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Measurements of the thermal neutron absorption Σ_a of boron of unknown isotopic ratio

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Abstract

The thermal neutron absorption cross section of natural boron fluctuates because of a fluctuating isotopic ratio of ^{10}B to ^{11}B. In the report the results of the measurement of the boron cross section are presented. The absorption of H_3BO_3 solutions has been measured with Czubek's method. From the obtained data the microscopic absorption cross section of boron has been found. A high accuracy of the result makes also possible to estimate the isotopic ratio of boron in the investigated material.

1. Introduction

Boron is an element characterised with a high absorption of thermal neutrons and it is often used as a poisoning medium in neutron experiments. A certain environmental variation of the abundance of the contributing isotopes ^{11}B and ^{10}B is the disadvantage of boron, because the microscopic absorption cross sections of the isotopes differ extremely: $\sigma_{aB\text{-}10} = 3837 \pm 9$ b and $\sigma_{aB\text{-}11} = 5.5 \pm 3.3$ mb [1], [2]. Therefore, even small differences in the natural isotopic abundance can lead to an uncertainty of the microscopic absorption cross section σ_{aB} of „natural" boron.

The isotopic abundance of ^{10}B in natural boron fluctuates from 19.098 % to 20.316 % [3]. The atomic isotopic ratio for boron, defined as $R = N_{10}/N_{11}$ (where N_{10} and N_{11} denote numbers of nuclei of isotopes ^{10}B and ^{11}B, respectively), varies from $R_{min} = 0.2361$ to $R_{max} = 0.2550$. Thus, the value of the microscopic absorption cross section of natural boron σ_{aB} can fluctuate between 733 b and 780 b. Therefore, either the actual absorption cross section or the actual isotopic ratio has to be known for boron in a given portion of a material used. In neutron experiments it is very often convenient to use water solutions of boric acid H_3BO_3. This allows us to obtain easily a required absorption cross section by a choice of the relevant concentration of H_3BO_3. When neither the cross section nor the isotopic ratio are known, the only way is to measure it.

2. Measurement of the absorption cross section of boric acid

Measurements were performed on several water solutions of boric acid. Samples of different concentrations k were prepared by a direct dissolution of H_3BO_3 in distilled water or by dilutions of the samples already existing. Individual standard deviations $s(k)$ were always estimated. The specification of the samples is given in Table 1. The densities $\rho(k)$ at 20 ^oC have been taken from a table in [4]. The absorptions were measured by Czubek's pulsed neutron method [5]. In this method the time decay constant λ of the fundamental mode of the pulsed thermal neutron flux in a two-region cylindrical system (the investigated sample of size $H_1 = 2R_1 = 6$ cm surrounded entirely by a moderator of size $H_{2g} = 2R_{2g}$) is measured. For each

Table 1. List of the samples.

Sample	k $s(k)$ [wt %]	$\rho(k)$ [g cm^{-3}]
Mf055	0.5500 0.0028	1.0004
Me06	0.6000 0.0028	1.0006
Mg065	0.6500 0.0028	1.0008
Md07	0.7000 0.0028	1.0010
Mh075	0.7500 0.0028	1.0012
Maa08	0.8006 0.0001	1.0014
Mba08	0.8000 0.0007	1.0014
Mi085	0.8500 0.0028	1.0016
Mab09	0.9006 0.0001	1.0018
Mca09	0.9000 0.0003	1.0018
Mab090b	0.9006 0.0001	1.0018
Mac095	0.9507 0.0003	1.0020

sample of the H_3BO_3 solution the decay constant λ was measured as a function of the size H_{2g} of the outer moderator. The method of the determination of the fundamental mode decay constant λ was described in [6]. These results, which define the experimental curves $\lambda(H_{2g})$, are listed in Table 2, where $s(\lambda)$ is the standard deviation of the determined value λ.

The thermal neutron absorption rate $\langle v\Sigma_{a1}\rangle_i$ for each i-th sample material is found from the intersection of the obtained experimental curve $\lambda_i(H_{2g})$ with a theoretical one $\lambda^*(H_{2g})$:

$$\langle v\Sigma_{a1}\rangle_i = \lambda_i(H_{2g}) = \lambda^*(H_{2g}) \quad , \qquad (1)$$

where Σ_a is the macroscopic absorption cross section and v is the thermal neutron speed. The theoretical curve $\lambda^*(H_{2g})$ is calculated using the thermal neutron diffusion theory for the two-region system, under assumption of zeroing the dynamic material buckling of the inner zone. The diffusion cooling coefficient C_2 of the outer moderator (here: Plexiglas) is modified as described in [7], where it has been obtained as $C_2^* = f(\lambda^*)$. The standard deviation $s(\langle v\Sigma_{a1}\rangle)$ of the determined absorption rate is calculated taking into account the standard deviations of the experimental points (*i.e.* $s(\lambda)$ of the measured decay constants) and the standard deviation $s(C_2^*)$ of the modified cooling coefficient C_2^* of Plexiglas in the system considered. The inaccuracy of the other two parameters of Plexiglas (the absorption rate and the diffusion constant) is of no importance because the Σ_a reference measurements [7] and the present experiments have been done using the same set of the

Table 2. Decay constants λ measured on samples of different concentrations of H_3BO_3.

a) Sample Mf055

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
12.4	14 525 59
	14 489 77
	14 481 25
	14 506 49
12.8	13 835 78
	13 751 121
	13 789 73
	13 817 58
13.2	13 242 51
	13 148 65
	13 173 68
	13 227 119
13.6	12 679 62
	12 596 107
	12 697 80
	12 616 88

b) Sample Me06

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
11.6	16 306 49
	16 294 73
12.0	15 491 47
	15 517 64
	15 476 66
12.4	14 703 80
	14 687 101
	14 647 71
	14 706 77
12.8	14 010 51
	14 002 39
	14 020 45

c) Sample Mg065

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
11.6	16 633 120
	16 572 55
	16 604 70
	16 589 63
12.0	15 751 110
	15 611 81
	15 733 82
	15 703 73
12.4	14 928 68
	14 933 26
	14 894 65
	14 893 101
12.8	14 242 79
	14 223 32
	14 204 55
	14 209 76

Table 2. (continued).

d) Sample Md07

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
11.2	17 781 106
	17 835 47
	17 837 50
	17 812 76
11.6	16 804 43
	16 825 52
	16 876 63
	16 857 58
12.0	15 912 43
	15 940 45
	15 880 64
	15 924 65
12.4	15 052 71
	15 153 43

e) Sample Mh075

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
10.8	19 219 92
	19 244 68
11.2	18 034 134
	18 084 176
11.6	17 080 56
	17 065 59
	17 050 95
	17 054 75
12.0	16 105 123
	16 148 90
12.4	15 257 145
	15 272 70

f) Sample Maa08

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
10.4	20 823 109
	20 799 62
	20 812 71
	20 809 103
10.8	19 511 90
	19 452 103
	19 551 53
	19 521 55
11.2	18 301 74
	18 377 45
	18 318 110
	18 412 90
11.6	17 267 38
	17 346 104
	17 236 104
	17 305 79
	17 242 45
	17 339 77
12.0	16 321 58
	16 382 55

Table 2. (continued).

g) Sample Mba08		**h)** Sample Mi085		**i)** Sample Mab09	
H_{2g}	λ $s(\lambda)$	H_{2g}	λ $s(\lambda)$	H_{2g}	λ $s(\lambda)$

Table 2. (continued).

j) Sample Mca09

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
10.4	21 455
	130
	21 453
	139
10.8	20 017
	126
	20 045
	161
11.6	17 720
	59
	17 727
	81

k) Sample Mab090b

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
10.4	21 398
	96
	21 479
	128
	21 410
	87
	21 443
	84
10.8	20 060
	129
	20 050
	101
	20 032
	162
	20 058
	134
11.2	18 862
	155
	18 831
	141
	18 839
	73
	18 801
	114
11.6	17 670
	145
	17 659
	128
	17 691
	174
	17 749
	83

l) Sample Mac095

H_{2g} [cm]	λ $s(\lambda)$ [s^{-1}]
10.4	21 698
	194
	21 708
	118
10.8	20 316
	131
	20 334
	81
11.2	19 142
	101
	19 142
	162
11.6	17 880
	53
	17 936
	123

Plexiglas moderators. Thus, any possible systematic error has been included into the uncertainty of the used function $C_2^*(\lambda^*)$.

From the absorption rate $\langle v\Sigma_{a1}\rangle$ measured for each sample the mass absorption cross section Σ_a^M of boric acid H_3BO_3 has been calculated:

$$\Sigma_a^M = \frac{1}{k}\frac{\langle v\Sigma_{a1}\rangle}{\rho v_0} - \frac{1-k}{k}\Sigma_w^M \quad , \tag{2}$$

where Σ_w^M is the mass absorption cross section of water. The above cross sections, Σ_a^M and Σ_w^M, are defined at the most probable thermal neutron velocity v_0 = 2200 m/s. The standard deviation $s(\Sigma_a^M)$ has been determined from the variances of the variables in Eq.(2). The results are given in Table 3. Finally, the mass absorption cross section Σ_a^M for the measured portion of H_3BO_3 has been obtained as:

$$\begin{aligned} \bar{\Sigma}_a^M &= 7.315 \ \text{cm}^2\,\text{g}^{-1} \ , \\ s(\bar{\Sigma}_a^M) &= 0.011 \ \text{cm}^2\,\text{g}^{-1} \ , \\ s(\Sigma_a^M) &= 0.036 \ \text{cm}^2\,\text{g}^{-1} \ , \end{aligned} \tag{3}$$

where the weighted mean $\bar{\Sigma}_a^M = \frac{1}{W}\sum_i w_i \Sigma_{ai}^M$ with $w_i = 1/s^2(\Sigma_{ai}^M)$ and $W = \sum_i w_i$. The unbiased estimator of the variance of the random variable Σ_a^M is $s^2(\Sigma_a^M) =$ $= \frac{q}{q-1}\sum_i \frac{w_i}{W}(\Sigma_{ai}^M - \bar{\Sigma}_a^M)^2$ with $q = 1/\sum_i (w_i/W)^2$, and the variance of the mean is $s^2(\bar{\Sigma}_a^M) =$ $s^2(\Sigma_a^M)/q$.

Table 3. Mass absorption cross sections Σ_a^M of boric acid H_3BO_3 from individual measurements.

Sample No. *i*	Sample	$\langle v\Sigma_{a1}\rangle$ $s(\langle v\Sigma_{a1}\rangle)$ [s^{-1}]	(Σ_a^M) $s[(\Sigma_a^M)]$ [$cm^2\ g^{-1}$]
1	Mf055	13 756 101	7.343 0.092
2	Me06	14 557 121	7.337 0.098
3	Mg065	15 406 109	7.366 0.083
4	Md07	16180 114	7.341 0.080
5	Mh075	16 946 153	7.315 0.097
6	Maa08	17 745 126	7.305 0.072
7	Mba08	17 834 122	7.361 0.070
8	Mi085	18 545 145	7.307 0.081
9	Mab09	19 301 148	7.277 0.075
10	Mca09	19 289 185	7.276 0.094
11	Mab090b	19 304 160	7.278 0.081
12	Mac095	20 074 193	7.261 0.092

3. Absorption cross section of boron

The microscopic absorption cross section σ_{aB} of boron has been calculated from the elemental composition of boric acid H_3BO_3:

$$\sigma_{aB} = \frac{M}{N_A}\Sigma_a^M - 3(\sigma_{aH} + \sigma_{aO}) \quad , \tag{4}$$

using the determined mass cross section $\bar{\Sigma}_a^M$ of H_3BO_3. In Eq.(4), *M* is the gram-molecule of

boric acid, N_A is Avogadro's number, $\sigma_{aH} = 0.3326 \pm 0.0007$ b and $\sigma_{aO} = 0.19 \pm 0.02$ mb [1] are the microscopic absorption cross sections of hydrogen and oxygen, respectively. Thus, the microscopic absorption cross section of boron in the measured portion of H_3BO_3 has been found:

$$\sigma_{aB} = 750.09 \pm 3.70 \text{ b} \quad . \tag{5}$$

This cross section, expressed by the cross sections of the contributing isotopes, is defined as

$$\sigma_{aB} = \frac{1}{1+R}\sigma_{aB\text{-}11} + \frac{R}{1+R}\sigma_{aB\text{-}10} \quad . \tag{6}$$

When all the cross sections are known the atomic isotopic ratio R of boron can be determined:

$$R = \frac{\sigma_{aB} - \sigma_{aB\text{-}11}}{\sigma_{aB\text{-}10} - \sigma_{aB}} \quad , \tag{7}$$

and it is equal to

$$R = 0.2430 \pm 0.0016 \quad . \tag{8}$$

The microscopic absorption cross sections $\sigma_{aB\text{-}10}$, $\sigma_{aB\text{-}11}$ with their standard deviations have been taken from [1] as quoted in paragraph 1.

4. Conclusions

In the presented experiment the mass absorption cross section Σ_a^M for a given portion of boric acid H_3BO_3 has been obtained with the relative standard deviation equal to 0.49 %. This result allows us to calculate the atomic isotopic ratio $^{10}B/^{11}B$ with the uncertainty of 0.66 %.

Routine methods to measure $^{10}B/^{11}B$ ratio are the thermal ionization mass spectrometric methods [8], [9], and the inductively coupled plasma mass spectrometry method (ICP-MS) [10]. They give the $^{10}B/^{11}B$ isotopic ratio with the uncertainty from 0.2 % to 0.7 %. The accuracy obtained in our measurement is comparable with the accuracy of the specific procedures. We suggest to make again the described experiment on samples of the known

isotopic ratio $^{10}B/^{11}B$. If the experimental results for R and $\sigma(R)$ are satisfactory, our method can be used in practice. The method to estimate the ratio R through the Σ_a^M measurements for H_3BO_3 is quite simple and competitive to the ICP methods.

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