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# Benchmark measurements of non-Rutherford proton elastic scattering cross section for boron

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ABSTRACT

In the literature several elastic scattering cross-sections data sets are available for protons on $^{10}$B and $^{11}$B at energies and scattering angles suitable for elastic backscattering spectrometry (EBS) analysis. However, agreement between these different data sets is generally poor, with systematic differences up to 20%, well beyond the stated absolute uncertainties. To resolve the conflict between the different data sets in the absence of the evaluated cross-section data, a benchmark experiment was performed. Proton backscattering spectra were obtained with a thick uniform $B_4C$ target at beam energies in the range of 2.0–4.0 MeV and at different scattering angles, followed by a standard direct simulation with the SIMNRA code using the available experimental cross-section data. As a result, recommendation on the most appropriate data set to be used in proton EBS analysis of boron is given.

## 1. Introduction

Boron is a very important technological element, being used, for instance, as dopant in semiconductor fabrication and as component for the coating of the walls of nuclear fusion devices, and the quantitative determination of the boron depth distribution in both heavy and light matrices is of great scientific and technological importance. Ion beam analysis (IBA) methods are widely used for material analysis, and in particular nuclear reaction analysis (NRA) and elastic backscattering spectroscopy (EBS) have been proposed for boron trace analysis and depth profiling. However, the quantitative analysis with these techniques is often limited by the lack of differential cross section data of the reactions involved and of a theoretical evaluation [1]. As EBS methods are concerned, the demand for experimental values of elastic backscattering cross sections of protons on light nuclei, like boron, is increasing, since the analytical use of proton rather than alpha particle backscattering is more and more common for light element detection (larger probing depth and better sensitivity due to the nuclear cross section enhancement) and the Rutherford formula for the elastic cross section cannot be applied any more.

In the literature several elastic scattering cross-sections data sets are available for protons on $^{10}$B and $^{11}$B at energies and scattering angles suitable for EBS analysis and are available to the scientific community through the IBANDL database [2], as summarized in Table 1. However, agreement between these different data sets is generally poor, with systematic differences up to 20%, well beyond the stated absolute uncertainties (typically ±5–10%), resulting in large systematic uncertainties if these data are used in material analysis.

In Fig. 1 the comparison between the existing $^{10}$B(p,p)$^{10}$B experimental cross-section data is shown for different scattering angles. In panel (a) the data in the angular range from 135° to 138° are compared; the oldest data by Brown et al. [3] are consistent with the data of Chiari et al. [4] for energies from 1.3 to 1.6 MeV, whereas for lower energies Brown et al. data are up to 30% lower. In contrast, the data obtained by Andreev et al. [5] are 15–70% higher than the Chiari et al. data; a shift in the position of the first broad resonance (at around 1.6 MeV) toward higher energies is evident as well. In panel (b) experimental data of Chiari et al. are compared with data from Overley and Whaling [6] at angles of 120° and 155°; in both cases the data by Overley and Whaling are consistently about 20% higher than those by Chiari et al., pointing out to a systematic error.

In Fig. 2 the comparison between the existing $^{11}$B(p,p)$^{11}$B experimental cross-section data is shown for different scattering angles, where at least three datasets are available. A comparison of the measurements at 120° is shown in panel (a): the data from

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**Table 1**
Summary of the p + $^{10,11}$B elastic cross-section data available in the literature, indicating also the proton energy range, the scattering angles and the total uncertainty (when given).

| Reaction | Energy (MeV) | Angles | Uncertainty | Authors |
|---|---|---|---|---|
| $^{11}$B(p,p)$^{11}$B | 0.50–3.30 | 170–100° in 5° steps | 4% | Chiari et al. [4] |
| | 3.00–5.00 | 169.6°, 139.8° | – | Rihet et al. [9] |
| | 1.69–2.69 | 165° | 6% | Mayer et al. [13] |
| | 1.00–3.80 | 161.4° | – | Segel et al. [14] |
| | 2.17–4.19 | 160–135° in 5° steps | 4–5% | Kokkoris et al. [10] |
| | 2.22–3.27 | 155° | – | Symons and Treacy [11] |
| | 0.59–1.99 | 150° | 7% | Tautfest and Rubin [12] |
| | 1.85–3.00 | 120° | 3–5% | Mashkarov et al. [7] |
| | 1.85–2.99 | 119.5° | 1–9% | Dejneko et al. [8] |
| $^{10}$B(p,p)$^{10}$B | 0.50–3.30 | 170–100° in 5° steps | 5% | Chiari et al. [4] |
| | 1.00–2.97 | 154°, 120.3° | 7% | Overley and Whaling [6] |
| | 1.03–3.50 | 137.09° | – | Andreev et al. [5] |
| | 0.84–1.60 | 137.8° | – | Brown et al. [3] |

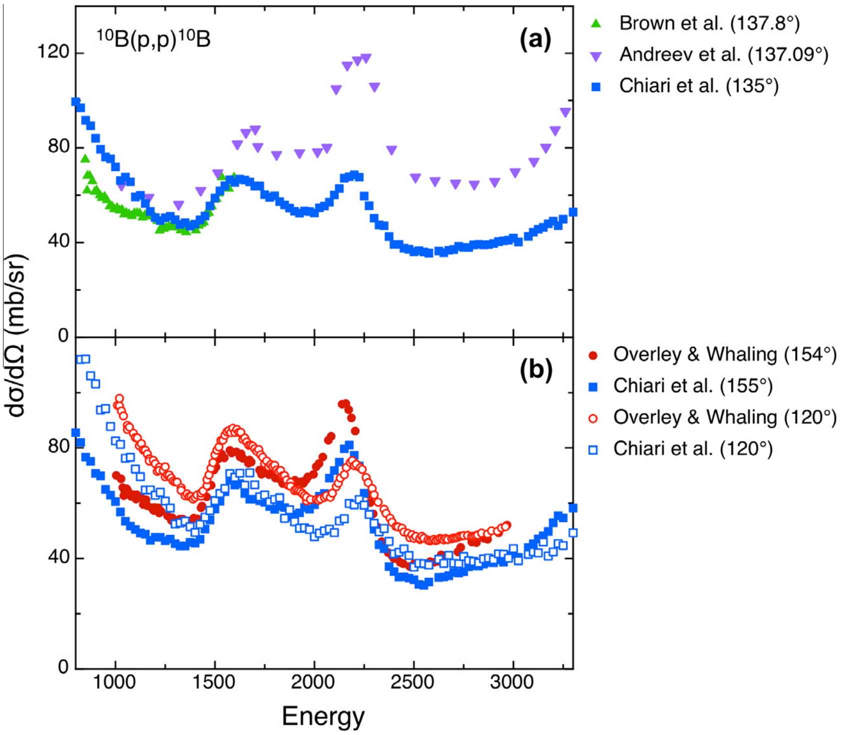

**Fig. 1.** Comparison between the available experimental data for the p + 10B elastic scattering cross section data at different scattering angles: 135–138° (panel a); 120° and 155° (panel b).

Mashkarov et al. [7], Dejneko et al. [8] and Chiari et al. [4] data agree quite well. The angle of 140° is shown in panel (b): the data from Rihet et al. [9] are about 10–15% lower than the data from Kokkoris et al. [10], but there exists a very good agreement between data from Kokkoris et al. and from Chiari et al., with differences generally consistent within their respective quoted uncertainties. A comparison of the measurements at 150° and 155° is shown in panel (c): Symons and Treacy data [11] agree with Chiari et al. and Kokkoris et al. data over most of the energy range, but the dip at 3.1 MeV is missing and this could be probably due to the relatively large energy step, 0.1 MeV, employed in the measurements; the oldest data by Tautfest and Rubin [12] are 15–20% lower than Chiari et al. ones, with deviations increasing up to 40% for the cross-section values below 600 keV. Again there exists a reasonably good agreement between data from Kokkoris et al. and Chiari et al. at both angles, but the Kokkoris et al. cross-section values at 150° are about 10% higher in the energy range from 2.2 to 2.6 MeV. In panel (d): the comparison between the data by Chiari et al., Kokkoris et al., Mayer et al. [13], and Segel et al. [14] for angles between 160° and 165° is shown. Mayer et al. data have the same shape as Chiari et al. data, but are consistently about 20% higher, pointing out to a systematic error. Segel et al. data are consistent with Chiari et al. data up to 2 MeV, but at higher energies large discrepancies occur and whereas the minima and maxima in the differential cross section are at the same energies, Segel et al. data cannot be simply scaled to Chiari et al. or Mayer et al. data. At 160° Kokkoris et al. data are about 10% higher than Chiari et al. data in the energy range from 2.2 to 2.6 MeV, as previously commented for the data at the scattering angle of 150°.

To resolve the above-discussed conflicts between the different data sets in the absence of a theoretically evaluated cross-section data, a benchmark experiment was performed. A benchmark is an integral experiment which consists of a measurement of the charged-particle spectrum from a well known uniform thick target