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Study of the Production Cross-Sections of the Neutron-rich ^{184}Ta and ^{186}Ta

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ABSTRACT

Synthesizing nuclei through reactions that produce a reasonable yield is important for the experimental study of neutron-rich nuclei. In this study, the cross-section values of ^{184}Ta and ^{186}Ta nuclei in various experiments were reviewed and analysed. The experimental data of (n, p), (p, x) and (n, α) reactions were compared to identify the best reaction to produce these nuclei for further study. Our study shows that (n, p) reactions on natural Tungsten targets are the most feasible reactions with a good yield of the neutron-rich Tantalum isotopes. New reactions have been proposed for the effective synthesis of ^{184}Ta and ^{186}Ta using tritium beams on Hafnium targets. The cross-section values of the proposed reactions were calculated by PACE4 software simulations.

1. Introduction

It is necessary to explore the extremes of the nuclear landscape for a comprehensive understanding of nuclear models. While the availability of experimental data has been on the rise lately, synthesizing neutron-rich nuclei has always been challenging. In such experiments, it is important to have a good cross-section for the production of the nuclei of interest. In the design of nuclear reactors, cross-section data of various nuclei is useful. Many experiments have been performed to determine the cross-section values of neutron-induced reactions around 14 MeV, specifically on Tungsten targets, as it is a promising material to be used in fusion reactors [1-4].

A survey of available literature reveals that there is a lacuna of experimental nuclear data on medium-heavy and heavy nuclei [5]. This is because, the cross-section of these unstable nuclei for most nuclear reactions is very low. The neutron-rich isotopes of Tantalum ^{184}Ta and ^{186}Ta fall under this category. A review of the experimental investigations undertaken so far on ^{184}Ta and ^{186}Ta reveal that, only three studies were completely dedicated to understanding these nuclei [6]. Furthermore, the level structures of these nuclei have not been deduced unambiguously [5]. The ground state and isomeric states of both ^{184}Ta and ^{186}Ta still remain uncharacterized. As a result, selecting an appropriate and feasible reaction which yields a good cross-section to produce these nuclei becomes crucial.

2. Methods

In this study, the experimental cross-section values of ^{184}Ta and ^{186}Ta determined in works published so far were compiled and analysed. The data were taken from the Nuclear Science References (NSR) database provided by the National Nuclear Data Centre [6]. The complied data on cross-section as a function of the beam energy of the incident particle has been represented graphically. Experiments performed from the 1950s till date were analysed to identify the best possible reaction that would produce these nuclei for further studies. Cross-section values of ^{184}Ta and ^{186}Ta were calculated theoretically using the statistical model and compared to the experimental data. Using software simulations, we also propose a new reaction to produce ^{184}Ta and ^{186}Ta with a good cross-section, in addition to the existing ones.

Our study shows that (n, p) reactions on tungsten targets were most commonly used by many research groups to produce ^{184}Ta and ^{186}Ta. The neutron beam energy used was in the range of 13.5-14.9 MeV. The neutron beam in all the (n, p) reactions was obtained from the reaction ^{3}H (d, n)^{4}He, where the deuteron beam energy was in the range of 250-500 keV. The neutron fluence rate was determined using monitor reactions - ^{93}Nb(n, 2n)^{92m}Nb and ^{27}Al(n, α)^{24}Na. The activation method was used to finally obtain the cross-section values of ^{184}Ta and ^{186}Ta.

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For ^{186}Ta production, ^{186}W (n, p)^{186}Ta is the only reaction known so far that yields a cross-section greater than 1 mb. As shown in Fig. 1, this (n, p) reaction gives a maximum cross-section of 3 mb, for neutron beam energy of 14.5 MeV [7]. With neutron energies in the range 14.3-14.9 MeV, the yield of ^{186}Ta is good enough for decay spectroscopy studies [8-14]. So far, the determination of the energy levels of ^{186}Ta has been undertaken only through the β-decay of ^{186}Hf [5]. The ^{186}W (n, p)^{186}Ta reaction with beam energy in the above-specified range can be used as an efficient alternative to establish its unknown parameters like the ground state spin-parity and its isomeric states.

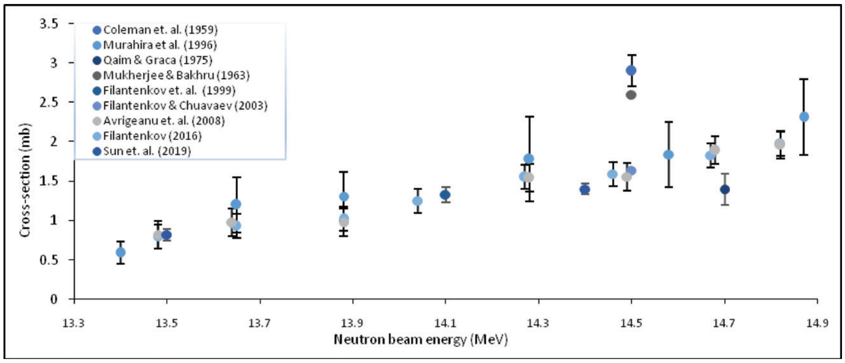

Figure 1: Cross-section values of ^{186}W(n, p)^{186}Ta reaction for various neutron energies.

In the case of ^{184}Ta, the ^{184}W (n, p)^{184}Ta reaction yields a cross-section of 3 mb when the neutron beam energy ranges between 14.3 MeV and 14.9 MeV, as shown in Fig. 2. Coleman et al. [7] observed the maximum cross-section at 14.5 MeV incident energy, with a cross-section value of 4.75 mb.

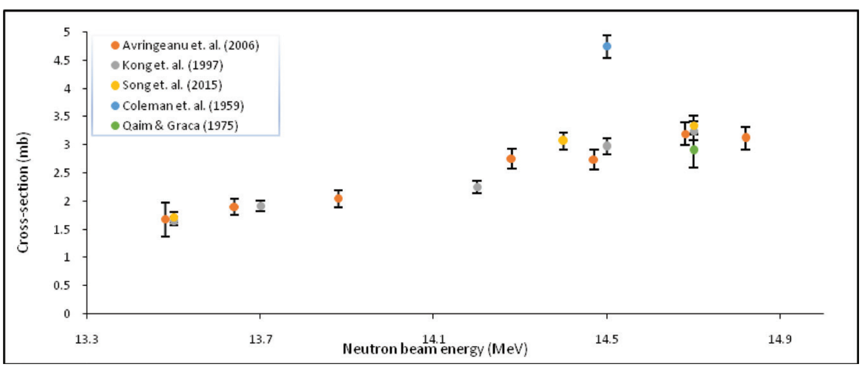

Figure 2: Cross-section values of ^{184}W(n, p)^{184}Ta reaction for different neutron energies.

Apart from the ^{184}W(n, p)^{184}Ta reaction, another neutron-induced reaction ^{187}Re(n, α)^{184}Ta with beam energy range of 14.8-18.3 MeV also produces a good cross-section for ^{184}Ta [2]. The cross-sections obtained in this reaction are shown in Fig. 3. However, the maximum yield of ^{184}Ta is observed in the (p, x) spallation reaction on natural tungsten targets [15, 16]. At a beam energy of 1199 MeV, the cross-section of ^{184}Ta is observed to be 5.5 mb, as seen in Fig. 4. This is the highest yield of ^{184}Ta obtained so far in any experiment [6].

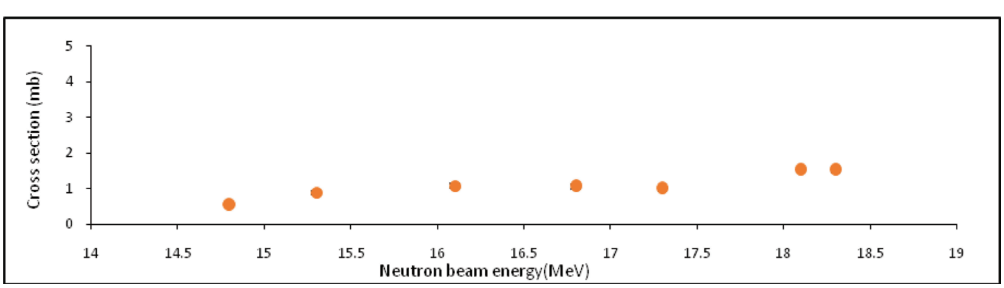

Figure 3. Cross-section values of ^{187}Re(n, α)^{184}Ta reaction for different neutron energies.

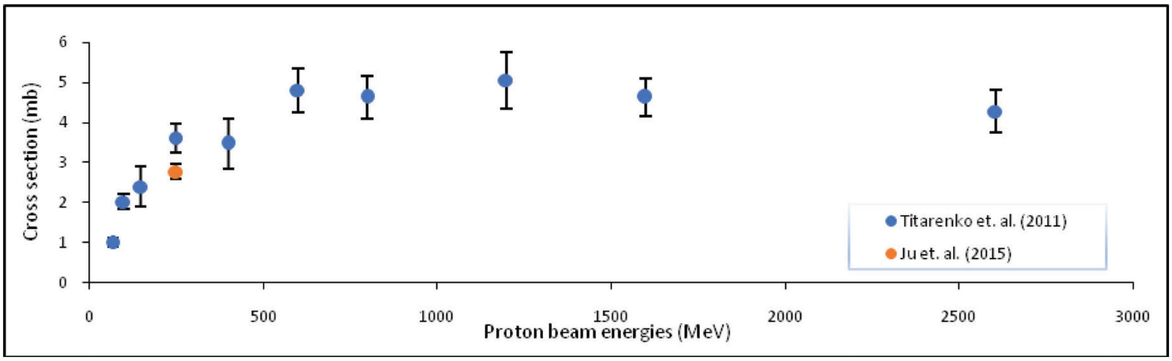

Figure 4: Cross-section values of nat.W(p, x)^{184}Ta reaction at various proton energies.

A multinucleon transfer reaction, where ^{198}Pt was irradiated by a high-energy ^{136}Xe beam yielded a very low cross-section of ^{184}Ta [17]. Ternary fission reaction on ^{238}U target using medium energy He-ions also resulted in a very low yield of ^{184}Ta with cross-sections ranging only in nano-barns [18].

3. Calculations and Simulations

In this work, we have calculated the theoretical cross-section values for (n, p) reactions at neutron beam energy E_n= 14.5 MeV, using the statistical model discussed in Habbani and Osman [19]. This method is based on the statistical model, which considers the Q-value dependence and odd-even effects. The empirical formula is as follows:

$$\sigma_{n,p} = \sigma_R \left(\frac{\Gamma_p}{\Gamma_n} \right) \quad (1)$$

where, σ_R is the reaction or formation cross-section for the incident neutrons, Γ_n is the decay width for a neutron, Γ_p is the decay width for a proton. The relation obtained from this formula, in terms of spin statistical factor, nuclear temperature, coulomb barrier and emitted energy of the proton, was fitted using Legendre least square method and the experimental cross-section values of (n, p) reactions at incident neutron energy 14.5 MeV for odd-A and even-A nuclei separately. The equation describing a good fit for even-A nuclei after substitution of fitting parameters and odd-even characters is given by

$$\sigma_{n,p} = 60.34 \left(A^{\frac{1}{3}} + 1 \right)^2 \exp\left(- \frac{34.44(N - Z + 1)}{A} \right) \quad (2)$$

where, A is the mass number of the target nuclei, N is the neutron number and Z is its proton number. The empirical values obtained using this equation were, in general, found to be in agreement with experimental values for even-mass nuclei. The comparison of the theoretical values calculated using equation (2) with the compiled experimental data is shown in Table 1.

Table 1: Comparison of experimental cross-section values of (n, p) reactions with empirical values calculated using statistical model for neutron energies of 14.5 MeV.

Reaction	Calculated Cross-section at E_n=14.5MeV (mb)	Neutron Energy (MeV)	Experimental Cross-section (mb)	References
^{184}W(n,p)^{184}Ta	2.6515	14.47±0.34	2.74±0.17	[20]
		14.5	2.9±0.3	[7]
		14.5±0.2	2.97±0.14	[4]
^{186}W(n,p)^{186}Ta	1.9845	14.46	1.59±0.18	[10]
		14.49±0.34	1.56±0.17	[9]
		14.4±0.2	1.40±0.07	[8]
		14.5	2.9±0.2	[7]
		14.5	2.6	[14]
		14.58	1.84±0.41	[13]

The theoretical calculations were found to be in agreement with the experimental data compiled from various studies. The calculations also give an idea of the average expected cross-section values in (n, p) reactions. Keeping these values as standard expected outcomes, possibilities of other reactions with comparable cross-section values were explored by using the fusion-evaporation code PACE4. PACE4 is a modified version of JULIAN evaporation code using Monte-Carlo code coupling angular momentum [21].

Calculations carried out using PACE4 software package show that ^{184}Ta and ^{186}Ta can be produced using low-energy tritium beams on Hafnium targets. The irradiation of ^{182}Hf target ($t_{1/2}$= 8.90x10^{6} y) by a 10 MeV tritium beam results in the production of ^{184}Ta along with a longer-lived isotope ^{183}Ta ($t_{1/2}$= 5.1 d). The cross-section of ^{184}Ta is found to be around1.35 mb, on repeated simulations. When the target is replaced by ^{184}Hf ($t_{1/2}$= 4.2 h), there is a cross-section of about 1.75mb for the production of ^{186}Ta. The other product formed in the reaction is ^{185}Ta ($t_{1/2}$= 49.4 min). Further reduction of the tritium beam energy can increase the cross-sections of ^{184}Ta and ^{186}Ta in the respective reactions. The outcome of the reactions as predicted by PACE4 is summarised in Table 2.

Table 2: Reaction products predicted by PACE4 for incident 10MeV tritium beams.

Target nucleus	Products	Production Percentage	Cross-section (mb)
^{182}Hf	^{184}Ta	0.4%	1.35±0.15
	^{183}Ta	99.6%	310±10
^{184}Hf	^{186}Ta	0.7%	1.76±0.15
	^{185}Ta	99.3%	310±15

While (n, p) reactions clearly appear to be the most feasible reaction for producing and studying ^{184}Ta and ^{186}Ta, neutron-induced reaction cross-sections are prone to experimental errors. Activation due to low-energy neutrons in the flux and residual activity due to possible (n, pn) and (n, pp) reactions are two of the most common errors [7]. Hence, the measured cross-section values in (n, p) reaction is less than the expected values. In the case of spallation reactions, where there are numerous products, a selective study of a particular nucleus is difficult irrespective of the cross-section obtained. The proposed reactions ^{182}Hf (^{3}H, n)^{184}Ta and ^{184}Hf (^{3}H, n)^{186}Ta have only one other by-product with a considerably longer half-life making it easy to study the decay characteristics of the nuclei of interest. The cross-section obtained is also on par with the yield of (n, p) reactions. It is a challenge to produce the short-lived target ^{184}Hf and high-purity tritium beams. However, these proposed reactions are a definite possibility in producing and further exploring the neutron-rich isotopes ^{184}Ta and ^{186}Ta.

Conclusion

The analysis and review of various reactions producing ^{184}Ta and ^{186}Ta identified (n, p) reactions on Tungsten targets as a good reaction to produce and study these nuclei. Through theoretical calculations and simulations with tritium beams on Hafnium targets, we also proposed new reactions. Heavier ion beams can also be used to produce neutron-rich nuclei, which could not be simulated due to limitations in the PACE4 software. Radioactive Ion Beams (RIB) may work out to be a good option, in the search of other possible reactions to produce ^{184}Ta and ^{186}Ta. RIBs are being widely used in the synthesis of neutron-rich nuclei in various mass regions in the recent times. They have opened up an experimental pathway in studying many heavy nuclei which were studied only through decays so far.

References

[1] Y. Song et al., Applied Radiation and Isotopes **98**, 29 (2015). https://doi.org/10.1016/j.apradiso.2014.11.018

[2] N. Jovančević et al., Eur. Phys. J. A **52**, 148 (2016). https://doi.org/10.1140/epja/i2016-16148-4

[3] S. M. Qaim and C. Graça, Nucl. Phys. A **242**, 317 (1975). https://doi.org/10.1016/0375-9474(75)90052-4

[4] X. Kong, S. Hu and J. Yang, Chin. Nucl. Sci. and Tech. Rep. Indc(Cpr)-042/L, **17**, 9-11 (1997).

[5] Evaluated Nuclear Structure Data Files (ENSDF). https://www.nndc.bnl.gov/ensdf/

[6] Nuclear Science References (NSR). https://www.nndc.bnl.gov/nsr/

[7] R. F. Coleman, B. E. Hawker, L. P. O'Connor and J. L. Perkin, Proc. Phys. Soc. **73**, 215 (1959). https://doi.org/10.1088/0370-1328/73/2/308

[8] X. J. Sun et al., Chin. Phys. Lett. **36**, 112501 (2019). https://doi.org/10.1088/0256-307X/36/11/112501

[9] M. Avrigeanu et al., Nucl. Phys. A **806**, 15 (2008). https://doi.org/10.1016/j.nuclphysa.2008.03.010

[10] A. Filantekov, EXFOR Data INDC(CCP)-0460, 4RUSRI, KhlopinRadium Inst., St. Petersburg, Russia, (2016).

[11] A. A. Filatenkov and S. V. Chuvaev, EXFOR Data KRI-259, 4RUSRI, KhlopinRadium Inst., St. Petersburg, Russia, (2003).

[12] A. A. Filatenkov et al., EXFOR Data (R, RI-252,199905), 4RUSRI, KhlopinRadium Inst., St. Petersburg, Russia, (1999).

[13] S. Murahira et al., EXFOR Data S, INDC(JPN)-175 **171**, 199603 (1996);

S, JAERI-C-96-008, 171, 199603 (2JPNNAG, Nagoya Univ., Nagoya, Japan; 2JPNOSA, Osaka Univ., Osaka, Japan)

[14] S. K. Mukherjee and H. Bakhru, 1963 XFOR Data C, 63BOMBAY,244, 196302 (Conf: Nucl. and Solution. State Physics Symp., Bombay 1963, India)

[15] Y. E. Titarenko et al., Physics of Atomic Nuclei **74**, 551 (2011). https://doi.org/10.1134/S1063778811040181

[16] Y. Q. Ju et al., J. Phys. G: Nucl. Part. Phys. **42**, 125102 (2015). https://doi.org/10.1088/0954-3899/42/12/125102

[17] V. V. Desai et al., Phys. Rev. C **99**, 044604 (2019). https://doi.org/10.1103/PhysRevC.99.044604

[18] R. H. Iyer and J. W. Cobble, Phys. Rev. **174**, 1186 (1968). https://doi.org/10.1103/PhysRev.172.1186

[19] F. I. Habbani and K. T. Osman, Appl. Rad. and Isot. **54**, 283 (2001). https://doi.org/10.1016/S0969-8043(00)00275-X

[20] V. Avrigeanu et al., Nuclear Physics A **765**, 1 (2006). https://doi.org/10.1016/j.nuclphysa.2005.10.003

[21] A. Gavron, Phys. Rev. C **21**, 230 (1980). https://doi.org/10.1103/PhysRevC.21.230

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