TITLE: CALCULATION OF NEUTRON CROSS SECTIONS FOR TUNGSTEN ISOTOPES

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Neutron-induced cross sections on tungsten isotopes have been calculated in the energy range between 1 and 20 MeV using pre-equilibrium-statistical model techniques. The success of these calculations, which form part of an effort to improve the evaluated neutron and gamma-ray production data for tungsten appearing in ENDF/B, depends strongly on the determination of consistent input parameter sets applicable over the entire range of interest. For example, neutron optical model parameters have been derived through a simultaneous analysis of total cross sections, resonance data, and angular distributions. These parameters, when used in multistep Hauser-Feshbach calculations, produce good agreement with various experimental data such as neutron inelastic scattering excitation functions and (n,2n) cross sections. Likewise, gamma-ray strength functions have been determined through fits to neutron capture data that produce calculated results that compare well to measured gamma-ray production cross sections. A description of the techniques used in such parameter determinations as well as comparison of calculated results to experimental data will be presented.

Preliminary calculations of neutron-induced cross sections on tungsten isotopes have been made using pre-equilibrium statistical model techniques from 0.2 to 20 MeV. This effort comprises part of a new tungsten evaluation which hopefully will correct problems in the present ENDF/B evaluation arising from energy imbalance at several energies.

The determination of neutron optical parameters plays an important role in the present calculations since parameters are needed which realistically describe low energy neutron emission such as in (n,2n) reactions while also producing reasonable values for compound nucleus formation cross sections at higher energies. To produce such parameters, we adopted the following approach. Since the tungsten isotopes are deformed, we determined the direct inelastic cross section from scattering on low lying collective states through use of coupled-channel calculations. This cross section was then subtracted from evaluated values of the experimental total cross section and an effort was made to fit this remainder using the spherical-optical model with realistic parameter values. By doing so, we sought to separate compound and direct reaction effects so that reaction cross sections determined from these optical parameters would in fact represent mainly the compound nucleus formation cross section. In this manner, Hauser-Feshbach calculations could be made without having to adjust the formation cross section to account for direct effects not included in the reaction mechanism.

To determine direct inelastic scattering cross sections from the 2+ and 4+ rotational states of the even tungsten isotopes, we used the JUPITER coupled-channel program along with deformed neutron optical parameters and B\(_2\), B\(_3\) values determined by Delarocha. We then took recent evaluations of the \(^{182,184,186}\)W total cross sections based mainly on new measurements of Guenther and also those of Foster and subtracted these calculated direct inelastic scattering contributions. For \(^{185}\)W we used an average of the evaluated total cross sections for \(^{184}\)W and \(^{186}\)W and subtracted contributions from direct inelastic scattering to the 1/2, 3/2\(^+\), 5/2\(^+\), and 7/2\(^+\) levels. As an example, the subsequent spherical optical parameters determined for \(^{184}\)W are shown in Table I.

Along with this effort, we also extracted approximate gamma-ray strength functions from fits to \(^{184,186}\)W(n,\(\gamma\)) cross sections. In doing so, we assumed a giant dipole resonance form consisting of one Lorentz shape whose width and location were adjusted to approximate the double Lorentz shape which exists because of deformation effects. We did not attempt, for these preliminary calculations, to include refinements such as the pygmy resonance and/or dip occurring for \(E_\gamma = 6\) MeV in the shape of the strength function. Our present gamma-ray strength functions enabled us to describe effectively gamma-ray competition to neutron emission, which is important especially around the (n,2n) reaction threshold.

To test our choice of neutron optical model and gamma-ray strength function parameters, we performed two sets of calculations, one for incident neutron energies below 5 MeV and one for energies from the (n,2n) threshold up to 15 MeV. The latter calculations also provided information concerning the suitability of the Gilbert-Cameron level density parameters we used throughout the calculations. Figure 1 illustrates results obtained for \(^{184}\)W from optical model and width-fluctuation corrected Hauser-Feshbach calculations using the optical parameters of Table I. For the calculations of the total cross section and the excitation cross sections.

### Table I. Spherical Optical Model Parameters for n + \(^{184}\)W

<table>
<thead>
<tr>
<th>(V_{\text{MeV}})</th>
<th>(r(\text{fm}))</th>
<th>(a(\text{fm}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.2 ± 0.13E</td>
<td>1.1</td>
<td>0.45</td>
</tr>
<tr>
<td>5.24 ± 0.23E</td>
<td>1.09</td>
<td>0.4</td>
</tr>
<tr>
<td>Above 6 MeV</td>
<td>(v_{\text{SD}(\text{MeV})} = 6.2)</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>(v_{\text{SD}(\text{MeV})} = 6.6)</td>
<td>0.75</td>
</tr>
</tbody>
</table>
sections for the 0.11 MeV (2+) and the 0.365 MeV (4+)
states, we added the appropriate direct inelastic scatter-
ing contribution (as obtained from JUPITOR) to the
Hauser-Feshbach or spherical optical model results.
The elastic cross section includes both contributions
from the shape elastic and compound elastic cross sec-
tions. Figure 2 compares calculated (n,2n) results to
the experimental 182,183,184,185W(n,2n) cross sections
measured by Frehaut1 from threshold to 14 MeV. Here
the multistep Hauser-Feshbach code GNASH1 was used
along with pre-equilibrium corrections based on the Kal-
bach1 excitation model. The agreement with these differ-
ing types of data confirms several things, particularly
the low and high energy behavior of the neutron trans-
mission coefficients as well as the value of the gamma-
ray strength functions. Finally, in Figure 3 we com-
pare our neutron emission spectrum obtained by a combi-
nation of calculated results from 182,183,184,185W with
measurements on natural tungsten by Hermadorf et al.11
This comparison provides a further check on our calcu-
lation, particularly with regard to pre-equilibrium correc-
tions applied above 10 MeV.

Thus, our preliminary efforts to determine and ver-
ify neutron and gamma-ray parameters have led to values
which appear to satisfactorily reproduce the majority
of neutron-induced reaction data for tungsten isotopes.

Fig. 1. Calculated values for the total, elastic, and
inelastic scattering cross sections are compared to the Guenther (Ref. 5) data
for 182W.
Fig. 2. Calculated $^{182,183,184,186}W(n,2n)$ cross sections are compared to the Frehaut (Ref. 8) results.

Fig. 3. A comparison of calculated and experimental (Ref. 11) values for the neutron emission spectra induced by 14.5 MeV neutrons.