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Propagation of Nuclear Level Density Uncertainties to Displacements Per Atom Calculations for Fusion Relevant Tungsten ^{184}W Isotope †

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Abstract

Tungsten is a leading plasma-facing material for fusion reactors, where neutron irradiation causes displacement damage. This work investigates the propagation of nuclear level density (NLD) uncertainties to displacements-per-atom (DPA) calculations for the fusion-relevant ^{184}W isotope. Neutron-induced cross-sections for the (n,γ), (n,2n), (n,p), and (n,α) channels are calculated up to 30 MeV using TALYS code and propagated through a simplified NRT-based framework to quantify the impact of NLD models on dpa predictions.

Keywords: tungsten; displacements per atom (DPA); nuclear level density (NLD); neutron-induced reaction cross-sections; fusion reactor materials

1. Introduction

Tungsten is the leading candidate for plasma-facing components in fusion reactors because of its excellent thermophysical properties and radiation resistance [1]. Under fusion-neutron irradiation, neutron-induced reactions produce atomic displacements, transmutation products, and activation, degrading the long-term performance of tungsten components. Radiation damage is commonly characterized by the DPA, which depends directly on neutron-induced reaction cross-sections and is widely used as an engineering measure of irradiation damage [2]. The prediction of neutron-induced reaction cross-sections relies on nuclear reaction models, in which NLD plays a key role in determining compound-nucleus decay probabilities and the competition among reaction channels. Consequently, different NLD models may lead to noticeable variations in the calculated cross-sections, particularly for the (n,γ), (n,2n), (n,p) and (n,α) reactions relevant to fusion applications [3–6]. Although neutron-induced reactions in tungsten have been extensively investigated, the propagation of NLD-model uncertainties to displacement-damage estimates has received limited attention.

In this work, the influence of NLD models on neutron-induced reactions of the fusion-relevant isotope ^{184}W is systematically investigated using TALYS code. Cross-sections for the (n,γ), (n,2n), (n,p) and (n,α) channels are calculated up to 30 MeV while keeping all other reaction-model parameters unchanged. The calculated cross-sections are subsequently propagated through a simplified NRT-based framework to quantify the impact of NLD

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uncertainties on DPA predictions and to identify the reaction channels and neutron-energy regions that contribute most to the overall uncertainty [4–7].

2. Materials and Methods

2.1. TALYS Calculations

The fusion-relevant isotope ^{184}W was selected because it is one of the major naturally occurring tungsten isotopes contributing to the neutron response of natural tungsten [1]. Neutron-induced cross-sections for the (n,γ), (n,2n), (n,p) and (n,α) reaction channels were calculated up to 30 MeV using the TALYS-2.0 nuclear reaction code [8]. Five TALYS NLD models (ldmodel 1–5) were employed, while all other reaction-model parameters were kept unchanged to isolate the influence of the NLD prescription [8,9]. Exclusive residual-production cross-sections were extracted directly from the TALYS output files to avoid inclusive particle-production quantities [10]. For each reaction channel, the spread among the five NLD models was evaluated using

$$U(E_n) = \frac{\sigma_{\max}(E_n) - \sigma_{\min}(E_n)}{\sigma_{\text{mean}}(E_n)}, \quad (1)$$

where σ_{mean}, $\sigma_{\max}$ and $\sigma_{\min}$ denote the mean, maximum and minimum cross-sections obtained from the selected NLD models.

2.2. Simplified NRT-Inspired DPA Framework

The calculated cross-sections were propagated into a simplified channel-weighted displacement response based on the Norgett–Robinson–Torrens (NRT) formalism [2]:

$$\sigma_d(E_n) = \sum_i \nu_i(E_n), \sigma_i(E_n), \quad (2)$$

where $\sigma_i(E_n)$ is the cross-section of reaction channel i, and $\nu_i(E_n)$ is its effective displacement weight. A threshold displacement energy of $E_d = 90$ eV was adopted for tungsten [11]. To represent fusion irradiation conditions, the DPA-like response was folded with a representative D–T neutron spectrum:

$$\int_0^{E_{\max}} \phi(E_n)\sigma_d(E_n)dE_n, \quad (3)$$

where $\phi(E_n)$ is the neutron flux spectrum. The spread of the integrated response was evaluated using Equation (1), while the contribution of each reaction channel was determined from its weighted fraction in the total DPA-like response.

3. Results and Discussion

3.1. Reaction Cross-Sections

3.1.1. (n,2n) Reaction

The calculated ^{184}W(n,2n) cross-sections obtained with the five TALYS NLD models are shown in Figure 1. As expected, the largest model dependence occurs in the threshold region, where compound-nucleus decay probabilities are most sensitive to the adopted NLD prescription. Above the reaction threshold, the cross-section increases rapidly, reaches its maximum near the fusion-relevant energy range, and then decreases gradually with increasing neutron energy. Although noticeable differences are observed close to the threshold, the predictions of the five NLD models converge at higher energies, indicating that the influence of the NLD model decreases as pre-equilibrium processes become more important. Since the (n,2n) reaction is the dominant contributor to recoil production in

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^{184}W, its uncertainty largely determines the propagation of NLD-model variations into the DPA-like response discussed in the following sections.

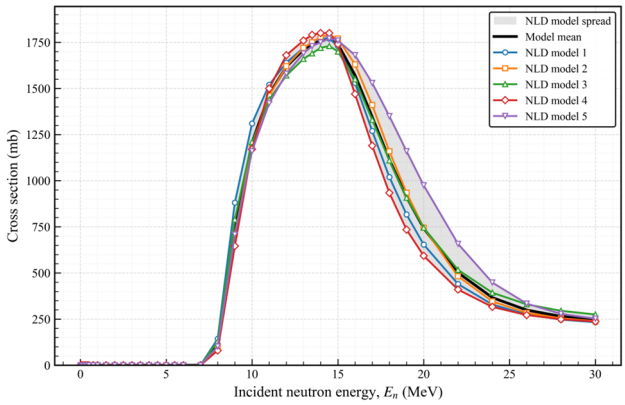

Figure 1. Calculated ^{184}W(n,2n) cross-sections obtained using the TALYS NLD models.

3.1.2. Charged-Particle Channels ((n,p) and (n,α))

The calculated cross-sections for the ^{184}W(n,p) and ^{184}W(n,α) reactions are presented in Figure 2. Both reactions exhibit threshold behavior and significantly smaller cross-sections than the (n,2n) channel over the investigated energy range. Differences among the NLD models are more pronounced near the reaction thresholds, whereas the calculated cross-sections become increasingly consistent at higher neutron energies. Although the relative model spread is larger for the charged-particle channels than for the (n,2n) reaction, their absolute cross-sections remain small. Consequently, their contribution to the overall DPA-like response is limited, and their influence on the propagated uncertainty is considerably smaller than that of the dominant (n,2n) channel.

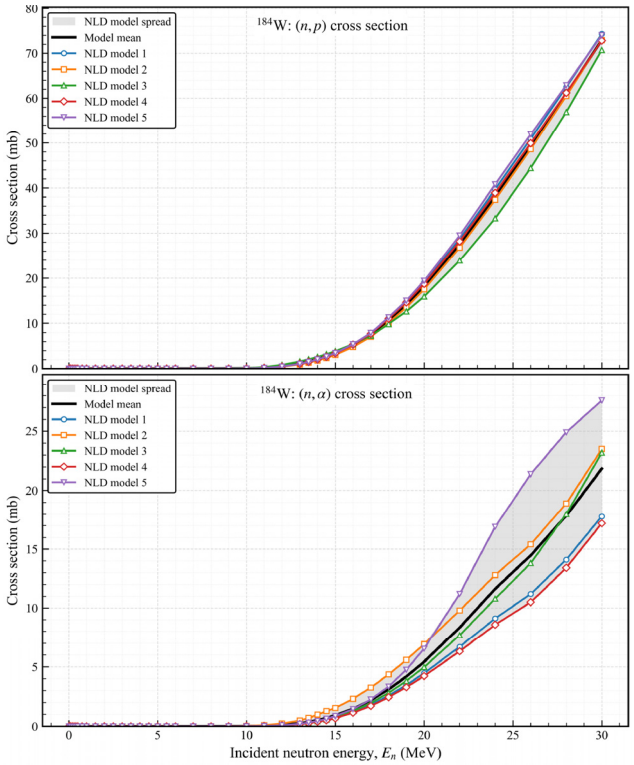

Figure 2. Calculated ^{184}W(n,p) and ^{184}W(n,α) cross-sections.

3.2. DPA-like Response

The reaction-channel cross-sections calculated with the five TALYS NLD models were propagated through the simplified NRT-inspired framework to obtain the energy-dependent DPA-like response. The calculated responses are presented in Figure 3. In all cases, the DPA-like response increases rapidly above the reaction thresholds, reaches its maximum in the fusion-relevant energy region, and gradually decreases at higher neutron energies. Although small differences are observed among the five NLD models, all calculations exhibit nearly identical energy dependence. This behavior indicates that the overall displacement response is considerably less sensitive to the choice of NLD model than the individual reaction cross-sections. The reduced model dependence results from the combined contribution of all reaction channels, with the dominant (n,2n) reaction governing most of the displacement production over the investigated energy range. The energy-dependent DPA-like response provides the basis for evaluating how NLD-model variations propagate into radiation-damage estimates. The corresponding relative uncertainty arising from the selected NLD models is analyzed in the following section. The maximum response occurs close to the D–T fusion-neutron energy, emphasizing the dominant role of the (n,2n) channel in fusion irradiation conditions.

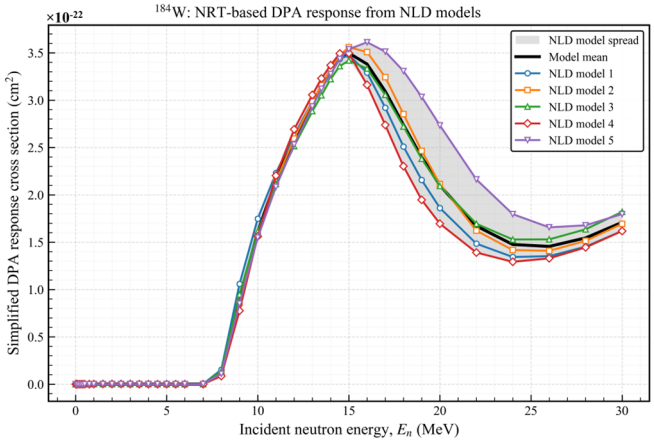

Figure 3. NRT-based DPA response from NLD models of ^{184}W.

3.3. Propagated NLD Uncertainty in DPA

The propagated relative uncertainty of the DPA-like response resulting from the five TALYS NLD models is shown in Figure 4. The largest model spread is observed near the reaction thresholds, where compound-nucleus decay is strongly influenced by the adopted NLD prescription. As the incident neutron energy increases, the relative uncertainty decreases progressively because the calculated reaction cross-sections become less dependent on the NLD model. Compared with the variation observed in individual reaction-channel cross-sections, the propagated uncertainty of the total DPA-like response is considerably reduced. This reduction reflects the combined contribution of multiple reaction channels and the dominant role of the (n,2n) reaction in the fusion-relevant energy region. These results indicate that, although NLD modeling affects individual reaction cross-sections, its impact on the overall displacement-damage response remains relatively limited under fusion-neutron irradiation conditions.

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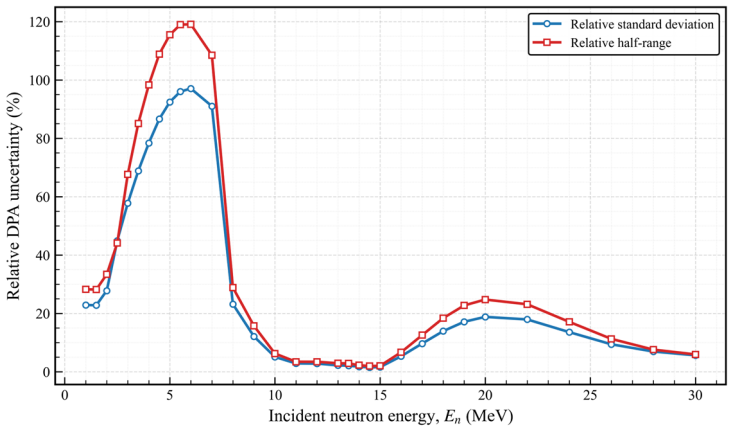

Figure 4. Relative uncertainty of the DPA response propagated from NLD models.

3.4. Channel Contributions and Spectrum-Integrated Response

The DPA-like response was integrated over a representative D–T fusion-neutron spectrum to evaluate the overall effect of NLD-model variation under realistic irradiation conditions. The spectrum-integrated results obtained with the five TALYS NLD models show only limited variation, indicating that the propagated uncertainty is significantly reduced after energy integration. The relative contributions of the individual reaction channels are presented in Figure 5. The (n,2n) reaction is the dominant contributor to the total DPA-like response over the fusion-neutron energy range, whereas the contributions of the (n,p), (n,α), and (n,γ) channels remain comparatively small. Consequently, although noticeable model dependence exists in some minor reaction channels, its influence on the final spectrum-integrated DPA-like response is limited. These results demonstrate that the uncertainty of the displacement-damage response is primarily controlled by the behavior of the (n,2n) channel. Therefore, improving the prediction of this reaction is expected to provide the greatest reduction in the overall uncertainty of radiation-damage estimates for fusion-relevant tungsten.

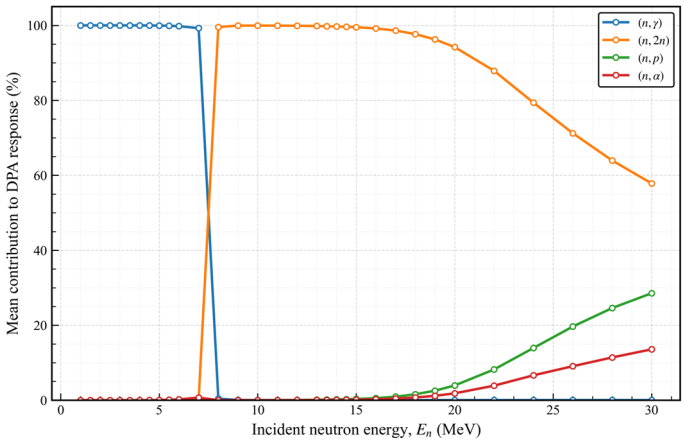

Figure 5. Reaction-channel contribution to DPA.

3.5. Implications for Fusion Applications

The present results demonstrate that uncertainties associated with NLD models have only a moderate impact on the predicted DPA-like response of ^{184}W under fusion-neutron irradiation conditions. Although noticeable model dependence exists in some individual reaction channels, the overall displacement response is largely controlled by the dominant (n,2n) reaction, leading to a relatively stable spectrum-integrated damage estimate. These findings indicate that improving the prediction of the (n,2n) reaction and its underlying

nuclear-model inputs is likely to provide the greatest benefit for reducing uncertainties in radiation-damage assessments of tungsten-based plasma-facing materials. The proposed framework can also support nuclear-data sensitivity studies and uncertainty quantification for other fusion structural and plasma-facing materials.

4. Conclusions

This work investigated the propagation of NLD model uncertainties to neutron-induced reaction cross-sections and a simplified NRT-inspired DPA-like response for the fusion-relevant isotope ^{184}W. TALYS calculations performed with five NLD models showed that the sensitivity to NLD strongly depends on both reaction channel and neutron energy. Among the investigated reactions, the (n,2n) channel dominates the DPA-like response in the fusion-neutron energy range and largely determines the propagated uncertainty of the damage indicator. Although noticeable differences were observed in individual reaction cross-sections, the corresponding variation in the spectrum-integrated DPA-like response remained relatively small because the overall response is governed primarily by the dominant (n,2n) reaction. These results indicate that improving the prediction and experimental validation of the ^{184}W(n,2n) excitation function would provide the greatest benefit for reducing uncertainties in fusion radiation-damage assessments. The proposed channel-resolved framework provides a simple and transparent approach for linking nuclear-model uncertainties to fusion-relevant damage indicators. Future work will extend the present analysis by including additional nuclear-model uncertainties and more realistic recoil-based DPA calculations.

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