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Title: Average and Effective Q-Values for Fission Product Average (n,2n) and (n,3n) Reaction Cross Sections

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Average and Effective Q-Values for Fission Product Average (n,2n) and (n,3n) Reaction Cross Sections

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1 Introduction

We define the "lumped" fission product average cross sections as

$$\overline{\sigma}_{2n}(E) = \sum_{Z,A} \frac{1}{2}\sigma_{2n}(Z,A,E)Y(Z,A), \tag{1}$$

$$\overline{\sigma}_{3n}(E) = \sum_{Z,A} \frac{1}{2}\sigma_{3n}(Z,A,E)Y(Z,A), \tag{2}$$

where $\sigma_{2n,3n}(Z,A,E)$ is the individual (n,2n) and (n,3n) reaction cross sections on the target (Z,A) at the neutron incident energy of E, $Y(Z,A)$ is the yield of the prompt fission product (Z,A). The (n,2n) and (n,3n) reactions on fission products are always endothermic, and each (Z,A) has different reaction Q-values. Here we denote these Q-values by $Q_{2n}(Z,A)$ and $Q_{3n}(Z,A)$. This causes a problem of definition of reaction Q-value when ENDF files for $\sigma_{2n,3n}(Z,A,E)$ are created. Because some of the fission products have a very small neutron separation energy, the reaction threshold energies for the average cross section tend to go much lower. However, these threshold energies do not correspond to the actual energy absorption for these reactions. This note explains what is the effective energy loss by the (n,2n) and (n,3n) reactions.

2 Definition of average and effective Q-values

First of all, despite we define the average and effective Q-values in this note, they are not used in nuclear physics in general. We define them just for convenience.

Suppose an incident neutron interacts with one of the fission products and induces the (n,2n) reaction, the probability of the target being (Z,A) is

$$p(Z,A,E) = \frac{\sigma_{2n}(Z,A,E)Y(Z,A)}{\sum_{Z'A'}\sigma_{2n}(Z',A',E)Y(Z',A')}, \tag{3}$$

and this reaction absorbs the energy of $Q_{2n}(Z,A)$. Therefore the average (n,2n) reaction Q-value can be defined as an average of individual reaction Q-value weighted by occurring reaction

$$\begin{aligned}\overline{Q}_{2n}(E) &= \sum_{Z,A} p(Z,A,E)Q_{2n}(Z,A) \\ &= \sum_{Z,A} \frac{\sigma_{2n}(Z,A,E)Y(Z,A)}{\sum_{Z'A'}\sigma_{2n}(Z',A',E)Y(Z',A')}Q_{2n}(Z,A) \\ &= \frac{1}{2\overline{\sigma}_{2n}(E)}\sum_{Z,A}\sigma_{2n}(Z,A,E)Y(Z,A)Q_{2n}(Z,A),\end{aligned} \tag{4}$$

which means the average Q-value is the incident energy dependent.

When we assume the energy variation of the (n,2n) reaction cross section for all the fission products is similar, an approximation

$$\sigma_{2\mathrm{n}}(Z,A,E) \simeq \overline{\sigma}_{2\mathrm{n}}(E) \tag{5}$$

applying to Eq. (4) yields

$$\begin{aligned}\overline{Q}_{2\mathrm{n}}(E) &\simeq \frac{1}{2\overline{\sigma}_{2\mathrm{n}}(E)}\sum_{Z,A}\overline{\sigma}_{2\mathrm{n}}(E)Y(Z,A)Q_{2\mathrm{n}}(Z,A)\\ &= \frac{1}{2}\sum_{Z,A}Y(Z,A)Q_{2\mathrm{n}}(Z,A)\\ &= \langle Q_{2\mathrm{n}}\rangle. \end{aligned} \tag{6}$$

Now this is an E-independent effective Q-value.

We calculated $\langle Q_{2\mathrm{n}}\rangle$ and $\langle Q_{3\mathrm{n}}\rangle$ for ^{235}U and ^{239}Pu, which are given in the table. For heating calculations in radiation transport, we should use the average Q-value. However, the effective Q-value could be a first-order approximation.

The effective Q-value should not be used as the Q-value in the ENDF file, since the threshold energy of $\overline{\sigma}_{2\mathrm{n},3\mathrm{n}}(E)$ goes much lower than these values.

Table 1: The effective Q-values of (n,2n) and (n,3) reactions for ^{235}U and ^{239}Pu. The values are in MeV.

	^{235}U	^{239}Pu
$\langle Q_{2\mathrm{n}}\rangle$	−5.561	−5.888
$\langle Q_{3\mathrm{n}}\rangle$	−11.38	−12.03