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# Boron as the Reference Material for the Thermal Neutron Absorption Measurements

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**Abstract**

Boron is an element characterised with a high thermal neutron absorption cross section. For that reason chemical compounds containing boron are applied as the absorption standards in thermal neutron experiments. A variation of the isotopic ratio $^{10}B/^{11}B$ in natural boron is observed, which influences the resulting value of the absorption cross section. An influence of the accuracy of knowledge of the boron isotopic ratio on accuracy of the thermal neutron absorption cross section of standards is considered in the paper on example of $H_3BO_3$ solutions. The conclusions is that the $^{10}B/^{11}B$ ratio should be known with the accuracy no worse than about 0.2 %.

## 1. Influence of the isotopic ratio of natural boron on the absorption cross section of boron and its chemical compounds

Boron is an element characterised with a high absorption of thermal neutrons and is utilised as the absorption standard. Boric acid, $H_3BO_3$, is often used for the purpose. It is used either as a powder added to another material or as a water solution in order to achieve a desired value of the reference absorption cross section. A certain environmental variation of the abundance of the contributing isotopes is the disadvantage of boron. The microscopic absorption cross sections of the isotopes are very different: $\sigma_{^{11}B}$ = 0.0055 b and $\sigma_{^{10}B}$ = 3837 b. Therefore, even small differences in the natural abundance can lead to an uncertainty of the cross section $\sigma_B$ of "natural" boron.

However, this high ability of absorbing thermal neutrons by boron is utilised in experiments which relate to the physics transport of thermal neutrons (e.g. a design of shields and collimators; Czubek's method [1] of the absorption cross section pulsed measurement) or as the standard material for a calculation of the calibration curves (e.g. Kreft's stationary method [2] of measurement of the absorption cross section). Therefore, good knowledge of the thermal neutron macroscopic absorption cross section of boron is a significant problem.

Let us consider $H_3BO_3$ acid. This compound is slightly soluble in water and makes solutions up to maximum 4 % (at 20 °C). The solutions of different concentrations $k$ can be applied as standards covering a wide range of variability of the macroscopic absorption cross section $\Sigma$. For pure water, $k$ = 0, $\Sigma$ = 0.0222 cm$^{-1}$ and for the 4 % $H_3BO_3$ solution $\Sigma$ = 0.3250 cm$^{-1}$, based on the microscopic cross section from table [3]. A dependence between the accuracy of $\Sigma$ calculated for the water solution of $H_3BO_3$ and the error value of the isotopic ratio of boron is obvious.

The linear macroscopic absorption cross section $\Sigma$ for water solution of $H_3BO_3$ is calculated basing on the elemental composition as

$$\Sigma = \rho N_A \left[ \left( \frac{2\sigma_H + \sigma_O}{M_1} \right)(1-k) + \left( \frac{3\sigma_H + \sigma_B + 3\sigma_O}{M_2} \right)k \right] , \qquad (1)$$

where $\rho$ – density of the solution, $N_A$ – Avogadro number, $\sigma_{B,\,H,\,O}$ – microscopic absorption cross section of boron, hydrogen, oxygen, respectively, $M_{1,2}$ – atomic mass of water and acid, respectively, $k$ – concentration of $H_3BO_3$ in the water solution.

The atomic isotopic ratio is defined for boron as $R = N_{10}/N_{11}$, where $N_{10}$ and $N_{11}$ denote numbers of atoms of isotopes $^{10}$B and $^{11}$B, respectively. For the defined isotopic ratio $R$, the microscopic cross section of boron $\sigma_B$ follows as

$$\sigma_B = \frac{1}{1+R}\sigma_{11B} + \frac{R}{1+R}\sigma_{10B} \quad . \tag{2}$$

For the standard deviation $s(\sigma_B)$ of the cross section $\sigma_B$ of natural boron the relation is:

$$s^2(\sigma_B) = \frac{1}{(1+R)^2}\left[\left(\frac{(\sigma_{11B} - \sigma_{10B})^2}{(1+R)^2}\right)s^2(R) + s^2(\sigma_{11B}) + R^2 s^2(\sigma_{10B})\right] \quad . \tag{3}$$

We can assume that the standard deviations of the microscopic cross section of oxygen $s(\sigma_O)$, of the density of the $H_3BO_3$ solution $s(\rho)$, and of the concentration $s(k)$ are negligible in comparison to other standard deviations. Then the calculated error for $\Sigma$ is dependent only on $s(R)$ and on the standard deviations of the microscopic cross sections $s(\sigma)$ of boron isotopes and hydrogen. Then it is possible to investigate the dependence of the precision of calculation $\Sigma$ of the $H_3BO_3$ solution on the value of $s(R)$ for boron isotopic ratio in this acid. The standard deviation $s(\Sigma)$ of the macroscopic cross section at the above assumption can be calculated using the formula:

$$s^2(\Sigma) = (N_A \rho)^2\left[s^2(\sigma_H)\left(\frac{3k}{M_2} + \frac{2(1-k)}{M_1}\right)^2 + s^2(\sigma_B)\left(\frac{k}{M_2}\right)^2\right] \quad , \tag{4}$$

where $s^2(\sigma_B)$ is given by formula (3).

The isotopic abundance of $^{10}$B and $^{11}$B in natural boron is variable. This value fluctuates in the following interval for $^{10}$B: from 19.098 % to 20.316 % (corresponding to the range from 79.684 % to 80.902 % for $^{11}$B) [4]. The boron isotopic ratio $R$ vary from $R_{min} = 0.2361$ to $R_{max} = 0.2549$. Thus, the value of the microscopic absorption cross section of natural boron $\sigma_B$ fluctuates from 733 b to 780 b in the limiting cases. The average value of $\sigma_B$, which corresponds to $R = 0.25$, is given in Table 1 (item 7). The standard deviation $s(\sigma_B)$ is high (about 1 %) in this case because it takes into account the natural variation of the boron isotopic ratio. That value of $s(\sigma_B)$ has to correspond to the standard deviation of the isotopic ratio $s(R_M) \leq 0.0032$ when $s(\sigma_B)$ is estimated from Eq. (2) using the individual standard

**Table 1**. Microscopic absorption cross sections for elements and isotopes considered in this paper.

| | Isotope/ Element | $\sigma$ [b] | $s(\sigma)$ [b] | Remarks |
|---|---|---|---|---|
| 1. | $^{10}$B | 3837 | 9 | [3] |
| 2. | $^{11}$B | 0.0055 | 0.0033 | [3] |
| 3. | H | 0.3326 | 0.0007 | [3] |
| 4. | O | 0.00019 | 0.00002 | [3] |
| 5. | B | 732.9 | 1.7 | $R_{min} = 0.2361$ $s(R_{min}) = 0$ |
| 6. | B | 779.6 | 1.8 | $R_{max} = 0.2549$ $s(R_{max}) = 0$ |
| 7. | B | 767 | 8 | $R_M = 0.25$ $s(R_M) \leq 0.0032$ [3] |

deviations of the absorption cross section of the two boron isotopes, $s(\sigma_{10_B})$ and $s(\sigma_{11_B})$ (as given in Table 1). In other words, knowledge of the isotopic ratio $R$ with the relative accuracy $s(R)/R \approx 1.3$ % allows to know the microscopic cross section $\sigma_B$ with the accuracy about 1 %. If the isotopic ratio were obtained error free then $s(\sigma_B)$ would depend only on the standards deviation $s(\sigma_{10_B})$ and $s(\sigma_{11_B})$, and the accuracy of the calculated value $\sigma_B$ would be about 0.23% (see Table 1, items 5, 6).

The conclusion from the above consideration is that the unawareness of the natural boron abundance for a particular material can be a source of additional errors for the calculation of the macroscopic absorption cross section. The boron isotopic ratio should be known with good accuracy. The determination of the boron isotopic ratio is carried by a variety of methods, including atomic absorption spectrometry, chemical ionization, and electron impact mass spectrometry. Because of their high precision, thermal ionization mass spectrometric methods [5], [6] have been favoured for many applications. A precision of $s(R)$ between 0.2 % and 0.3 % is typically reported. An important disadvantage of these methods is the time required for the sample preparation and for the isotopic ratio determination. One of

advantages of the inductively coupled plasma mass spectrometry (ICP-MS) [7] over other techniques is a speed of the analysis and a relative short time to prepare the sample. This method consists in the ionization of boron in state of plasma. The boron isotopic ratio is determined with a precision of about 0.7 %. For a portion of $H_3BO_3$ used in measurements by Czubek's method [8] the ratio $R$ was known with precision of about 0.129 % ($s(R) = 0.00032$ at $R = 0.24726$). This Isotope Reference Material (IRM) was prepared by the Joint Research Centre, Geel, in Belgium.

## 2. Influence of the boron isotopic ratio accuracy on the $\Sigma$ accuracy of the $H_3BO_3$ solution

The value $\Sigma$ of the $H_3BO_3$ water solution is dependent on the concentration $k$ and on the values $\sigma$ of elements in the mixture (Eq.1). We can investigate an influence of the standard deviation $s(R)$ on the standard deviation $s(\Sigma)$ of the absorption cross section of the solution when the isotopic ratio $R$ is fixed. The calculation has been made for the data $\sigma_{^{10}B}$, $\sigma_{^{11}B}$ and $s(\sigma_{^{11}B})$, $s(\sigma_{^{10}B})$ quoted in Table 1, items 1, 2. The results at different concentrations $k$ are collected in Table 2.

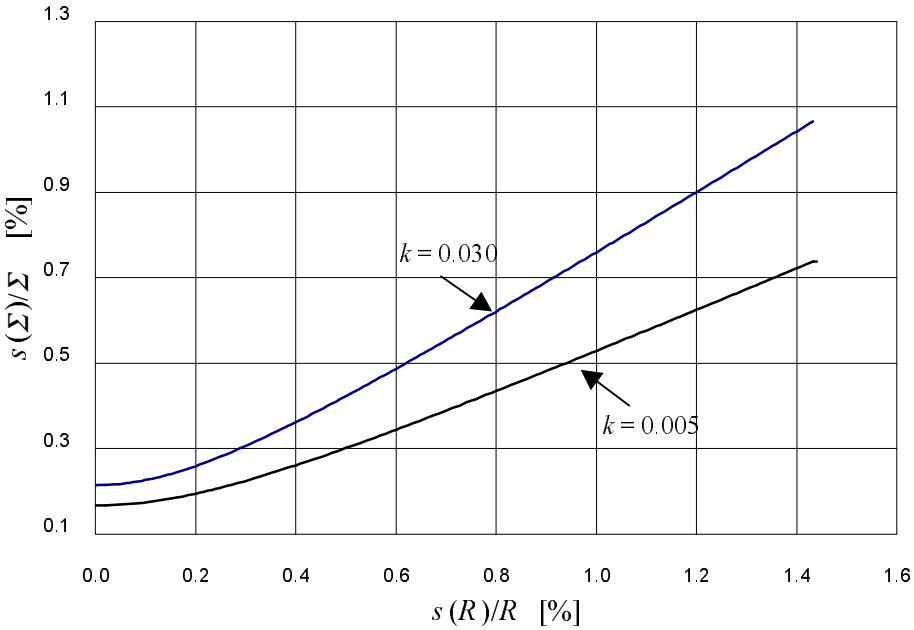
**Table 2.** Relative standard deviation $s(\Sigma)/\Sigma$ for selected values $s(R)$ of the isotopic ratio for different concentrations $k$ of $H_3BO_3$ water solutions ($R = 0.25$, $s(k) = 0$).

| $k$ | $\Sigma$ [$cm^{-1}$] | $s(\Sigma)/\Sigma$ | | | | |
|---|---|---|---|---|---|---|
| | | $s(R)$ = 0 | $s(R)$ = 0.00032 | $s(R)$ = 0.0005 | $s(R)$ = 0.00175 | $s(R)$ = 0.0032 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0.000 | 0.0222 | 0.0021 | 0.0021 | 0.0021 | 0.0021 | 0.0021 |
| 0.005 | 0.0596 | 0.0017 | 0.0018 | 0.0019 | 0.0039 | 0.0091 |
| 0.010 | 0.0971 | 0.0019 | 0.0020 | 0.0022 | 0.0047 | 0.0094 |
| 0.015 | 0.1347 | 0.0020 | 0.0022 | 0.0024 | 0.0051 | 0.0094 |
| 0.020 | 0.1724 | 0.0021 | 0.0023 | 0.0025 | 0.0053 | 0.0095 |
| 0.025 | 0.2103 | 0.0021 | 0.0023 | 0.0026 | 0.0054 | 0.0096 |
| 0.030 | 0.2483 | 0.0022 | 0.0024 | 0.0026 | 0.0055 | 0.0097 |

Column 3 in Table 2 presents the evaluation when the precision of the calculation of $R$ is error free. Column 4 is for $s(R)$ obtained for the reference material from the Joint Research Centre, and Column 5 for $s(R)$ available by thermal ionization mass spectrometric methods. Column 6 is a result for error of isotopic ratio obtained by using the ICP-MS method. The values in Column 7 are obtained for the data from Mughabghab's table.

Fig.1 presents the influence of the error in which the isotopic ratio is determined on the accuracy of the calculated $\Sigma$. The dependence is shown for two different concentrations of the $H_3BO_3$ solutions. The curves are plotted for $R = 0.25$.

**Fig.1**. Dependence between the standard deviation of the calculated macroscopic absorption cross section $\Sigma$ for the $H_3BO_3$ solutions and the standard deviation of the isotopic ratio $^{10}B/^{11}B$ for boron in this acid.




From the examples performed result the following conclusions. First, the isotopic ratio $R$ of boron must be known for any material which is used as a reference. Second, ratio $R$ ought to be defined with a high accuracy. The results collected and the curves presented in Fig.1 allow to check whether a given experiment can be performed with a desired accuracy. For example, in Czubek's method the resulting measured absorption cross section $\Sigma$ of a material is obtained with the relative standard deviation $s(\Sigma)/\Sigma$ equal from 1 to 2 %. A reference material which is to be used for tests should be expected to have the relative standard deviation of one order smaller. This corresponds to $s(R)/R$ not worse than 0.2 % which is difficult to obtain. It is worth to notice that for 3 % water solution of $H_3BO_3$ the minimum

relative standard deviation of $\Sigma$ is 0.22 %. The better knowledge of this value would be possible only if the microscopic cross section of each isotope which create the $H_3BO_3$ molecule were known with better accuracy than the data in the Mughabghab's table.

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