Validation of neutron data libraries by differential and integral cross sections

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Some new activation cross sections were measured in the discrepant regions of the excitation functions of the following reactions: Hg-198(n,2n)Hg-197m, Hf-176(n,2n)Hf-175, Tl-203(n,2n)Tl-202, Nb-93(n,2n)Nb-92m, Zr-90(n,2n)Zr-89, Re-185(n,2n)Re-184g, Re-185(n,2n)Re-184m. Results obtained for these reactions could contribute to the improvement of the IAEA Reference Neurtron Activation Library and through it to the quality of neutron data.The relative values of reflection $R_\beta = \sigma_{\beta,X}/\sigma_{\beta,H}$ and elastic scattering $R_{EL} = \sigma_{EL,X}/\sigma_{EL,H}$ cross sections of thermal neutrons normalized to hydrogen render possible the validation of different neutron data libraries taking the σ_{EL} data from the JEF Report 14. From the R_β/R_{EL} values the recommended libraries for the σ_{EL} elastic scattering cross sections of elements could be deduced.

1. Introduction

The IAEA Nuclear Data Section established in 1994 a Coordinated Research Project for the improvement of the quality of neutron data used in science and technology and to produce a library of neutron activation cross sections. The library produced under the CRP contains cross sections for 256 neutron induced reactions relevant to a wide range of applications [1]. According to the proposed programme goals of this IAEA CRP we have measured, evaluated and calculated a number of new cross sections [2-6] in an international collaboration especially in the discrepant regions of the excitation functions from threshold to 16 MeV. A recent analysis of the excitation functions of (n,2n) reactions has indicated that the precision of the data below 14 MeV should be improved. Therefore, some new and more precise data were determined for the reactions summarized in the abstract of this paper.

The reflection cross section of thermal neutrons as a microscopic parameter for the characterization of the reflection property of substances introduced by Csikai and Buczkó [7] has been determined for 26 elements from H to Pb and for 38 organic and inorganic compounds in addition to the different mixtures of elements. A strong correlation was found between the reflection cross section $\sigma_{\beta,Z}$ and the Maxwellian spectrum averaged elastic scattering cross section $\sigma_{EL,Z}$ of the elements Z. For the cross section ratio $R = \sigma_\beta/\sigma_{EL}$ a value of 0.60 ± 0.02 was obtained in the given source-detector-sample geometry. It seems to be worthwhile to use this method for validation of neutron data libraries of elastic scattering cross sections.

2. Experimental procedure

The activation method and high resolution gamma spectrometry were used for the measurements of (n,2n) cross sections. Neutrons were produced via the $^2H(d,n)^3He$ and $^3H(d,n)^4He$ reactions using D_2 gas and TiT solid targets in the MGC-20 cyclotron (ATOMKI) and the 200kV intense neutron generator (IEP), respectively. Details of the irradiation arrangements have been described elsewhere [5]. Neutron flux density spectra and mean energies were determined by the multiple foil activation technique combined with the unfolding code SULSA [8] and a pulse height response spectrometer. The mean energy of neutrons has been controlled by using the NEUT code [9]. The variation of the neutron flux in time was monitored by a BF_3 long-counter.

The reflection method based on a point like Pu-Be neutron source and a small BF_3 counter being placed onto the surface of a moderator together with the reflector substance as shown in Fig. 1 is suitable for the determination of the reflection cross section of thermal neutrons. The relative excess count rate $\eta = (I-I_0)/I_0$ measured with (I) and without (I_0) a reflector is proportional to the product of the surface density of atoms N (atoms/cm^2) and the reflection cross section, i.e. $\eta = CN\sigma_\beta$ and so, $\sigma_\beta = \eta/CN$. If $C = 10^{-24}$ cm^2 the value of σ_β is obtained in barn. The sensitive length of the detector is comparable with the 102 mm diameter of the sample, therefore, the reflection cross section is averaged over the ~1cm thick sample. If the target consists of molecules then $\sigma_{\beta mol} = \Sigma_i n_i\sigma_{\beta i} = \eta/CN_{mol}$ where N_{mol} is the number of molecules/cm^2 in the reflector material and n_i is the number of atoms of type i with cross section $\sigma_{\beta i}$ in the molecule. The same expression holds for the mixture of elements, compounds and alloys.

3. Results and conclusions

The (n,2n) cross sections determined by the well known activation expression are summarized in Table 1. Data for Hg-198(n,2n)Hg-197m have been measured for the first time. Cross sections for Hf-176(n,2n)Hf-175 and Tl-203(n,2n)Tl-202 reactions given in ENDF/B-VI and JENDL-3 libraries are in disagreement with the measured trends except of JENDL-3 at 11.2 MeV for Hf. As shown in Fig. 2 the data given in JENDL-3 are lower especially beyond 15 MeV as compared to the ENDF/B-VI. No data are available in the IAEA-NDS library [12] for the above three reactions. The cross section ratios of the Zr-90(n,2n)Zr-89 and Nb-93(n,2n)Nb-92m reactions are used as energy standards around 14 MeV neutron energy. The data given in the three libraries consistent with the measured shape and magnitude of the excitation function for the Zr-90(n,2n)Zr-89 reaction, however, only our data is available at 11.3 MeV, i.e. just at the threshold energy. In the case of Nb-93(n,2n)Nb-92m reaction the measured cross section at 14.1 MeV are in good agreement with the data given in the IAEA-NDS, ENDF/B-VI and JENDL-3 libraries. Considering the strong energy dependence of the reaction cross section near to the threshold further precise measurements are recommended. For Re-185(n,2n)Re-184g and Re-185(n,2n)Re-184m reactions the data are scanty and discrepant. Our measured cross sections support the IAEA-NDS evalutaions, however, the data must be completed and improved both for the isomeric and ground states especially close to the threshold. In Table 2 the evaluated data are given for the same energies as the measured values by interpolation.

The σ_β values were found to be constant up to about 1 cm thick powder, liquid and solid reflectors except for Zn, Fe, Ni and Cu as well as highly absorbing elements (Cl, Co, Ag, Hg) and their compounds. The neutron flux depression caused by such type of samples could be taken into account by a combination of the reflector substances with thin polyethylene foils [10], i.e. the well known reflection cross section (37.6 ± 1.0 b) of CH_2 can be used as a reference (see Fig. 1).

Studies on the cross correlation between the σ_β values deduced from the $\sigma_{\beta mol}$ data have proved that the reflection cross sections are additive. Therefore, the summing expression is valid for different mixtures of elements and compounds and so, the determination of the reflection cross sections is possible even for complex matrices.

The relative values of reflection $R_\beta = \sigma_{\beta,X}/\sigma_{\beta,H}$ and elastic scattering $R_{EL} = \sigma_{EL,X}/\sigma_{EL,H}$ cross sections normalized to hydrogen render possible the validation of different neutron data libraries taking the σ_{EL} data from the JEF Report 14 [11]. The ratio R_β/R_{EL} gives the unity if the measured and accepted data are correct. The recommended libraries for σ_{EL} of different elements are summarized in Table 2. The σ_{EL} data for Hg can be deduced from the measured σ_{β} value.

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References

[1] Reference Neutron Activation Library, (1999), (http://www-nds.iaea.or.at/).

[2] Buczkó Cs. M., Csikai J., Sudár S., Grallert Á., Jonah S. A., Jimba B. W., Chimoye T. and Wagner M. : Phys. Rev., C52, 1940 (1995).

[3] Qaim S. M., Cserpák F. and Csikai J. : Appl. Radiat. Isot., 47, 569 (1996).

[4] Csikai J., Semkova V., Dóczi R., Majdeddin A. D., Várnagy M., Buczkó Cs. M. and Fenyvesi A. : Fusion Eng. Design, 37, 65 (1997).

[5] Dóczi R., Semkova V., Fenyvesi A., Yamamuro N., Buczkó Cs. M. and Csikai J. :Nucl. Sci. Eng., 129, 164 (1998).

[6] Dóczi R., Sudár S., Csikai J. and Qaim S. M. : Phys. Rev., C58, 2577 (1998).

[7] Csikai J. and Buczkó Cs. M. : Appl. Radiat. Isot., 50, 487 (1999).

[8] Sudár S. : INDC(HUN)-026/L, IAEA, Vienna (1989).

[9] Birn I.-G. : Internal Report KFA-INC-IB-1/92, Forschungszentrum Jülich GmbH (1992).

[10] Csikai J., Király B. and Buczkó Cs. M. :20th World Conference of the INTDS, October 2-6, 2000 Antwerp, Belgium.

[11] JEF Report 14, Table of simple integral neutron cross section data from JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 and CENDL-2, NEA OECD, France (1994).

[12] http://iaeand.iaea.or.at/ndspub/rnal/www/rnal.html#top (22 Sept. 2000).

Table 1.

Some measured and evaluated (n,2n) cross sections

Reaction	E_n (MeV)	Measured σ (mb)	IAEA-NDS σ (mb)	ENDF/B-VI σ (mb)	JENDL-3 σ (mb)
$^{198}Hg(n,2n)^{197m}Hg$	11.2 ± 0.20	702 ± 35	—	—	—
	12.5 ± 0.25	910 ± 45	—	—	—
$^{198}Hg(n,2n)^{197g}Hg$	14.7 ± 0.30	1030 ± 60	—	—	—
$^{198}Hg(n,2n)^{197m+g}Hg$	14.7 ± 0.30	1950 ± 70	—	—	—
$^{176}Hf(n,2n)^{175}Hf$	11.2 ± 0.20	1694 ± 85	—	1970	1698
	14.3 ± 0.15	1990 ± 100	—	2043	1890
	14.7 ± 0.30	2050 ±100	—	2045	1895
$^{203}Tl(n,2n)^{202}Tl$	11.2 ± 0.20	1340 ± 70	—	—	2147
	12.5 ± 0.25	1454 ± 80	—	—	2350
	14.7 ± 0.30	1970 ± 110	—	—	2513
$^{93}Nb(n,2n)^{92m}Nb$	11.3 ± 0.20	265 ± 25	323	—	323
	14.1 ± 0.15	460 ± 5	473	—	463
$^{90}Zr(n,2n)^{89}Zr$	11.3 ± 0.20	6.4 ± 1.0	—	—	—
	14.1 ± 0.15	626 ± 6	627	622	634
$^{185}Re(n,2n)^{184g}Re$	11.2 ± 0.20	1530 ± 100	1507	—	—
	14.3 ± 0.15	1670 ± 95	1773	—	—
	14.7 ± 0.15	1780 ± 120	1787	—	—
$^{185}Re(n,2n)^{184m}Re$	11.2 ± 0.20	322 ± 50	368	—	—
	14.3 ± 0.15	380 ± 50	434	—	—
	14.7 ± 0.15	390 ± 70	436	—	—
$^{185}Re(n,2n)^{184m+g}Re$	11.2 ± 0.20	1852 ± 115	1875	1876	1588
	14.3 ± 0.15	2050 ± 110	2207	2205	2029
	14.7 ± 0.15	2170 ± 130	2223	2224	2044

Table 2.

Relative values of reflection and elastic scattering cross sections of thermal neutrons

Element	R_β in %	R_{EL} in %	R_β/R_{EL}	Accepted library
H	$\sigma_{\beta,H} = 17.3$ b	$\sigma_{EL,H} = 29.026$ b	1.000	<JEF Rep.>
C	17.34	17.01	1.019	JEF-2.2
N	35.84	35.69	1.004	JENDL-3.2
O	14.45	13.87	1.042	ENDF/B-VI
F	13.87	14.14	0.981	JEF-2.2
Na	10.66	10.65	1.001	JEF-2.2
Mg	13.00	12.42	1.047	JENDL-3.2
Al	4.97	4.99	0.996	JEF-2.2
Si	7.69	7.62	1.009	JENDL-3.2
S	3.58	3.58	1.000	JENDL-3.2
Cl	57.80	57.74	1.001	ENDF/B-VI
K	7.51	7.59	0.989	JEF-2.2
Ca	9.83	10.08	0.975	CENDL-2
Ti	14.45	14.23	1.015	JENDL-3.2
Mn	7.69	7.55	1.019	ENDF/B-VI
Fe	38.15	39.20	0.973	CENDL-2
Co	20.81	20.91	0.995	JENDL-3.2
Ni	61.85	61.70	1.002	BROND-2
Cu	27.17	27.02	1.006	CENDL-2
Zn	14.45	14.57	0.992	BROND-2
Sr	18.38	18.48	0.995	JENDL-3.2
Zr	24.28	22.37	1.085	JEF-2.2
Nb	21.96	21.89	1.003	JENDL-3.2
Sn	17.92	16.97	1.056	BROND-2
Sb	12.72	12.87	0.988	JENDL-3.2
Hg	27.63	no data	—	—
Pb	38.73	38.69	1.001	JEF-2.2

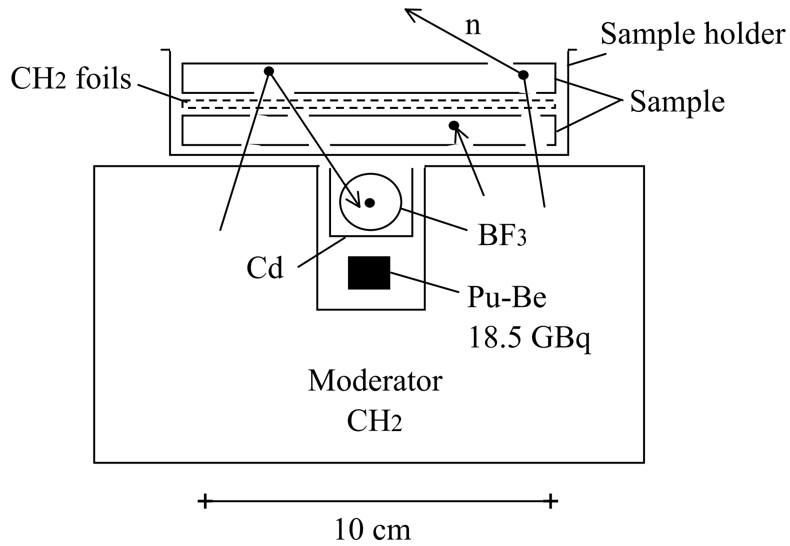

Fig. 1. Geometrical setup for reflection cross section measurements (CH_2 layer for absorbing samples)

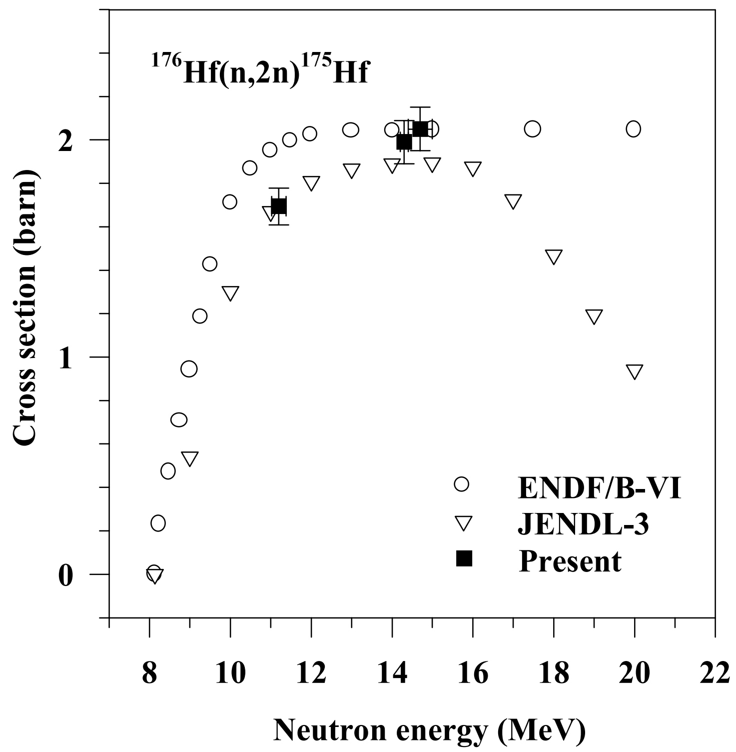

Fig. 2. A comparison of the measured and evaluated data for Hf-176(n,2n)Hf-175 reaction