Measurement of $^{232}$Th($n, \gamma$) and $^{232}$Th($n, 2n$) cross-sections at neutron energies of 13.5, 15.5 and 17.28 MeV using neutron activation techniques

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Abstract. The $^{232}$Th($n, \gamma$) reaction cross-section at average neutron energies of 13.5, 15.5 and 17.28 MeV from the $^7$Li($p, n$) reaction has been determined for the first time using activation and off-line $\gamma$-ray spectrometric technique. The $^{232}$Th($n, 2n$) cross-section at 17.28 MeV neutron energy has also been determined using the same technique. The experimentally determined $^{232}$Th($n, \gamma$) and $^{232}$Th($n, 2n$) reaction cross-sections from the present work were compared with the evaluated data of ENDF/BVII and JENDL-4.0 and were found to be in good agreement. The present data, along with literature data in a wide range of neutron energies, were interpreted in terms of competition between $^{232}$Th($n, \gamma$), ($n, f$), ($n, nf$) and ($n, xn$) reaction channels. The $^{232}$Th($n, \gamma$) and $^{232}$Th($n, 2n$) reaction cross-sections were also calculated theoretically using the TALYS 1.2 computer code and were found to be in good agreement with the experimental data from the present work but were slightly higher than the literature data at lower neutron energies.

Keywords. $^{232}$Th($n, \gamma$) and $^{232}$Th($n, 2n$) reaction cross-sections; off-line $\gamma$-ray spectrometric technique; $E_n = 13.5$, 15.5 and 17.28 MeV; $^7$Li($p, n$) reaction.

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1. Introduction

Presently, advanced heavy water reactors (AHWR) [1,2] and fast reactors [3–6] are of interest for power production. Recently, accelerator-driven sub-critical systems (ADS) [7–12] are also of primary interest from the point of transmutation of long-lived fission products (\(^{93}Zr, ^{99}Tc, ^{107}Pd, ^{129}I\) and \(^{135}Cs\)), and incineration of long-lived minor actinides (\(^{237}Np, ^{240}Pu, ^{241}Am, ^{243}Am\) and \(^{244}Cm\)) to solve the problem of radioactive wastes. In AHWR, \(^{232}Th–^{233}U\) is the primary fuel for power generation. However, \(^{232}Th–^{233}U\) fuel in combination with ADS is another method for power generation besides for transmutation of long-lived fission products and incineration of long-lived minor actinides. The advantage of \(^{232}Th–^{233}U\) fuel in AHWR [1,2] and ADS [7–12] over the present reactors based on uranium fuel is that it produces thousand times less radiotoxic wastes. Studies have shown that thorium-based fuels in fast spectrum systems can efficiently perform the task of reducing reactor-grade and weapons-grade plutonium stockpile [13] while maintaining acceptable safety and control characteristics of the reactor system. Besides these, thorium in the Earth’s crust is three to four times more abundant than uranium and thus can help to greatly extend the nuclear fuel resources. It is a fact that \(^{232}Th\) is the only nucleus present in nature which can give rise to an excess of fissile material \(^{233}U\) in the presence of either thermal or fast neutrons, thus making it an excellent choice for nuclear reactors of the future. Furthermore, thorium-based fuel is an attractive option because no trans-uranics are produced compared to uranium-based fuels. This reduces the cost of fuel cycle.

In the thorium–uranium fuel cycle, the fissile nucleus \(^{233}U\) is generated by \(^{232}Th(n, \gamma)–^{233}Th\) reaction followed by two successive \(\beta\)-decays. The \(^{232}Th(n, 2n)^{231}Th\) reaction cross-section rapidly increases above a threshold energy of 6.648 MeV. A schematic diagram of the Th–U fuel cycle is given below:

\[
^{232}\text{Th} (n, \gamma) \rightarrow ^{233}\text{Th} \rightarrow ^{233}\text{Pa} \rightarrow ^{233}\text{U} \\
\downarrow (n, 2n) \quad 1.405 \times 10^{10} \text{y} \quad 22.3 \text{m} \quad 26.97 \text{d} \quad 1.52 \times 10^{5} \text{y} \\
^{231}\text{Th} \rightarrow ^{231}\text{Pa} (n, \gamma) \rightarrow ^{232}\text{Pa} \rightarrow ^{232}\text{U} \\
25.32 \text{h} \quad 52760 \text{y} \quad 1.31 \text{d} \quad 68.7 \text{y}
\]

Thus, the production of the fissile nucleus \(^{233}U\) depends on the \(^{232}Th(n, \gamma)\) reaction cross-section, which is required with an accuracy of 1–2% for predicting the dynamical behaviour of complex arrangements in fast reactors or ADS [14,15]. In fusion–fission hybrid systems, a sensitivity study has shown that the production rate of \(^{233}U\) can be predicted within 1%, provided the \(^{232}Th(n, \gamma)\) cross-section is known within 2% [16,17]. Thus, the neutron interactions and fission cross-sections for \(^{232}Th\) and \(^{233}U\) in the low neutron energy are important for AHWR [1,2], whereas the neutron interactions and fission cross-sections in the higher energy range are important for ADS [7–12] because they dominate the neutron transport and neutron regeneration. Thus, the \(^{232}Th(n, \gamma)\) reaction cross-section at higher neutron energy has a strong impact on the performance and safety assessment for ADS [18]. In ADS a 10% change in the \(^{232}Th\) neutron capture cross-section gives rise to a 30% change in the needed proton current of the accelerator if the