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Deterministic modeling of higher angular moments of resonant neutron scattering

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ABSTRACT

An exact scattering kernel formulation for anisotropic scattering up to angular order 10 has been developed and implemented into a deterministic code. The effects of accounting for lattice dynamics on the modeling of neutron scattering in ^{235}U, ^{238}U, ^{238}Pu, and other nuclides have been demonstrated. The new formulation essentially reproduces other investigators previous results for isotropic scattering and quantifies the departures from the isotropic values when higher angular orders are accounted for. The correct accounting for the lattice effects influences the estimated values for the probability of neutron absorption and scattering, which in turn affect the estimation of core reactivity and burnup characteristics. It is shown that, when using the exact scattering kernel formulation, the probability for upscattering significantly increases with increasing temperatures. For example, upscattering for ^{238}U from below the 20.67 eV resonance increases from 5.57% at 300 K to 30.41% at 1000 K, respectively. Thus, it is shown that the exact scattering kernel is strongly sensitive to temperature, a fact of major importance for High Temperature Reactor fuels. The slowing down process is important in thermal reactors because it results in the neutrons entering the thermal energy range in which the majority of fission events occur. Correctly modeling the slowing down and hence slowing down source into the thermal energy range and consequently allowing the correct modeling of the thermal energy neutron fluxes (or the correct thermal range portion of the spectrum) is paramount to the correct prediction of criticality and safety features such as the Doppler effect. These artifacts are important for all thermal spectrum reactors. In High Temperature Reactors such as the NGNP or the Deep Burn HTR these effects are even more important.

1. Introduction

The purpose of the study reported on in this paper is the demonstration of the effects of improved modeling of neutron scattering within resonances on the scattering kernels that are used in neutronics calculations. The neutron slowing down process in thermal reactors is important because it results in neutrons entering the thermal energy range from which the majority of neutron-induced fission events occur. In High Temperature Reactors (HTRs) such as the Next Generation Nuclear Plant (NGNP) and the Deep Burn HTR, the correct modeling of the slowing down process and hence the slowing down source into the thermal energy range and consequently allowing the correct modeling of the thermal energy neutron fluxes (or the correct thermal range portion of the spectrum) is paramount to the correct prediction of criticality and of safety features such as the Doppler effect. The work of previous researchers has shown that the exact scattering kernel increases LWR Doppler coefficients by a quantity of the order of 10% compared to the asymptotic model and results in a decrease in the hot full power eigenvalues by an amount of about ~200 pcm for LWRs and ~450 pcm for NGNPs (Lee et al., 2008).

The principal physical mechanism underlying the establishment of neutron spectra is the succession of nuclear reactions in which neutrons lose or gain energy, i.e., the scattering processes. As long as neutrons are only losing energy, they are "slowing down." The loss of energy by the neutrons is the dominant energy exchange mechanism for very fast (and hence very energetic) neutrons. In the past this fact led to the use of approximations in which the gain of energy by neutron in collisions with the lattice atoms (fuel, cladding, moderator, or other materials) was assumed negligible in the energy range above the thermal range. This assumption was demonstrated to be inaccurate and unacceptable when scattering resonances are present at intermediate energies (the lower energy domain within the slowing down range). Previous work by others that addressed these issues was limited to isotropic scattering (angular dependence of order 0) implementation in both deterministic and Monte Carlo applications (Ouisloumen and Sanchez, 1991; Lee et al., 2008; Becker et al., 2009). The present work extends the analytical determinis-

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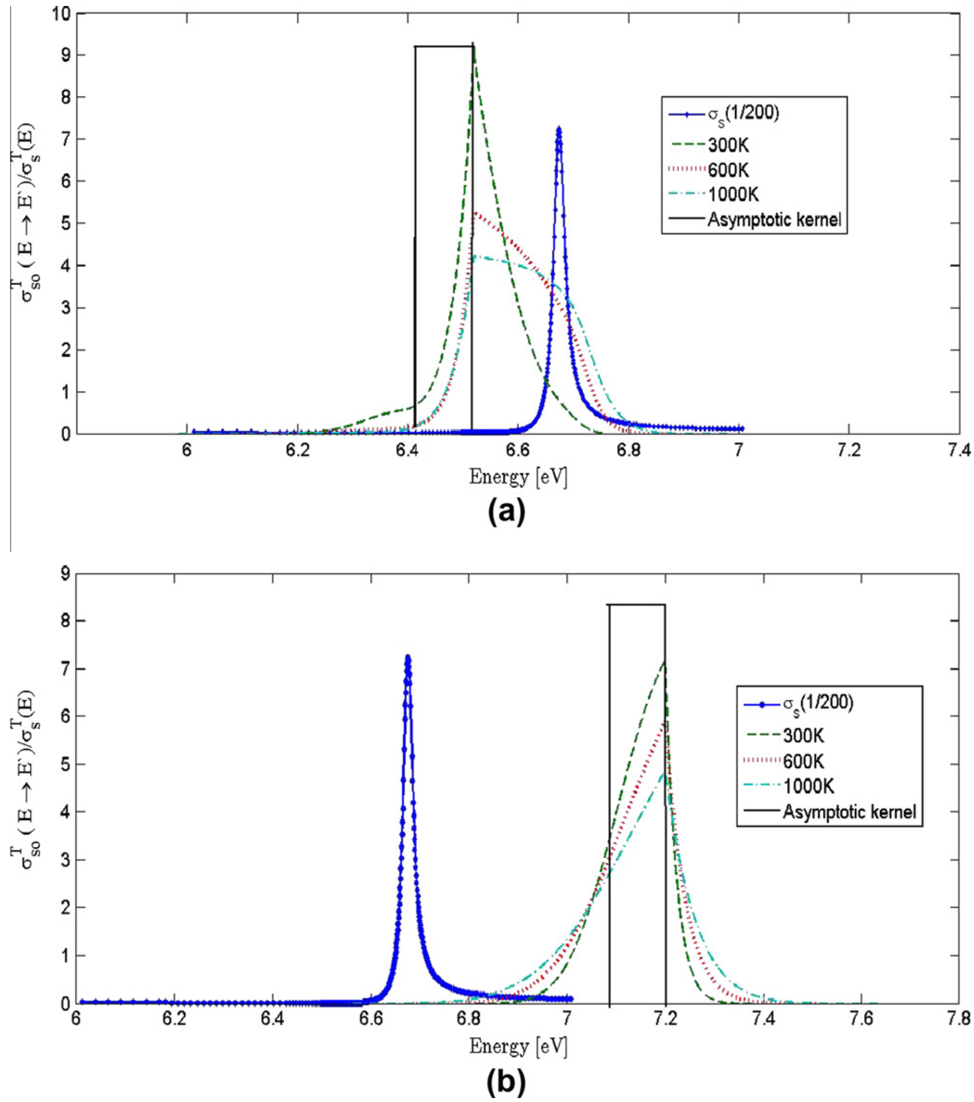

Fig. 1. Effective transfer kernel of ^{238}U at various temperatures near the 6.67-eV resonance for neutrons of energy (a) 6.52 eV and (b) 7.2 eV.

tic approach for application to anisotropic scattering cases of up to order 10 angular dependence.

2. The scattering transfer kernel

The formula of the moments for the energy transfer kernel from elastic scattering events, corrected for lattice interactions in which energy may be both lost or gained by the neutron, was originally derived by Ouisloumen and Sanchez (1991). It states

$$\sigma_{sn}^{T}(E \to E') = \gamma \int_0^\infty t\sigma_s^{tab}\left(\beta \frac{kT}{A} t^2\right) e^{-\frac{t^2}{A}} \psi_n(t)dt \tag{1a}$$

where

$$\gamma = \frac{\beta^{\frac{5}{2}}}{4E} e^{\frac{E}{kT}} \tag{1b}$$

and where t a variable proportional to the neutron speed, β has its usual meaning,

$$\beta = \frac{A+1}{A} \tag{1c}$$

where A is the atomic mass number of lattice atoms (ratio of the lattice nucleus mass to the mass of the neutron), k is Boltzmann's constant, and t designates the temperature of the lattice.

In Eq. (1a), the function $\psi_n(t)$ is the nth order component of the angular dependence of the scattering kernel. An explicit mathematical expression for $\psi_n(t)$ was derived by Ouisloumen and Sanchez (1991) and is reproduced in Appendix A for completeness, with corrections.

The symbol σ_s^{tab} stands for the tabulated cross section values at 0 K. Eq. (1a) was explicitly evaluated analytically and then also numerically using Gauss–Legendre Quadratures. In order to verify the analytic evaluation for Eq. (1a), neutrons were started at various energies and temperatures and the corresponding scattering kernels were computed. Cross-section values for σ_s^{tab} were generated using NJOY99.336 (MacFarlane and Muir, 1999) and interpolated from a linear piecewise continuous tabulation.

3. Application: numerical examples of resonance scattering kernels

The first tests used to verify the implementation of the scattering kernel both analytically and numerically are illustrated here. Numerical results of the program compared well with those reported by Ouisloumen and Sanchez for the case of ^{238}U and ^{56}Fe. Fig. 1 displays the scattering transfer kernels at energies below and above the first resonance of ^{238}U (6.67 eV), compared to the asymptotic model. The same work has been extended for other