of the available cross-section data for the ^{59}Co$(n, 3n)^{57}$Co and ^{209}Bi$(n, 3n)^{207}$Bi reactions at neutron energies above 20 MeV. Experimental data for the ^{59}Co$(n, 3n)^{57}$Co reaction in Fig. 1 are based on experimental data collected in the 1970s [2], then again in the late 1990s [3, 4], followed by the more recent data [5]. Experimental data from Yashima (2017) are still to be verified by the IAEA-INDC(NDS) [6]. In Fig. 1, both experimental and evaluated data agree in shape but not in absolute values. Similar observations exist in Fig. 2 for the ^{209}Bi$(n, 3n)^{207}$Bi reaction, moreover with no experimental data above 40 MeV in this reaction.

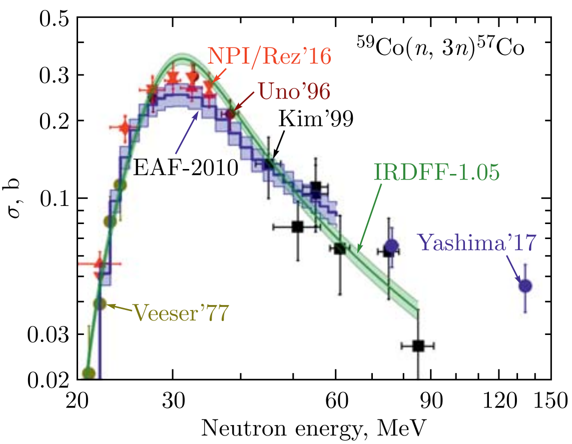

Fig. 1. Compilation of experimental data and calculated neutron production cross section of ^{59}Co$(n, 3n)^{57}$Co reaction in the energy range from 20 to 150 MeV [6]

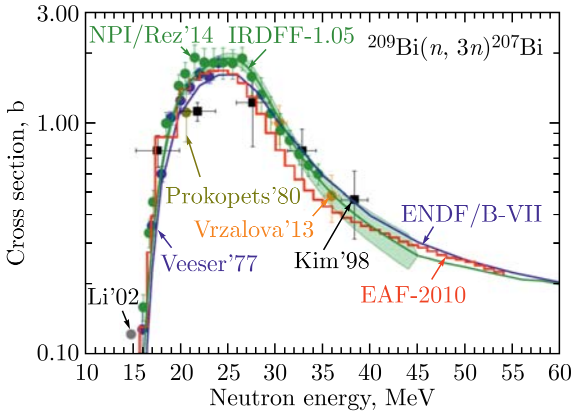

Fig. 2. Compilation of experimental data and calculated neutron production cross section of $^{209}Bi(n, 3n)^{207}Bi$ reaction in the energy range from 15 to 100 MeV [7]

At iThemba LABS, quasi-monoenergetic neutron beams are typically produced in the D-line experimental vault (see Fig. 3) via the $^{7}Li(p, n)^{7}Be$ or $^{10}Be(p, n)^{10}B$ reactions. Collimated fan beams are possible at various neutron emission angles, including 0° and 16°. The peak is made up of neutrons emitted at 0° from the $^{7}Li(p, n)^{7}Be$ reaction going to the ground and first excited states of ^{7}Be [8, 9]. The continuum is made up of neutrons from the breakup of ^{7}Li, which is mainly isotropic up to an angle of 16°. Possible neutron flight paths extend from about 4 to about 10 m. These neutron beams at iTL have been well characterized [9] in recent experiments (see, for example, [10]) and methods for the accurate measurement of the spectral fluence have been developed [11]. Subtracting the yield produced in the 16°

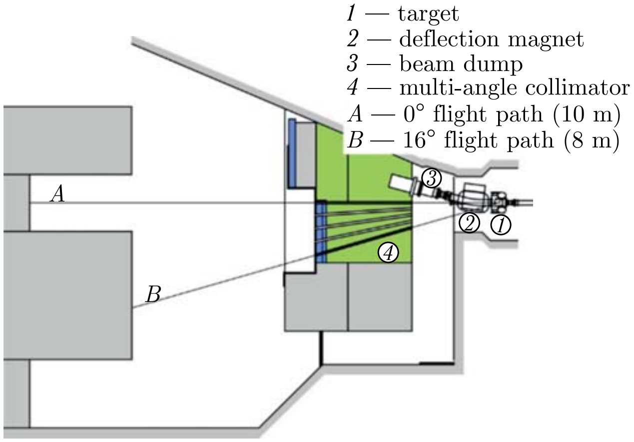

Fig. 3. Schematic view of the iThemba LABS neutron beam facility (drawn not to scale)

beam (after appropriate normalization) from that simultaneously produced at 0°, results in a yield determined for quasi-monoenergetic neutron energy, refer also to [10] for more details.

The Svedberg laboratory (TSL) facility was a part of Uppsala University, Sweden. The Svedberg Cyclotron produced neutron beam with energy up to 200 MeV. The quasi-monoenergetic neutron (QMN) facility is located in the underground hall (Blue Hall) [12] (Fig. 4). Neutrons were produced over there, by the accelerated proton beam, going through a 4 or 23.5 mm thick ^{7}Li target. The neutrons, after passing the magnet area and the tubes vacuum system, in state of a pure quasi-monochromatic neutron beam arrived to foils/targets area located at the distance of 198 cm from the ^{7}Li target, called Close User Position (CUP) [13] (Fig. 5). In CUP location, the beam intensity was much higher than in the standard user area after the collimator. The TSL

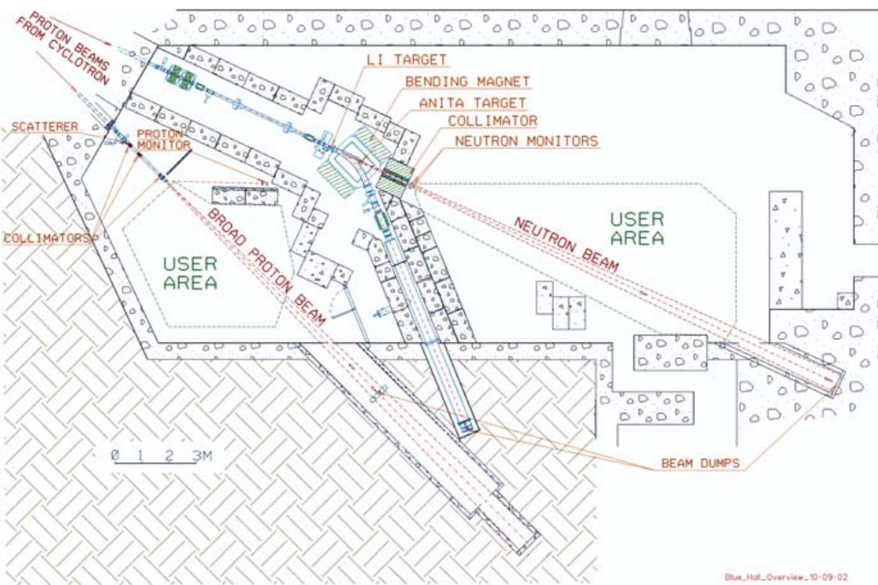

Fig. 4. The Blue Hall scheme. The CUP position is between the magnet and collimator

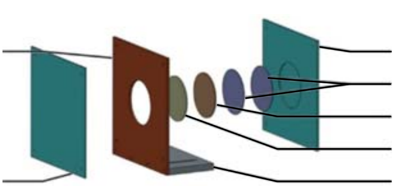

Fig. 5. Target stack arrangement for iTL irradiation

facility with QMN was closed and cross-section measurement experiments are impossible to continue in this laboratory.

2. EXPERIMENTAL MEASUREMENTS

In 2014, two experiments were performed at the iTL facility using the two-peak neutron energies, ~ 90 and 140 MeV. Neutrons were produced by a proton beam accelerated from the cyclotron to interact with a 8-mm-thick ^{7}Li target. The proton beam is deflected by magnets into the beam dump after passing the target. Two identical target stacks that included amongst others cobalt and bismuth were irradiated simultaneously for each neutron energy measurement, one placed in the 0° beam line and the other in the 16° beamline (see Figs. 3 and 5). Both irradiation positions were located at a distance of about 5 m from the neutron production Li target. In addition, Al and Cu targets are added as monitors. Laser beams were used to align the centre of the target with the neutron beam line. All target materials were supplied by GoodFellow Corp. with the following specifications, 99.9% pure and disc shapes with 25 mm in diameter and 0.5 mm thickness.

The activated samples were thereafter counted using a low-background setup of gamma-ray detector, hyper-pure germanium (HPGe) (p type, 45% relative efficiency, 2 keV FWHM resolution at 1.33 MeV). The pulses from the amplifier are collected and sorted by the ATOMKI Palmtop software multichannel analyzer.

In 2015, four experiments were performed at the quasi-monoenergetic neutron facility [12] at TSL. The ^{89}Y foils were located at CUP before metallic collimator (Fig. 6, left) on the paperboard which was driven down on special lift (Fig. 6, right). The distance from the ^{7}Li target was 198 cm. The ^{89}Y foils were irradiated by four neutron peak energies — 35.5, 47.5, 60.5 and 92.5 MeV (see the table for description of two of the energies). The description of calibration and calculation procedure as well as the cross-section preliminary results for two energies were shown in [14] (see the table). Results from the

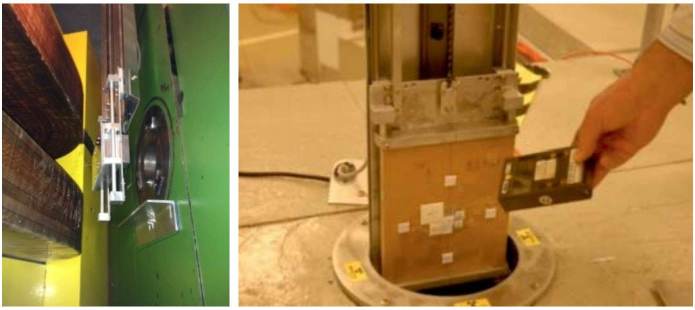

Fig. 6. Left: the lift on CUP position between magnet and collimator; right: the samples/foils on the paperboard on the upper lift position (outside the bunker)

Beam and calculation parameters

Proton energy	38 MeV	50 MeV
Neutron energy peak (calc.)	35.5 MeV	47.5 MeV
Fraction of neutrons in the peak (calc.)	21.6%	25.7%
$^{89}\mathrm{Y}(n, 2n)^{88}\mathrm{Y}$	103 (31) mb	95 (28) mb
$^{89}\mathrm{Y}(n, 3n)^{87}\mathrm{Y}$	319 (64) mb	198 (40) mb
$^{89}\mathrm{Y}(n, 4n)^{86}\mathrm{Y}$	338 (68) mb	132 (26) mb

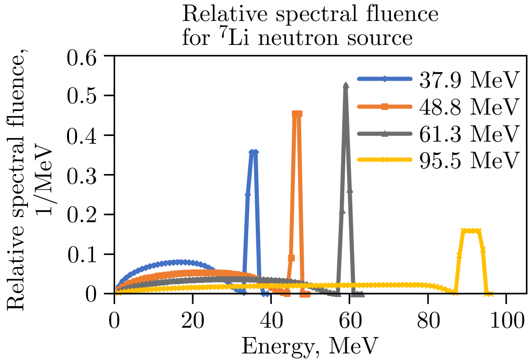

Fig. 7. Relative spectral fluence of quasi-monochromatic neutrons with peak energies of 37.9, 48.8, 61.3, and 95.5 MeV at 0° angle, calculated according to the algorithm from [15] and normalized so that the peak area is unity

four experiments need to be reexamined in order to better identify the number of protons and value of background correction factor (BCF).

The QMN facility provides neutron beams with spectra comprising the high-energy peak and the low-energy tail (Fig. 7), with approximately equal fractions in the neutron spectrum. This feature of the neutron beams necessitates the second step in the data processing, namely, the determination of the background correction factor. BCF is defined as the ratio between the numbers of nuclei produced by the high-energy peak and by the whole neutron spectrum (high-energy peak plus low-energy tail) [14].

3. CROSS-SECTION RESULTS AND CONCLUSION

In this paper, we present the status of analysis of the two target materials, cobalt and bismuth, irradiated at the iTL facility. These preliminary results show the discrepancy which we suspect was a result of proton beam instability during the irradiations.

The neutron spectra are shown in Fig. 8, for the first experimental runs at (90.0 ± 3.6) MeV and the follow-up runs at (140.5 ± 6.0) MeV. These data show some stability for the first runs, however the continuum in the follow-up experiments shows some inconsistency with what was expected.

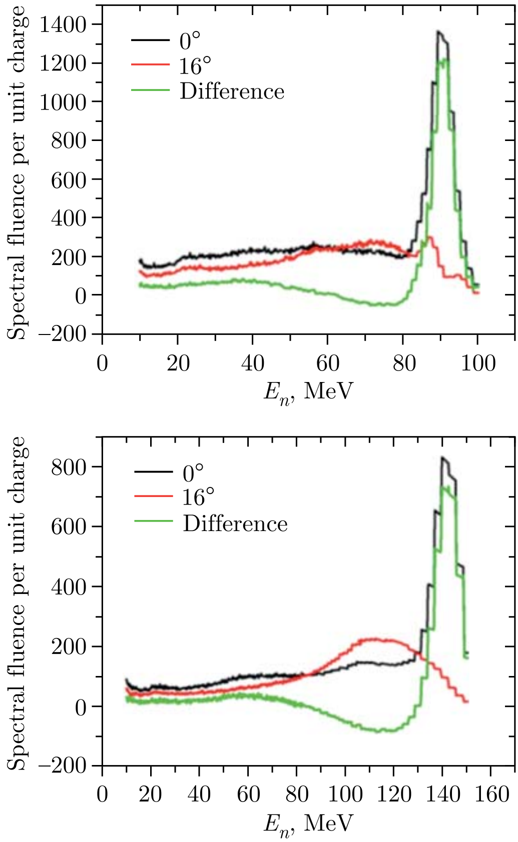

Fig. 8. Spectral fluence of quasi-monoenergetic neutrons with peak energies of 90 MeV (top) and 140 MeV (bottom) at 0°, 16° angle and the normalized one using the difference method

In order to finalize the calculations for the cross section, corrections are required to be made for the contribution of the low-energy tail in the incident neutron spectrum. In the previous study [10], with experimental data collected using the iTL facility, it was estimated as about 7% contribution for the determination of the neutron fluences. With the observation in Fig. 8, for these experiments we predict this contribution to be much higher than 20% for the (90.0 ± 3.6) MeV and far worse for the (140.5 ± 6.0) MeV neutron energy. The total uncertainty budget in these cross-section measurements will result from individual contributions, peak fluence determination, peak to continuum ratio, fluence monitor, HPGe detection efficiency and the counting statistics.

Gamma-ray spectra analysis is still ongoing to determine whether the information could be used to calculate the cross section despite the neutron spectra discrepancies. In conclusion, new irradiation initiatives are planned for the coming year and the approach is to include more neutron energies, from 35 up to 197 MeV.

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REFERENCES

1. *Zolotarev K. I.* IAEA, INDC(NDS)-0584 Rep., 2010.
2. *Veeser L. R. et al.* // Phys. Rev. C. 1977. V. 16. P. 1792–1802.
3. *Kim E. J. et al.* // J. Nucl. Sci. Technol. 1999. V. 36. P. 29.
4. *Uno Y. et al.* // Nucl. Sci. Eng. 1996. V. 122. P. 247–257.
5. *Majerle M. et al.* IAEA, INDC(CZR)-0002 Rep., 2016.
6. IAEA-NDS-Co: https://www-nds.iaea.org/IRDFFtest/Co(n,xn).pdf.
7. IAEA-NDS-Bi: https://www-nds.iaea.org/IRDFFtest/Bi(n,xn).pdf.
8. *Iwamoto Y. et al.* // Nucl. Instrum. Meth. Phys. Res. A. 2015. V. 804. P. 50–58.
9. *Nolte R. et al.* // Nucl. Instrum. Meth. Phys. Res. A. 2002. V. 476. P. 369–373.
10. *Sisterson J. M. et al.* // Nucl. Instrum. Meth. Phys. Res. B. 2005. V. 240. P. 617–624.
11. *Mosconi M. et al.* // Radiat. Meas. 2010. V. 45. P. 1342–1345.
12. *Prokofiev A. V. et al.* // Radiat. Prot. Dosim. 2007. V. 126. P. 18–22.
13. *Prokofiev A. V. et al.* // IEEE Trans. Nucl. Sci. 2014. V. 61. P. 1929–1936.
14. *Bielewicz M. et al.* // Eur. Phys. J. Web Conf. 2017. V. 146. P. 11032.
15. *Prokofiev A. V. et al.* // J. Nucl. Sci. Technol. Suppl. 2. 2002. V. 1. P. 112–115.

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