Analyses of JAEA/FNS iron in-situ experiment with latest nuclear data libraries

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Abstract. We found ENDF/B-VIII.0 caused the following problems through our analyses of the iron in-situ experiment at JAEA/FNS; 1) the neutron flux of 1 - 10 keV is overestimated more in the shallower region of the iron assembly, 2) the reaction rate of $^{113}$In (n,n)$^{115m}$In is underestimated more in the deeper region, 3) the neutron flux above 10 MeV is underestimated more in the deeper region. The reasons for these problems were investigated in detail and it was specified that the inelastic scattering data of $^{56}$Fe in ENDF/B-VIII.0 mainly caused the first and second problems and that the cross section of the (n,2n) reaction and the angular distribution data of the elastic scattering of $^{56}$Fe in ENDF/B-VIII.0 caused the third problem.

1 Introduction

For the JENDL-5 [1] development we analyzed the iron in-situ experiment [2] at the DT neutron source facility FNS (Fusion Neutronics Source) in JAEA (Japan Atomic Energy Agency) with the two-dimensional Sn code DORT [3] and the latest nuclear data libraries in 2020: JENDL-4.0 [4], ENDF/B-VIII.0 [5] and JEFF-3.3 [6]. As a result, the calculation results with JENDL-4.0 and JEFF-3.3 agreed with the measured data well, while the result with ENDF/B-VIII.0 reproduced the measured data worse than those with JENDL-4.0 and JEFF-3.3. Here we investigate the reasons of this ENDF/B-VIII.0 issue.

2 Overview of JAEA/FNS iron in-situ experiment

Figure 1 shows an experimental configuration of the iron in-situ experiment at JAEA/FNS. The cylindrical iron assembly of 1000 mm in diameter and 950 mm in height was irradiated with the DT neutron source. Neutron spectra over almost the whole energy with an NE213 detector, proton recoil counters, and the slowing down time method and reaction rates of the reactions in Table 1 were measured along the centerline inside the iron assembly. The details of the measurement are described in Ref. 2.

![Fig. 1. Experimental configuration.](image)

Table 1. Reactions of reaction rates measured.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Sensitive neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{9}$Nbn(2n)$^{10}$Nb</td>
<td>&gt; 10 MeV</td>
</tr>
<tr>
<td>$^{27}$Al(n,γ)$^{28}$Na</td>
<td>&gt; 3 MeV</td>
</tr>
<tr>
<td>$^{113}$In(n,γ)$^{115m}$In</td>
<td>&gt; 0.3 MeV</td>
</tr>
<tr>
<td>$^{197}$Au(n,γ)$^{199}$Au</td>
<td>low energy</td>
</tr>
</tbody>
</table>

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3 Calculation Method

The two-dimensional Sn code DORT was used because of short calculation time, no statistical error and similar results to those with the Monte Carlo code MCNP [7]. The latest nuclear data libraries in 2020, JENDL-4.0, ENDF/B-VIII.0 and JEFF-3.3, were selected for the analysis of the iron experiment. ENDF/B-VII.1 [8] was additionally used because the calculation result with ENDF/B-VII.1 agreed the measured data better than that with ENDF/B-VIII.0 as described in the next section.

MATXS files [9] (neutron: 199 groups) of these nuclear data libraries were produced with the NJOY2016 code [9]. Multigroup libraries for the iron experiment with the self-shielding correction were generated from the MATXS files with the TRANSX code [10].

The P$_S$-S$_{16}$ approximation was adopted in the calculation. The R and Z intervals of the iron assembly...
Neutron spectra at depth of 110 mm.

Neutron spectra at depth of 210 mm.

Neutron spectra at depth of 410 mm.

Neutron spectra at depth of 610 mm.

Fig. 2. Neutron spectra at depth of 110 mm.

Fig. 3. Neutron spectra at depth of 210 mm.

Fig. 4. Neutron spectra at depth of 410 mm.

Fig. 5. Neutron spectra at depth of 610 mm.

Fig. 6. C/Es of integrated neutron fluxes in specific energy regions.

Fig. 7. C/Es of reaction rates.

were both 20 mm except for near the boundary of the iron assembly and air, where the intervals were 5 or 10 mm. Before the DORT calculation a first collision source was calculated with the GRTUNCL code [3].

4 Calculation Results

Figures 2 - 5 show the neutron spectra at the depths of 110, 210, 410 and 610 mm. Most of the calculated neutron spectra agree with the measured ones. However, the neutron flux around 1 - 10 keV with ENDF/B-VIII.0 is much larger than those with the other nuclear data libraries and the measured one at the depths of 110 and 210 mm.

For detail comparison of the measured and calculated neutron spectra, the ratios of the calculated neutron fluxes to the measured ones (C/E) in specific energy regions from the neutron spectra are plotted in
Fig. 6. Most of the calculated neutron fluxes agree with the measured ones within 20%. However, the calculated neutron fluxes above 10 MeV with ENDF/B-VIII.0, JEFF-3.3 and ENDF/B-VII.1 underestimate the measured one at the deeper region and that from 1 to 10 keV with ENDF/B-VIII.0 overestimates the measured one at the shallower region.

Figure 7 shows the C/E of the reaction rates. The C/E of the $^{90}$Nb(n,2n)$^{90}$Nb and $^{27}$Al(n,$\alpha$)$^{24}$Na reaction rates are similar with those of the neutron flux above 10 MeV. The C/E of the $^{197}$Au(n,$\gamma$)$^{198}$Au reaction rate are similar with those of the neutron flux from 10 to 100 eV. However the C/E of the $^{115}$In(n,$\alpha$)$^{115m}$In reaction rate have a different trend; only the calculated reaction rate with ENDF/B-VIII.0 underestimates the measured one at the deeper region, while the other calculation results agree with the measurement well.

5 Problems of ENDF/B-VIII.0

The following problems of ENDF/B-VIII.0 are found from the calculation results shown in Section 4.

Problem 1:
The neutron flux of 1 - 10 keV is overestimated more at the shallower region.

Problem 2:
The reaction rate of $^{115}$In(n,$\alpha$)$^{115m}$In sensitive to neutrons above 0.3 MeV is underestimated more at the deeper region.

Problem 3:
The neutron flux above 10 MeV is underestimated more at the deeper region.

Note that Problem 3 is also true of JEFF-3.3 and ENDF/B-VII.1. We investigate the reasons of these problems in detail.

5.1 Problems 1 and 2

In order to specify which iron isotope causes Problems 1 and 2, we replaced the iron isotope files one by one from ENDF/B-VIII.0 to ENDF/B-VII.1, which did not cause the problems, and analyzed the experiment. Figure 8 shows the result, where for example ‘ENDF/B-VIII.0 (Fe54;b71)’ means that $^{54}$Fe is ENDF/B-VII.1 and the other iron isotopes are ENDF/B-VIII.0, and indicates that $^{56}$Fe in ENDF/B-VIII.0 mainly causes Problems 1 and 2. Note that inelastic scattering and (n,2n) reaction produce secondary neutrons from 1 to 10 keV.

Next, we compared each reaction data of $^{56}$Fe in ENDF/B-VIII.0 with that in ENDF/B-VII.1. Then the inelastic scattering and (n,2n) reaction cross sections were different between ENDF/B-VIII.0 and ENDF/B-VII.1 as shown in Fig. 9. These data of $^{56}$Fe in ENDF/B-VIII.0 were replaced with those in ENDF/B-VII.1 separately and the experiment was analyzed with the modified $^{56}$Fe files. Figure 10 shows the result, where ‘ENDF/B-VIII.0 (Fe56(n,2n);b71)’ means that the (n,2n) reaction data of $^{56}$Fe are ENDF/B-VII.1 and the other $^{56}$Fe data are ENDF/B-VIII.0 and ‘ENDF/B-VIII.0 (Fe56 inelas;b71)’ means that the inelastic scattering data of $^{56}$Fe are ENDF/B-VII.1 and the other $^{56}$Fe data are ENDF/B-VIII.0, and demonstrates that the inelastic scattering data of $^{56}$Fe in ENDF/B-VIII.0 mainly cause Problems 1 and 2.

The inelastic scattering consists of the discrete inelastic scattering (mt=4 except for mt=91) and continuum inelastic scattering (mt=91). Figure 11 compares the cross sections of the discrete and continuum inelastic scatterings of $^{56}$Fe in ENDF/B-VIII.0 and ENDF/B-VII.1. Both the cross sections in ENDF/B-VIII.0 are larger than those in ENDF/B-VII.1, but the energy regions of the differences are distinct.
below 7 MeV for the discrete inelastic scattering and around 10 MeV for the continuum inelastic scattering. Then we studied effects of the discrete and continuum inelastic scatterings separately by replacing the data of the discrete and continuum inelastic scatterings of $^{56}$Fe in ENDF/B-VIII.0 with those in ENDF/B-VII.1, respectively. The result with the modified $^{56}$Fe files is shown in Fig. 12, where ‘inel.’, ‘disc.’ and ‘cont.’ mean ‘inelastic scattering’, ‘discrete’ and ‘continuum’, respectively. From Fig. 12 it is concluded that Problem 1 is mainly caused by the discrete inelastic scattering data of $^{56}$Fe in ENDF/B-VIII.0 and Problem 2 is caused by both the discrete and continuum inelastic scattering data of $^{56}$Fe in ENDF/B-VIII.0.

5.2 Problem 3

The same procedure as that for Problems 1 and 2 was also carried out for Problem 3, but JENDL-4.0, not ENDF/B-VII.1, was used because only JENDL-4.0 did not cause Problem 3 as shown in Fig. 6 (a). Figure 13 shows the results by replacing the iron isotope file one by one from ENDF/B-VIII.0 to JENDL-4.0. It suggests that $^{56}$Fe in ENDF/B-VIII.0 also causes Problem 3 mainly.

Next, we compared each reaction data above 10 MeV of $^{56}$Fe in ENDF/B-VIII.0 with those in JENDL-4.0. Then the (n,2n) reaction cross section and angular distribution of elastic scattering around 0 degree were different between ENDF/B-VIII.0 and JENDL-4.0 as shown in Fig. 14. Then these data above 10 MeV of $^{56}$Fe in ENDF/B-VIII.0 were replaced with those in JENDL-4.0 separately and the experiment was analyzed with the modified $^{56}$Fe files. Figure 15 shows the result, where ‘$^{14}$O’ and ‘scat. ang.’ mean ‘JENDL-4.0’ and ‘scattering angular distribution’, respectively. It specifies that both the (n,2n) reaction cross section and angular distribution of elastic scattering in $^{56}$Fe of ENDF/B-VIII.0 mainly cause Problem 3. Note that we studied the same issue for ENDF/B-VI in 1998 [11].

6 Conclusion

We analyzed the iron in-situ experiment at JAEO/FNS for the JENDL-5 development with the latest nuclear data libraries in 2020. The results clearly showed that ENDF/B-VIII.0 caused the following problems.

Problem 1:
The neutron flux of 1 - 10 keV is overestimated more at the shallower region.

Problem 2:
The reaction rate of the $^{114}$In(n,n)$^{115}$In reaction is underestimated more at the deeper region.

Problem 3:
The neutron flux above 10 MeV is underestimated more at the deeper region.

Our detail study specified reasons of the problems as follows.

Problem 1: the discrete inelastic scattering data of $^{56}$Fe.

Problem 2: the discrete and continuum inelastic scattering data of $^{56}$Fe.

Problem 3: the (n,2n) reaction data and angular distribution data of elastic scattering of $^{56}$Fe.

We hope that the $^{56}$Fe data in ENDF/B-VIII.0 will be revised in the next ENDF/B based on this study.

References