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Systematic effects on cross-section data derived from reaction rates at a cold neutron beam

Gašper Žerovnik [a,b], Björn Becker [b], Tamás Belgya [c], Christoph Genreith [d], Hideo Harada [e], Stefan Kopecky [b], Vladimir Radulović [a,f], Tadafumi Sano [g], Peter Schillebeeckx [b,*], Andrej Trkov [a,h]

[a] Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[b] European Commission, Joint Research Centre, Retieseweg 111, B-2440 Geel, Belgium
[c] Institute for Energy Security and Environmental Safety, Centre for Energy Research, Hungarian Academy of Sciences, 29-33 Konkoly-Thege Miklós Street, H-1121 Budapest, Hungary
[d] Heinz Maier-Leibnitz Zentrum (MLZ), Technische Universität München, Lichtenbergstr. 1, D-85748 Garching, Germany
[e] Japan Atomic Energy Agency, Tokai-mura, 319-1195 Ibaraki, Japan
[f] CEA, DEN, DER, Instrumentation, Sensors and Dosimetry Laboratory, Cadarache, F-13108 St-Paul-Lez-Durance, France
[g] Research Reactor Institute, Kyoto University, Kumatori-cho, 590-0494 Osaka, Japan
[h] International Atomic Energy Agency, Vienna Int. Centre, A-1400 Vienna, Austria

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ABSTRACT

The methodology to derive cross-section data from measurements in a cold neutron beam was studied. Mostly, capture cross-sections at thermal energy are derived relative to a standard cross-section, e.g. the cross-section of the ^{1}H(n,γ), ^{14}N(n,γ), or ^{197}Au(n,γ) reaction, and proportionality between the standard and the measured cross-section, evaluated at different energies in the sub-thermal region, is often assumed. Due to this assumption the derived capture cross-section at thermal energy can be biased by more than 10%. Evidently the bias depends on how much the energy dependence of the cross-section deviates from a direct proportionality with the inverse of the neutron speed. The effect is reduced in case the cross-section is not derived at thermal energy but at an energy close to the average energy of the cold neutron beam. Nevertheless, it is demonstrated that the bias can only be avoided in case the energy dependence of the cross-section is known and proper correction factors are applied. In some cases the results are also biased when the attenuation of the neutron beam within the sample is neglected in the analysis. Some of the cross-section data reported in the literature suffer from such bias effects. Hence, the results have to be corrected using the correction factors presented in this paper.

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1. Introduction

Cross-sections for neutron induced reactions at thermal energy can be derived from measurements in a cold neutron beam to minimize contribution from resonance capture. From these experiments an average reaction rate integrated over the neutron energy spectrum is measured. To derive from such an integral quantity a cross-section at a specific energy, e.g. at thermal energy (25.3 meV or 2200 m/s), reference is made to a standard cross-section. The ^{1}H(n,γ) [1], ^{14}N(n,γ) [2] or ^{197}Au(n,γ) [3] cross-sections are mostly used as standard cross-section.

It is often supposed that both the standard and unknown cross-sections are proportional to the inverse of the incident neutron speed, i.e. that they have a pure $1/v$ shape. This assumption is not valid when the cross-section is dominated by the contribution from low energy resonances or from bound states close to the neutron separation energy. For such reactions the energy dependence of the cross-section is required to deduce a cross-section at a given energy.

In this work bias effects due to cross-sections deviating from a $1/v$ shape and due to the shape of the neutron energy spectrum are investigated. In addition, the effect of the attenuation of the neutron beam and the contribution of multiple interaction events within the sample are verified. The analysis in this work is limited

* Corresponding author. Tel.: +32 14571475; fax: +32 571862.
E-mail addresses: gasper.zerovnik@ijs.si (G. Žerovnik), belgya.tamas@energia.mta.hu (T. Belgya), christoph.genreith@frm2.tum.de (C. Genreith), harada.hideo@jaea.go.jp (H. Harada), stefan.kopecky@ec.europa.eu (S. Kopecky), vladimir.radulovic@ijs.si (V. Radulović), t-sano@rri.kyoto-u.ac.jp (T. Sano), peter.schillebeeckx@ec.europa.eu (P. Schillebeeckx), andrej.trkov@ijs.si (A. Trkov).

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to reaction rates. No attempt is made to study bias effects due to emission probabilities, decay constants or missing transitions.

The study is focused on the cross-sections for the ^{241}Am(n,γ) and ^{237}Np(n,γ) reactions. These cross-sections were selected since they are strongly influenced by bound states close to the neutron separation energy and by low energy resonances. In addition, results of direct measurements of the energy dependence are available [4,5]. In the study two cold neutron beam facilities and a pure thermal Maxwellian spectrum at room temperature are considered.

2. Methodology

Measurements in cold neutron beams are very useful to determine capture cross-sections in the thermal and sub-thermal energy region. From such measurements an average reaction rate is obtained. This rate is used to derive the cross-section at a given energy E_0, mostly taken at thermal energy, i.e. at 25.3 meV corresponding to a neutron speed of 2200 m/s. The theoretical estimate of the rate for a neutron induced capture reaction with nuclide x is

$$R_x = \frac{1}{V_x} \int \sigma_x(E)\varphi(E, \vec{r})\, dE\, dV \tag{1}$$

where R_x is the average reaction rate per nucleus, V_x the sample volume, $\varphi(E, \vec{r})$ the spatial and energy dependent neutron fluence rate and $\sigma_x(E)$ the energy dependent cross-section for the capture reaction with nuclide x.

Mostly reference is made to a standard cross-section that is used to determine the neutron fluence rate. The cross-section of interest at a specific energy E_0, denoted by $\sigma_{0,x}$, is derived from the standard cross-section $\sigma_{0,s}$ at this energy and the ratio of reaction rates:

$$\sigma_{0,x} = \sigma_{0,s}\frac{R_x}{R_s}\frac{\frac{1}{V_s}\int \sigma'_s(E)\varphi(E, \vec{r})\, dE\, dV}{\frac{1}{V_x}\int \sigma'_x(E)\varphi(E, \vec{r})\, dE\, dV} \tag{2}$$

where R_x and R_s are the reaction rates per nucleus of the reaction of interest and the standard reaction, respectively. The energy dependences of the corresponding cross-sections, which are denoted by $\sigma'_s(E)$ and $\sigma'_s(E)$, are normalized to unity at the energy E_0 by

$$\sigma'_i(E) = \sigma_i(E)/\sigma_{0,i}, \quad i = x, s. \tag{3}$$

Cold neutron beams are characterized by a close-to-Maxwellian neutron spectrum, with a peak energy that is significantly lower than 25.3 meV. In this region most of the cross-sections are directly proportional to the inverse of the neutron speed. For this reason it as often assumed that the cross-sections at energy E_0 can be derived directly from the ratio of the reaction rates [6–8] and Eq. (2) reduces to

$$\sigma_{0,x} = \sigma_{0,s}\frac{R_x}{R_s}. \tag{4}$$

Such an assumption is not always justified and can result in bias effects even if the cross-section is derived at an energy E_0 below the thermal energy. Also, by applying Eq. (4) the attenuation of the neutron flux within the samples is neglected.

To derive accurate cross-sections, the energy dependence of the cross-sections is required [9] and the unknown cross-section should be derived from the following equation:

$$\sigma_{0,x} = \sigma_{0,s}\frac{R_x}{R_s}\frac{F_s}{F_x}\frac{F_{\varphi,s}}{F_{\varphi,x}} \tag{5}$$

where

$$F_i = \frac{\int \sigma_i(E)\varphi_0(E)\, dE}{\int \sigma_{0,i}\sqrt{\frac{E_0}{E}}\varphi_0(E)\, dE}, \quad i = x, s \tag{6}$$

is a correction factor accounting for the deviation from $1/v$ energy dependence of the cross-section. The correction factor

$$F_{\varphi,i} = \frac{\frac{1}{V_i}\int \sigma_i(E)\varphi(E, \vec{r})\, dE\, dV}{\int \sigma_i(E)\varphi_0(E)\, dE}, \quad i = x, s \tag{7}$$

accounts for the attenuation of the neutron beam in the samples, where $\varphi_0(E)$ is the energy dependent fluence rate of the unperturbed neutron field (e.g. the incoming neutron beam). While the correction factor F_i depends only on the cross-section shape, the correction factor $F_{\varphi,i}$ also depends on the absolute value of the cross-section.

2.1. Cross-section shape correction factors

The correction factors $F_{i=x,s}$ are due to the deviation from a $1/v$ dependence of the cross-section. The factors equal unity only if the cross-sections are proportional to the inverse of the speed in the energy region contributing to the reaction rate and in the region that includes the energy E_0 at which the cross-section is derived.

The cross-sections for the ^{1}H(n,γ), ^{14}N(n,γ) and ^{197}Au(n,γ) reactions are often used as standard cross-sections. Their recommended cross-sections at thermal energy are reported in Table 1. The cross-sections for ^{1}H(n,γ) and ^{14}N(n,γ) are expected to behave as $1/v$ in a broad energy region covering the sub-thermal and epithermal regions. However, the cross-section for the ^{197}Au(n,γ) reaction deviates from $1/v$ behaviour in the thermal region. This deviation can be described by a correction factor which can be approximated by a linear function $F_s(k_BT) = a + bk_BT$, where T is the effective temperature of the neutron beam and k_B the Boltzmann constant. Assuming a Maxwellian distribution at different temperatures and using the cross-section recommended in the JEFF-3.2 library [10], the parameters a and b are 0.9910 and 0.5822 eV^{-1}, respectively. For k_BT between 0.1 meV and 100 meV this approximation deviates at most 0.1% from the original values. The non-$1/v$ behaviour can also be concluded from the Westcott factor $g = 1.005$ at $k_BT = 25.3$ meV that differs from unity. One should note, however, that a Westcott factor $g = 1$ at room temperature does not necessarily imply that no corrections for non-$1/v$ behaviour are required.

The thermal cross-section for ^{197}Au(n,γ) is recommended with a small uncertainty, i.e. $\sigma_{0,Au} = 98.68 \pm 0.12$ b [3]. This value at 25.3 meV is predominantly determined by the result of transmission measurements in the energy region between 0.04 meV and 3.55 meV carried out by Dilg et al. [13]. In Ref. [13] all corrections, i.e. the contributions due to coherent and incoherent neutron scattering and those for the non $1/v$-behaviour, are described in detail. Below the Bragg cutoff at 3.69 meV, corresponding to a plane with Miller indices (111) and a neutron wavelength of 0.471 nm, the contribution due to coherent elastic scattering can be neglected [13].

Table 1
Cross-sections of standard neutron induced capture reactions at thermal energy $E_0 = 25.3$ meV.

Reaction	$\sigma_{s,0}$ / b	Ref.
^{1}H(n,γ)	0.3326 ± 0.0007	[1]
^{14}N(n,γ)	0.0803 ± 0.0008	[2]
^{197}Au(n,γ)	98.68 ± 0.12	[3]

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