

Original Article



Nuclear Behaviour of Neutron-Induced Thorium (^{232}Th) at 20 MeV Using OPTMAN Code

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ABSTRACT

In this study, the neutron-induced fissile isotopes of Thorium-232 using the Coupled-Channel Optical Model code (OPTMAN) code up to 20 MeV. The high demand for nuclear reactor fuels has necessitated this research. As one of the major naturally occurring radionuclides with lots of fuel prospect, Thorium-232 occur in 99.98%. Some steps process away from Thorium-232 on neutron capture can produce fissile materials to be used as reactor fuel. Computations were done for both the Potential Expanded by Derivatives (PED) which account for the Rigid-Rotor Model (RRM) that treat nuclei as rigid vibrating sphere as well as account for nuclear volume conservation and Rotational Model Potentials (RMP) which account for the Soft-Rotator Model (SRM) that treat nuclei as soft rotating spherical deformed shapes. Each of the calculated data was compared with the retrieved data from Evaluated Nuclear Data File (ENDF) which was found to be in good agreement. The threshold energies in all cases were found to be ≤ 4 MeV for both PED (Potential Expanded by Derivatives) and RMP (Rotational Model Potentials). It is observed that results from RMP much better agreed with the retrieved data than one obtained from PED.

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Introduction

The needs for Fissile isotopes of uranium are due to their practical applications. These isotopes or materials can be used as fuel in nuclear reactors of both power plants and research reactors, as they can be split by neutrons in a self-sustaining nuclear chain reaction. The amount of energy released during these reactions is large enough to generate electricity. Aside from being used as nuclear reactor fuels, fissile materials can undergo fission reaction processes. They are the key components of nuclear weapons or other nuclear explosives devices. Those mostly used in nuclear weapons are highly enriched uranium (uranium-235 and plutonium-239). However, this research is for nuclear research reactor application. As such, we shall focus on nuclear reactor fuels [1]. It is pertinent to search for alternative fuel means in some isotopes that are radioactive aside the uranium-235 and plutonium-239. We may recall that the two most important fissile materials normally used as fuels are uranium-235 and Plutonium-239. These are weapon-grade materials that can also be used as reactor fuels. Uranium 235 is a natural isotope of uranium with an abundance of 0.72%. This concentration is very small. Nuclear physicists have made efforts to increase this concentration through the enrichment process. However, due to the prevalent need for reactor fuels, we ought to seek alternative isotopes that can be used as fuels [2].

The fissile materials Plutonium-239 and uranium-233, which do not occur in nature, are produced by the transmutation of uranium-238 and thorium-232, respectively. These materials are called fertile materials. For fuel cycles using plutonium-239 and uranium-233 as fuel, irradiation of uranium-238 and thorium-232 in the fuel blanket and reprocessing to extract the plutonium-239 and uranium-233 become important steps in the cycle [3]. Plutonium-239 is not a natural isotope of plutonium. It is bred from the naturally occurring uranium-238 whose natural abundance is 99.9%. Uranium-238 is irradiated by fast neutrons to produce Uranium-239 and this Uranium-239 can

undergo a radioactive decay to produce Plutonium-239. Plutonium-239 just like Uranium-235 is a fissile material. The Plutonium-239 can then be bombarded with high-speed neutrons. When a Plutonium nucleus absorbs one such free neutron, it splits into two fission fragments. This fission releases heat as well as neutrons, which in turn splits other plutonium nuclei present, freeing still more neutrons. As this process is repeated, it becomes a self-sustaining chain reaction, yielding a steady source of energy, chiefly in the form of heat which is transported from the reactor core by a liquid sodium coolant to a system of heat exchange. This system utilizes heat to produce steam for a turbine that drives an electric generator [4-5].

Uranium-233 is a fissile isotope of uranium that is bred from thorium-232 as part of the thorium fuel cycle. Uranium-233 was investigated for use in nuclear weapons and as reactor fuel. It has been successfully used or tested in experimental nuclear reactors and has been proposed for much more or wider use as nuclear fuel. It has a half-life of 160,000 years [3]. Uranium-233 is produced by neutron irradiation of thorium-232. When thorium-232 absorbs a fast neutron, it becomes thorium-233 with a half-life of 22 minutes. After 22 minutes, thorium-233 decay by beta to protactinium 233 with a half-life of 27 days, and beta decays to uranium 233. Just like uranium-235 and plutonium 239, uranium-233 has also been proposed to be used as nuclear fuel as asserted above. The only challenge with uranium-233 is that its fission occurs on neutron capturing, but, sometimes retains the neutron to become uranium-234 which is a fertile material [6]. Therefore, uranium-235 being naturally occurring isotope, is a breeder fissile material [7].

A research was conducted by Avrigeanu and Avrigeanu (2019) [8] on the analysis of neutron bound states of ^{208}Pb by a dispersive optical model potential, in their research, they discussed the effect of dispersive-correction terms on the calculation of the bound-state energies and finally reported that, the derived ^{208}Pb root mean square radius shows good

agreement with measured data. Another research was carried out by Avrigeanu and Avrigeanu *et al.* (2021) [9] on the dispersive optical model description of nucleon scattering on Pb–Bi isotopes and reported that the new potential is shown to give a very good description of nucleon scattering data on near-magic targets $^{206,207}\text{Pb}$ and ^{209}Bi .

This work investigates the effects of excitation in neutron induced fissile isotopes of uranium for 20 MeV using Coupled-Channels Optical Model OPTMAN code with adjustment for soft and rigid rotation of the nucleus.

Theory

$$W_D(E) = A_D \left[\frac{(E-E_f)^{-2}}{(E-E_f)^{-2} + (B_D)^2} - \exp(-\lambda_D(E - E_f)) \right] \quad (1)$$

Where, A_D , B_D , and λ_D are constants (undetermined) and E and E_f are Proton and femi energy, respectively [15-19].

$$A_{D,V} = W_{D,V}^{DISP} \left[1 + (-1)Z' + 1 \frac{C_{wiso,wviso} N-Z}{W_{D,V}^{DISP} A} \right]. \quad (2)$$

Where, $W_{D,V}^{DISP}$ and $C_{wiso,wviso}$ are constants (undetermined), and also A , N , and Z are mass, neutron, and atomic number, respectively [22-25].

Utilized energy (dependence) for the volume (imaginary) term has been confirmed in studies of nuclear matter theory by Gopalakrishna *et al.* (2018) [26].

$$W_V(E) = A_V \frac{(E-E_f)^2}{(E-E_f)^2 + (W_V^{DISP})^2} \quad (3)$$

In which, A_V and W_V^{DISP} are constants (undetermined), E and E_f are proton and femi energy, respectively [27-31].

Method

The OPTMAN code for this work was downloaded from the IAEA website at <http://nds-IAEA.org>. The optical model code OPTMAN was chosen because it can study nucleon interactions with light-mass, medium-mass, and heavy-mass nuclei for a broad range of energy up to 200 MeV. In addition, it has a

The current optical potential encompasses corrections (relativistic) as reported by Avrigeanu and Avrigeanu (2022) [10] and expanded by Avrigeanu and Avrigeanu *et al.* (2018) [11].

Surface variation $W_D(E)$ and potential for volume absorption $W_V(E)$ can wisely be presented in terms of energy which could be suitable for the dispersive optical model analysis [12,13]. The most utilized energy (dependence) for the surface (imaginary) term has been pointed out by Avrigeanu and Avrigeanu *et al.* (2023) [14], as described in Equation (1):

Another utilized energy (dependence) for the surface (imaginary) term has been pointed out by Naik *et al.* (2021) [20] and Naik *et al.* (2020) [21] as follow:

Soft-Rotator model in addition to its Rigid-Rotator model, which improves the precision of the even-even nuclide.

The selection of the appropriate record cards and switches determines how the code will run when the software has been successfully installed using the G-FOTRAN compiler. Record cards that describe input data are themselves described by switches for the description of the model. The "va" executable file is used to invoke each calculation's input data and is produced using the Windows command.

The code is executed immediately the command "va" is issued, the input file name is requested and supplied, the output file name is requested and supplied, and the enter key is pushed. The OPTMAN code computation was based on Equations (1) to (6).

Results and Discussion

The results obtained from the computer software (OPTMAN code) based on the Equations (1) to (6) for Rotational Model

Potential (RMP) which accounts for Soft-Rotor Model and Potentially Expanded by Derivatives (PED) accounts for Rigid-Rotor Model by calculating the neutron-induced Total Potentially Expanded by Derivatives (TPED), Total Rotational Model Potential (TRMP),

Reaction Potentially Expanded by Derivatives (RPED), Reaction Rotational Model Potential (RRMP), Elastic Potentially Expanded by Derivatives (EPED), and Elastic Rotational Model Potential (ERMP) cross section reactions for ^{235}U are presented in Table 1.

Table 1 Results obtained for Soft and Rigid-Rotor Model for Thorium-232 (^{232}Th)

Energy (MeV)	Cross Section (Reaction)			Cross Section (Elastic)			Cross Section (Total)		
	RPED	RRMP	RENDF	EPED	ERMP	EENDF	TPED	TRMP	TENDF
4.00	1.66	1.65	0.14	1.69	2.27	4.36	3.35	3.92	4.50
5.00	1.85	1.62	0.15	1.95	2.07	4.12	3.80	3.69	4.27
6.00	1.63	1.57	0.16	2.25	2.29	3.68	3.88	3.86	3.84
7.00	1.66	1.59	0.39	2.17	2.29	3.23	3.83	3.88	3.62
8.00	1.65	1.61	0.37	2.32	2.48	2.87	3.97	4.09	3.24
9.00	1.66	1.62	0.34	2.45	2.62	2.64	4.11	4.24	2.98
10.0	1.63	1.58	0.32	2.53	2.67	2.52	4.16	4.25	2.84
12.0	1.56	1.52	0.30	2.31	2.38	2.53	3.87	3.90	2.83
14.0	1.56	1.52	0.35	2.19	2.24	2.72	3.75	3.76	3.07
16.0	1.57	1.54	0.45	1.94	1.97	2.94	3.51	3.51	3.39
18.0	1.58	1.56	0.48	1.72	1.73	3.11	3.30	3.29	3.59
20.0	1.57	1.56	0.53	1.53	1.54	3.20	3.10	3.10	3.73

To compare the obtained results from this study with retrieved data (TENDF), charts for the computation of the excitation function for

the cross-section (Total), cross-section (Reaction), and cross-section (Elastic) of ^{232}Th are plotted and presented in Figures 1, 2, and 3.

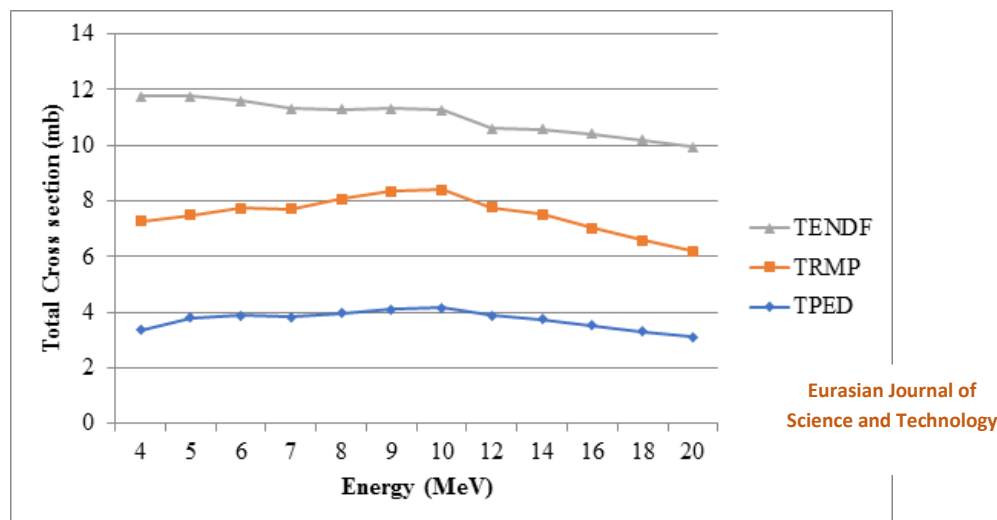


Figure 1 Cross-section (Total) of Thorium-232 (^{232}Th)

According to Figure 1, the excitation function of the total cross section induced by neutrons in ^{232}Th displays a consistent pattern: an escalation from 4 to 10 MeV followed by a decline from 10 to 20 MeV. Notably, the outcomes derived from the Total Rotational Model Potential (TRMP) exhibit a higher degree of concurrence with the data obtained from the

Thermal Neutron-Induced Fission Data File (TENDF), in comparison to the outcomes produced by the Total Potential Expanded by Derivatives (TPED). Furthermore, the impact of rotational excitation becomes more conspicuous, with the Rotational Model Potential emerging as the optimal approach for effectively accounting for this phenomenon.

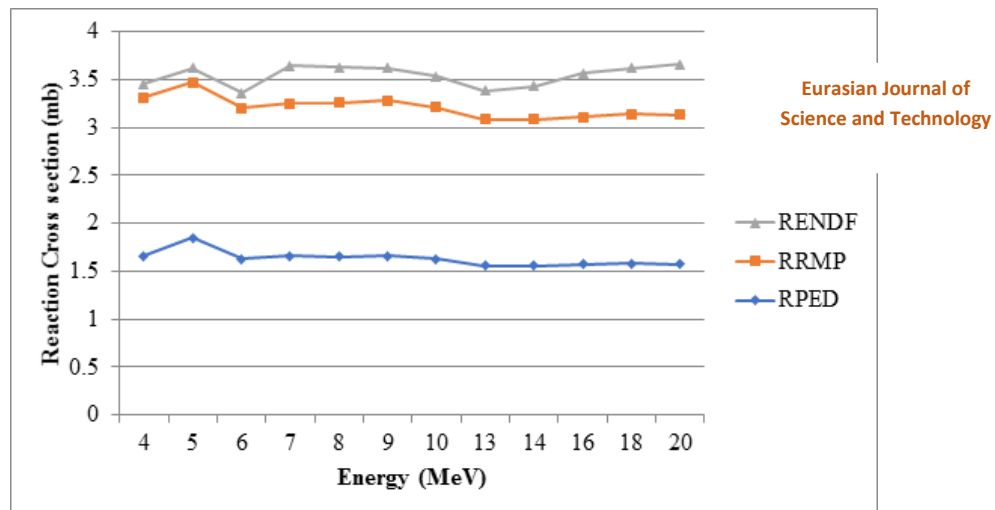


Figure 2 Reaction cross-section of Thorium-232 (^{232}Th)

As depicted in Figure 2, the excitation function of Thorium-232 exhibits a noteworthy alignment between the Potential Expanded by Derivatives (RPED) and the Rotational Model Potential (RRMP), particularly within the energy range of 4-6 MeV, as evidenced by the congruence with the established reference data (RENDF). This alignment suggests that the threshold energy for neutron-induced reactions in both RPED and RRMP lies at ≤ 4 MeV. However, a marked disparity arises between the calculated PED values and the established ENDF standard data within the energy span of 6-12 MeV. Notably, the results derived from the Rotational Model Potential exhibit superior accord with the reference data (RENDF) when contrasted with the outcomes obtained from the Potential Expanded by Derivatives. This underscores the capacity of the Rotational Model Potential to effectively characterize the dynamic alterations in the nuclear structure brought about by rotation.

As illustrated in Figure 3, a noteworthy correspondence is evident in neutron-induced elastic scattering between the Potential Expanded by Derivatives (EPED) and the Rotational Model Potential (ERMP), specifically within the energy intervals of 4 to 6 MeV and 10 to 20 MeV, where alignment with the retrieved reference data (EENDF) is observed.

However, a lack of consensus emerges between EPED and the established EENDF standard data within the energy span of 6 to 9 MeV. This discrepancy underscores the efficacy of the Rotational Model Potential, which incorporates the soft-Rotor model of the Coupled-channels Optical Model, in effectively elucidating the impact of excitation-induced rotation on neutron capture.

Notably, this approach exhibits a stronger concurrence with the reference data (EENDF), solidifying its suitability for describing the intricate interplay between rotation and neutron interactions.

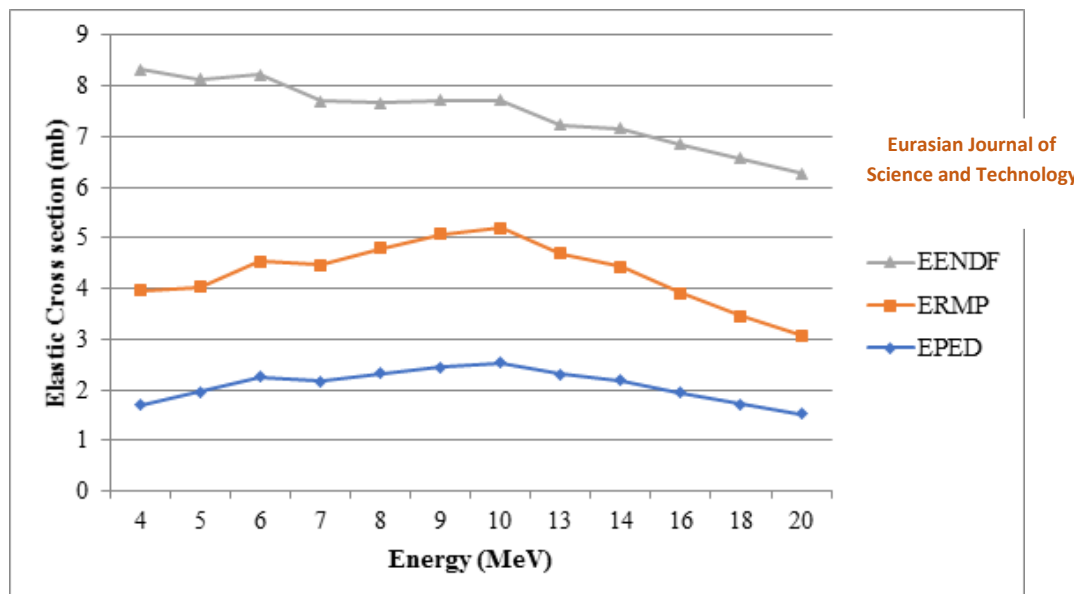


Figure 3 Elastic cross-section of Thorium-232 (^{232}Th)

Conclusion

A coupled-channel optical model OPTMAN code was used to investigate the effects of neutron-induced fissile isotopes of Thorium-232. Optical model computations were carried out via the OPTMAN code using the Coupled-Channel Rotational Model Potential (CC-RMP) which describe the Soft-Rotor model that treat nuclei as soft rotational sphere or deformed nuclei and Potential Expanded by Derivatives (CC-PED) which described Rigid-Rotor Model that treat nuclei as rigid vibrating sphere and account for nuclear volume conservation. From the computations performed for both PED and RMP, the energies agreed with the standard retrieved data (ENDF) are observed to be 4 MeV. It was revealed also that the obtained results of using Rotational Model Potential (RMP) are generally higher and are in better agreement with the standard ENDF data than those obtained from the Potential Expanded by Derivatives (PED).

However, results using both PED and RMP for elastic scattering cross sections are generally higher for ^{235}U and showed better agreement with the retrieved ENDF data. Furthermore, the Odd-A nuclides tend to have higher cross section values when compared with the Even-A nuclides. Since the oddness of both Z and N tends to lower the nuclear binding energy,

making odd nuclei less stable and more likely to undergo fission, all odd-A nuclei used in this research could be best for reactor fuel, except for the fissionable but not fissile materials. It is therefore recommended that, the odd-A nuclei used in this work be tested as reactor fuel.

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Authors' contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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References

- [1] Ahmad I., Koki F.S., Calculation of Reactions Cross Section for Neutron-Induced Reactions on 127I Isotope, *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology*, 2017, **6**:344 [Crossref], [Google Scholar], [Publisher]
- [2] I. Ahmad, Y.Y. Ibrahim & F.S, Koki, Evaluation of Reaction Cross Section of Radionuclide by Particles Induced Nuclear Reactions Using EXIFON Code. *Boson Journal of Modern Physics*, 2018, **3**:220 [Google Scholar], [Publisher]
- [3] Kara A., Excitation function calculations of neutron-induced reactions of some zirconium target isotopes, *Journal of Fusion Energy*, 2017, **36**:230 [Crossref], [Google Scholar], [Publisher]
- [4] Naik H., Kim G., Kim K., Zaman M., Nadeem M., Sahid M., Neutron-induced reaction cross-sections of ⁹³Nb with fast neutron based on ⁹Be (p, n) reaction, *Nuclear Physics A*, 2018, **970**:156 [Crossref], [Google Scholar], [Publisher]
- [5] Liang H., Wu Z., Zhang Z., Han Y., Jiao X., Calculations and Analysis of n+ ⁹³Nb Reaction, *Nuclear Science and Engineering*, 2017, **187**:107 [Crossref], [Google Scholar], [Publisher]
- [6] Koning A., Rochman D., Sublet J.C., Dzysiuk N., Fleming M., Van der Marck S., TENDL: complete nuclear data library for innovative nuclear science and technology, *Nuclear Data Sheets*, 2019, **155**:1 [Crossref], [Google Scholar], [Publisher]
- [7] Avrigeanu M., Avrigeanu V., Optical potential for incident and emitted low-energy α particles. III. Non-statistical processes induced by neutrons on Zr, Nb, and Mo nuclei, *arXiv preprint*, 2023, **arXiv:2302.09845** [Crossref], [Google Scholar], [Publisher]
- [8] Avrigeanu V., Avrigeanu M., Role of consistent parameter sets in an assessment of the α -particle optical potential below the Coulomb barrier, *Physical Review C*, 2019, **99**:044613 [Crossref], [Google Scholar], [Publisher]
- [9] Avrigeanu V., Avrigeanu M., Validation of an optical potential for incident and emitted low-energy α -particles in the A~ 60 mass range, *The European Physical Journal A*, 2021, **57**:54 [Crossref], [Google Scholar], [Publisher]
- [10] Avrigeanu V., Avrigeanu M., Validation of an optical potential for incident and emitted low-energy α -particles in the A~ 60 mass range: II. Neutron-induced reactions on Ni isotopes, *The European Physical Journal A*, 2022, **58**:189 [Crossref], [Google Scholar], [Publisher]
- [11] Avrigeanu V., Avrigeanu M., Consistent assessment of neutron-induced activation of ⁹³Nb, *Frontiers in Physics*, 2023, **11**:223 [Crossref], [Google Scholar], [Publisher]
- [12] Goriely S., Dimitriou P., Wiedeking M., Belgya T., Firestone R., Kopecky J., Krtička M., Plujko V., Schwengner R., Siem S., Reference database for photon strength functions, *The European Physical Journal A*, 2019, **55**:1 [Crossref], [Google Scholar], [Publisher]
- [13] Anthony M.I., Ige O.O., Rilwan U., Jonah S.A., Aliyu M.A., Atef El-Taher, Comparative Analysis of the Excitation Functions of ²³⁸U as Breeder Fuel Using OPTMAN Code., *Kirkuk Journal of Science*, 2023, **18**:1 [PDF], [Google Scholar]
- [14] Avrigeanu V., Avrigeanu M., Consistent optical potential for incident and emitted low-energy α particles. II. α emission in fast-neutron-induced reactions on Zr isotopes,

- Physical Review C*, 2017, **96**:044610 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [15] Bykhalo G., Stopani K., Reliability of Neutron Yield Cross Sections on ^{12}C - ^{127}I Isotopes in Proton-Induced Reactions Evaluated Using GEANT4 Package for Proton Therapy Applications, *Physics of Atomic Nuclei*, 2019, **82**:1476 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [16] Anthony M.I., Ige O.O., Rilwan U., Mohammed A.A., Margaret J., Atef El-Taher, Effect of Excitation in Neutron Induced Fissile Isotope of Uranium Using the OPTMAN Code Up to 20 MeV, *Kirkuk Journal of Science*, 2023, **18**:13 [[PDF](#)], [[Google Scholar](#)]
- [17] Gandhi A., Sharma A., Pachau R., Singh N., Patil, P.N., Mehta, M., Danu, L., Suryanarayana, S., Nayak B., Lalremruata B., Neutron capture reaction cross section measurement for iodine nucleus with detailed uncertainty quantification, *The European Physical Journal Plus*, 2021, **136**:819 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [18] Zhang Y., Li J., Zhang X., Cai H., Yan X., Yu L., Fu F., Lin P., Gao X., Zhang Z., Neutronics performance and activation calculation of dense tungsten granular target for China-ADS, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2017, **410**:88 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [19] Wang Q., Liu T., Qiu Y., Lan C., Chen B., Zhang Q., Zhan X., Fang K., Measurement of the cross sections for ^{238}U (n, γ) ^{239}U reaction in the energy range of 14.1–14.8 MeV using neutron activation method, *Radiation Physics and Chemistry*, 2018, **152**:125 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [20] Naik H., Kim G., Kim K., Nguyen T.H., Nadeem M., Sahid M., Measurement of cross sections of Zr-isotopes with the fast neutrons based on the ^{99}Be (p, n) reaction, *The European Physical Journal A*, 2021, **57**:1 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [21] Naik H., Kim, G., Kim, K., Nadeem, M., Sahid, M., Production cross-sections of Mo-isotopes induced by fast neutrons based on the ^{9}Be (p, n) reaction, *The European Physical Journal Plus*, 2020, **135**:1 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [22] Kerveno M., Dupuis M., Bacquias A., Belloni F., Bernard D., Borcea C., Boromiza M., Capote R., De Saint Jean C., Dessagne P., Measurement of U 238 ($n, n' \gamma$) cross section data and their impact on reaction models, *Physical Review C*, 2021, **104**:044605 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [23] Johnstone E.V., Mayordomo N., Mausolf E.J., Discovery, nuclear properties, synthesis and applications of technetium-101, *Communications Chemistry*, 2022, **5**:131 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [24] International Atomic Energy Agency, Evaluated Nuclear Data for Nuclides within the Thorium-Uranium Fuel Cycle, Non-Serial Publications, *IAEA Vienna*, 2010 [[Publisher](#)]
- [25] Waldemar W, Changing the Shape of a Zirconium Nucleus. *Physical Review*, 2018, **8**:1 [[Publisher](#)]
- [26] Gopalakrishna A., Kim G., Naik H., Kim K., Nayak B., Zaman M., Measurement of ^{99}Mo production cross-section from the ^{100}Mo ($n, 2n$) reaction with quasi monoenergetic neutron based on the ^{9}Be (p, n) reaction, *Journal of Radioanalytical and Nuclear Chemistry*, 2018, **316**:561 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [27] Keiichi S., Evaluation of Neutron Nuclear Data on Iodine Isotopes. *Journal of Nuclear Science and Technology*, 2018, **52**:1174 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [28] Shmelev A.N., Kulikov G.G., Kulikov E.G., Apse V.A, Protactinium-231 as a New Fissionable Material for Nuclear Reactors that can Produce Nuclear Fuel with Stable Neutron-Multiplying Properties. *Kerntechnik*, 2016, **81**:34 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]

- [29] Pupillo G., Mou L., Manenti S., Groppi F., Esposito J., Haddad F., Nuclear Data for Light Charged Particle Induced Production of Emerging Medical Radionuclides. *Radiochemica Acta.*, 2022, **110**:6 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [30] Johnstone E.V., Mayordomo N., Mausolf E.J., Discovery, Nuclear Properties, Synthesis and Applications of Technetium-101. *Commun. Chem.* 2022, **5**:1 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]
- [31] Kawano T., Cho Y., Dimitriou P., Filipescu D., Iwamoto N., Plujko V., Tao X., Utsunomiya H., Varlamov V., Xu R., IAEA photonuclear data library 2019, *Nuclear Data Sheets*, 2020, **163**:109 [[Crossref](#)], [[Google Scholar](#)], [[Publisher](#)]