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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 2.0–2.7 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.

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Keywords: Cross-sections; Elastic scattering; Proton; Boron; Thick target; Benchmark

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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% to 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 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 followed by a standard direct simulation using measured cross-section data in order to validate them.

2. Experimental

The benchmark test measurements of the elastic scattering cross-section of protons on ^{10}B and ^{11}B were performed at the 1.7 MV Tandetron accelerator of IMM-CNR in Bologna (Italy), using a high-purity B_4C thick target (only surface contamination of N, O, Si, Cr and Fe at trace level were found), mounted normal to the beam in an electrically insulated scattering chamber acting as a Faraday cup. Experimental conditions were selected according to the availability of measured cross-section data sets to be compared and verified. Proton beams of 2000, 2250, 2500 and 2600 keV (± 2-3 keV) with a 2×1 mm^2 cross-section were used. Backscattered protons were collected by a ion-implanted Si detector (25 mm^2 area. 300 μm thickness) having 13 keV FWHM energy resolution and a dead-layer equivalent thickness of $250\cdot10^{15}$ Si/cm^2. The detector was collimated by a circular aperture of 5.05 mm diameter set at 100.5 mm from the target. Scattering angles of 165°, 160°, 155° and 120° (with uncertainties estimated at 0.2°) were chosen to match available experimental data. The proton beam current was 9 nA in order to have negligible dead time corrections; all the measurements were allowed to run until integrating a beam charge of 10 μC. The electronic gain of the detection system was determined from 2 MeV proton spectra of a thin ($40 \cdot 10^{15}$ at/cm^2) Pb-doped BiSCCO film, containing Bi, Pb, Sr, Cu, Ca and O, deposited on a carbon substrate. The pulse height defect correction was applied, except for the effect of the non-ionising (nuclear) energy loss. The resulting uncertainty in the electronic gain (i.e. keV/channel) is about ±1%. A prudently conservative uncertainty for the charge×solid-angle product is about ±1.6% [15, 16].

3. Data analysis and results

In Fig. 3 the comparisons between the experimental spectra and the results of simulations using SIMNRA [17] with SRIM2003 stopping powers [18] are shown, for the different scattering angles and a selected proton beam energy of 2.6 MeV. In the simulations the following ^{10}B(p,p)^{10}B cross-section data were compared with the benchmark spectra: Chiari et al. [4] at all measured angles, Overley and Whaling [6] at 155° (used at 160° and 165° as well) and 120°. The following ^{11}B(p,p)^{11}B cross-section data were compared: Chiari et al. [4] again at all measured angles, Mayer et al. [13] at 165°, Segel et al. [14] at 160°, Kokkoris et al. [10] at 160° and 155°, Symons and Treacey [11] at 155° and Mashkarov et al. [7] at 120°. The evaluated SigmaCalc cross-section for ^{12}C(p,p)^{12}C [19, 20] was used in all the simulations. All the other experimental cross-sections were retrieved from the IBANDL database.

The statistical uncertainty of the benchmark spectrum height (including dead time corrections) is about ±1-3%, whereas the uncertainty of the simulation itself is dominated by the systematic uncertainty in the stopping power (conservatively ±5%, considering an overall accuracy for protons of 4.2% [21] and that in B_4C deviations from Bragg's rule may occur), while other systematic contributions come from the charge×solid-angle product and the electronic gain (±2%). The total combined uncertainty is about ±6%.

From this benchmark experiment it turns out that $^{10}B(p,p)^{10}B$ and $^{11}B(p,p)^{11}B$ cross-section data taken from the large measurements series done by Chiari et al. are underestimated by a systematic factor. Using the $^{11}B(p,p)^{11}B$ cross-section values by Mayer et al. and the $^{10}B(p,p)^{10}B$ cross-section values by Overley and Whaling the simulation is in good agreement with experimental data (see the b) curve in the leftmost panel of Fig. 3). Spectra simulated from the other datasets (Segel et al., Symons and Treacy, Kokkoris et al. and Mashkarov et al.), do not reproduce the benchmark spectra.

Since differential cross-section data from Chiari et al. are systematically underestimated in all the benchmark measurements done at different beam energies and scattering angles, this single systematic factor appears consistent with an error in the determination of the target thickness value adopted for the cross-section measurements in the original paper [4]. Upon scaling these cross-section values by applying a multiplicative "correction factor", the agreement between experimental spectra and simulations is good (Fig. 4). This "correction factor" has a value of 1.1890 ± 0.0012 (fitting uncertainty) ± 0.0640 (systematic uncertainty), obtained from a global fit of the simulated spectra to the experimental ones (4 energies, 4 angles), using a single multiplicative factor for the partial spectra of both boron isotopes as free parameter. In the fit the region of the spectra at 2.0 MeV proton beam energy around the $^{12}C(p,p)^{12}C$ resonance at 1734 keV was excluded, since the used version of SIMNRA (v6.0) does not reproduce adequately deeply buried sharp resonances, due to the neglected effect of beam energy spread before the interaction [22].

As an additional test of its validity at yet another scattering angle and beam energy, the corrected cross-section was used to recalculate the simulated spectrum originally published in [23] as Fig. 4(a). As shown in Fig. 5 the comparison between the experimental backscattering spectrum of a BN thick target at 150° and 3.24 proton beam energy (the measurements were done at the 6.0 MV Tandem Van de Graaff accelerator at the Ruđer Bošković Institute in

Zagreb) and the SIMNRA simulation using the scaled-up cross sections by Chiari et al. yields an agreement better than 5%.

4. Conclusions

A benchmark experiment to resolve the conflict between the different experimental datasets for the p+^{10,11}B elastic cross sections, in the absence of evaluated cross-section data, was designed and performed. Proton backscattering spectra were obtained with a thick uniform B_4C target at beam energies in the range of 2.0–2.7 MeV and at different scattering angles, followed by a standard direct simulation. The data from Chiari et al. [4] have to be corrected by a factor of 1.189 ± 0.064 due to a systematic error in the original measurements. Once corrected, these data can be reasonably assumed as verified cross-section values for ^{10}B(p,p)^{10}B and ^{11}B(p,p)^{11}B cross sections at scattering angles from 170° to 110°, in the proton energy range up to 3.3 MeV.

References

[1] D. Abriola, N.P. Barradas, I. Bogdanović-Radović, M. Chiari, A.F. Gurbich, C. Jeynes, M. Kokkoris, M. Mayer, A.R. Ramos, L. Shi, I. Vickridge, Nucl. Instr. and Meth. B 269 (2011) 2972

[2] Ion Beam Analysis Nuclear Data Library, http://www-nds.iaea.org/ibandl/

[3] A.B. Brown, C.W. Snyder, W.A. Fowler, C.C. Lauritsen, Phys. Rev. 82 (1951) 159

[4] M. Chiari, L. Giuntini, P. A. Mandò, N. Taccetti, Nucl. Instr. and .Meth. B 184 (2001) 309

[5] G.B. Andreev et al. Izvestiya Akademii Nauk 26 (1962) 1134

[6] J.C. Overley and W. Whaling, Phys. Rev. 128 (1962) 315

[7] Ju.G.Mashkarov et al., Jour. Izv. Rossiiskoi Akademii Nauk, Ser.Fiz. 39 (1975) 1736

[8] A.S.Dejneko et al., Jour. Izv. Rossiiskoi Akademii Nauk, Ser.Fiz. 38 (1974) 1694

[9] Y. Rihet et al., Le Jurnal De Fhysique 38 (1977) 17

[10] M. Kokkoris, A. Kafkarkou, V. Paneta, R. Vlastou, P. Misaelides, A. Lagoyannis, Nucl. Instr. and .Meth. B 268 (2010) 3539

[11] G.D. Symons and P.B. Treacy, Nucl. Phys., 46 (1963) 93

[12] G.W. Tautfest and S. Rubin, Phys. Rev. 103 (1956) 196

[13] M. Mayer, A. Annen, W. Jacob, S. Grigull, Nucl. Instr. and .Meth. B 143 (1998) 244

[14] R.E. Segel, S.S. Hanna, R.G. Allaset, Phys. Rev. B 139 (1965) 818

[15] G. Lulli, E. Albertazzi, M. Bianconi, G.G. Bentini, R. Nipoti, R. Lotti, Nucl. Instr. and .Meth. B 170 (2000) 1

[16] M. Bianconi, F. Abel, J.C. Banks, A. Climent Font, C. Cohen, B.L. Doyle, R. Lotti, G. Lulli, R. Nipoti, I Vickridge, D. Walsh, E. Wendler, Nucl. Instr. and Meth. B 161-163 (2000) 293

[17] M. Mayer, AIP Conf. Proc. 475 (1999) 541

[18] J.F. Ziegler, M.D. Ziegler and J.P. Biersack, Nucl. Instr. and Meth. B 268 (2010) 1818

[19] D. Abriola, A.F. Gurbich, M. Kokkoris, A. Lagoyannis, V. Paneta, Nucl. Instr. and Meth. 269 (2011) 2011

[20] http://www.surreyibc.ac.uk/sigmacalc/

[21] J.F. Ziegler, Nucl. Instr. and Meth. B 219-220 (2004) 1027

[22] N.P. Barradas, K. Arstila, G. Battistig, M. Bianconi, N. Dytlewski, C. Jeynes, E. Kótai, G. Lulli, M. Mayer, E. Rauhala, E. Szilágyi, M. Thompson, Nucl. Instr. and Meth. B 262 (2007) 281

[23] I.Bogdanović Radović, Z. Siketić, M. Jakšić, A. F. Gurbich, J. Appl. Phys. 104 (2008) 0749052

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., 2001 [4]
	3.00 - 5.00	169.6°, 139.8°	-	Rihet et al., 1977 [9]
	1.69 - 2.69	165°	6%	Mayer et al., 1998 [13]
	1.00 - 3.80	161.4°	-	Segel et al., 1965 [14]
	2.17 - 4.19	160° - 135° in 5° steps	4-5%	Kokkoris et al., 2010 [10]
	2.22 - 3.27	155°	-	Symons and Treacy, 1963 [11]
	0.59 -1.99	150°	7%	Tautfest and Rubin, 1956 [12]
	1.85 - 3.00	120°	3-5%	Mashkarov et al., 1975 [7]
	1.85 - 2.99	119.5°	1-9%	Dejneko et al., 1974 [8]
^{10}B(p,p)^{10}B	0.50 - 3.30	170° - 100° in 5° steps	5%	Chiari et al., 2001 [4]
	1.00 - 2.97	154°, 120.3°	7%	Overley and Whaling, 1962 [6]

	1.03 – 3.50	137.09°	-	Andreev et al. [5]
	0.84 - 1.60	137.8°	-	Brown et al., 1951 [3]

FIGURE CAPTION

Figure 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).

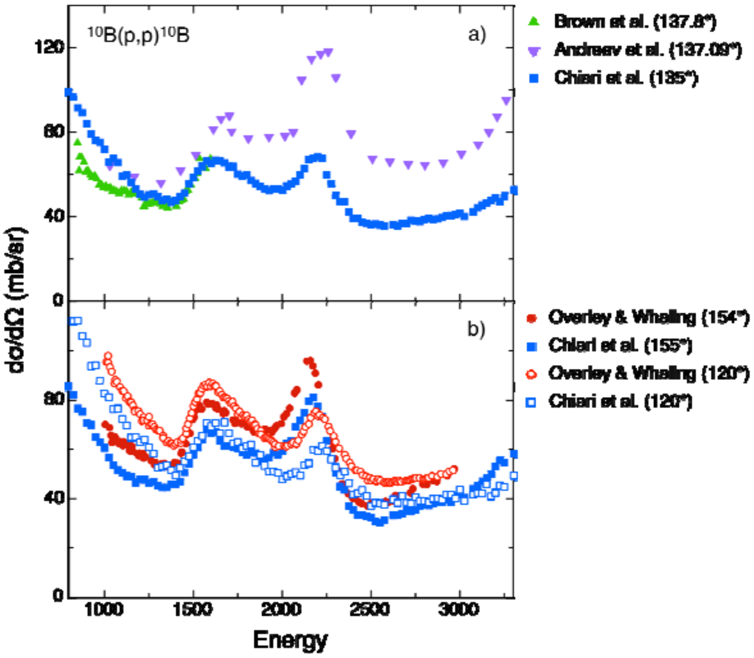
Figure 2 – Comparison between the available experimental data for the p+11B elastic scattering cross section data at different scattering angles: 119° and 120° (panel a); 140° (panel b); 150° and 155° (panel c); 160° and 165° (panel d).

Figure 3 – Comparison between experimental and simulated spectra of B_4C target at 2.60 MeV proton energy and different scattering angles. Open squares represent experimental data, while SIMNRA simulations are shown as lines. For $^{12}C(p,p)^{12}C$ the evaluated SigmaCalc cross section was used, whereas for B(p,p)B the following cross-section values were used in the simulations: a) Chiari et al. for $p+^{10,11}B$ [4]; b) Mayer et al. for $p+^{11}B$ [13] and Overley and Whaling for $p+^{10}B$ [6]; c) Segel et al. for $p+^{11}B$ [14] and Overley and Whaling for $p+^{10}B$ [6]; d) Kokkoris et al. for $p+^{11}B$ (no data below 2.2 MeV) [10] and Overley and Whaling for $p+^{10}B$ [6]; e) Symons and Treacey for $p+^{11}B$ (no data below 2.2 MeV) [11] and Overley and Whaling for $p+^{10}B$ [6]; f) Mashkarov et al. for $p+^{11}B$ [7] and Overley and Whaling for $p+^{10}B$ [6].

Figure 4 – Comparison between experimental and simulated spectra of B_4C target at different proton energies and scattering angles. Open squares represent experimental data, while SIMNRA simulation using the B(p,p)B cross-sections values from [4] scaled up by 19% (see

text for details) are shown as lines. For $^{12}C(p,p)^{12}C$ the evaluated SigmaCalc cross section was used.

Figure 5 – Comparison between experimental and simulated backscattering spectra of BN thick target at 150° and 3.24 MeV proton energy. Solid line is SIMNRA simulation and circles represent experimental data; in the simulation the scaled-up B(p,p)B cross sections by Chiari et al. were used.



^{10}B(p,p)^{10}B
a)
b)
Brown et al. (137.8°)
Andreev et al. (137.09°)
Chiari et al. (135°)
Overley & Whaling (154°)
Chiari et al. (155°)
Overley & Whaling (120°)
Chiari et al. (120°)
dσ/dΩ (mb/sr)
Energy
120
80
40
0
80
40
0
1000
1500
2000
2500
3000

FIGURE 1

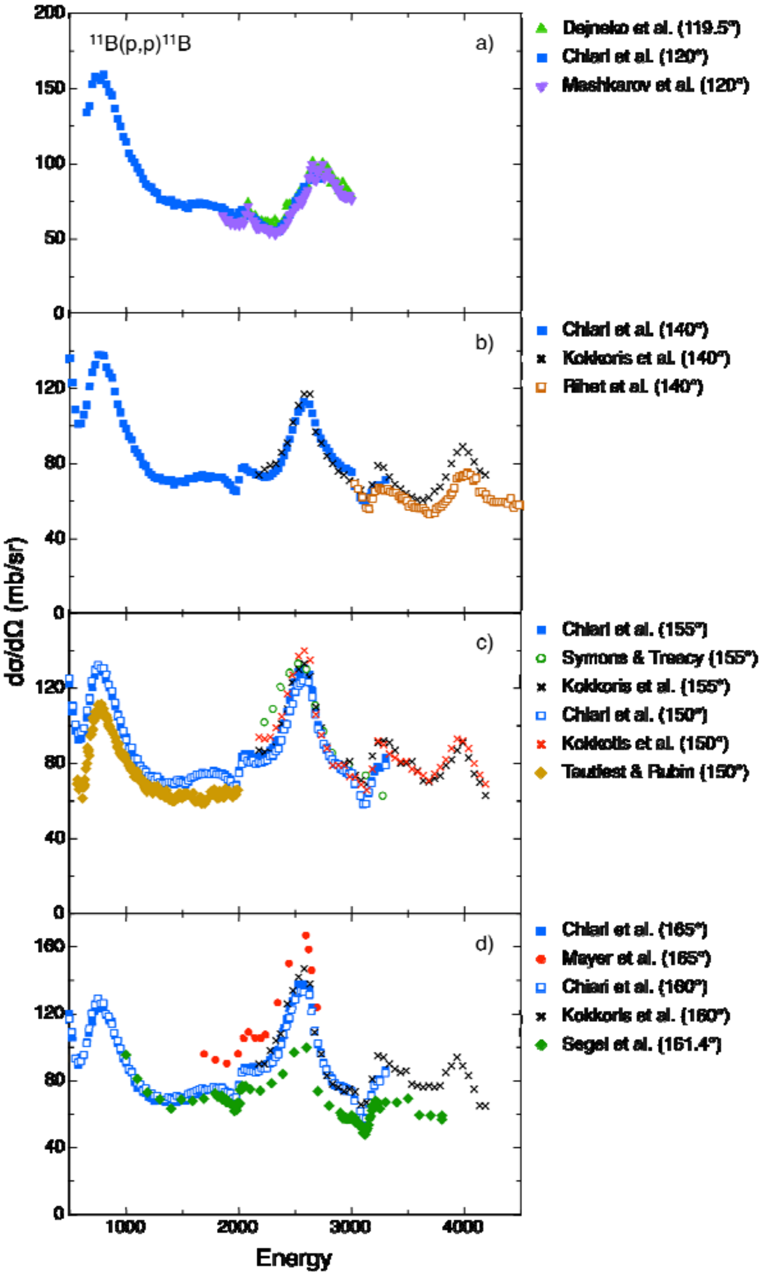

^{11}B(p,p)^{11}B
a)
b)
c)
d)
dσ/dΩ (mb/sr)
Energy
0
50
100
150
200
40
80
120
160
1000
2000
3000
4000
Dejneko et al. (119.5°)
Chiari et al. (120°)
Mashkarov et al. (120°)
Chiari et al. (140°)
Kokkoris et al. (140°)
Rihet et al. (140°)
Chiari et al. (155°)
Symons & Treacy (155°)
Kokkoris et al. (155°)
Chiari et al. (150°)
Kokkoris et al. (150°)
Tautfest & Rubin (150°)
Chiari et al. (165°)
Mayer et al. (165°)
Chiari et al. (160°)
Kokkoris et al. (160°)
Segel et al. (161.4°)

FIGURE 2

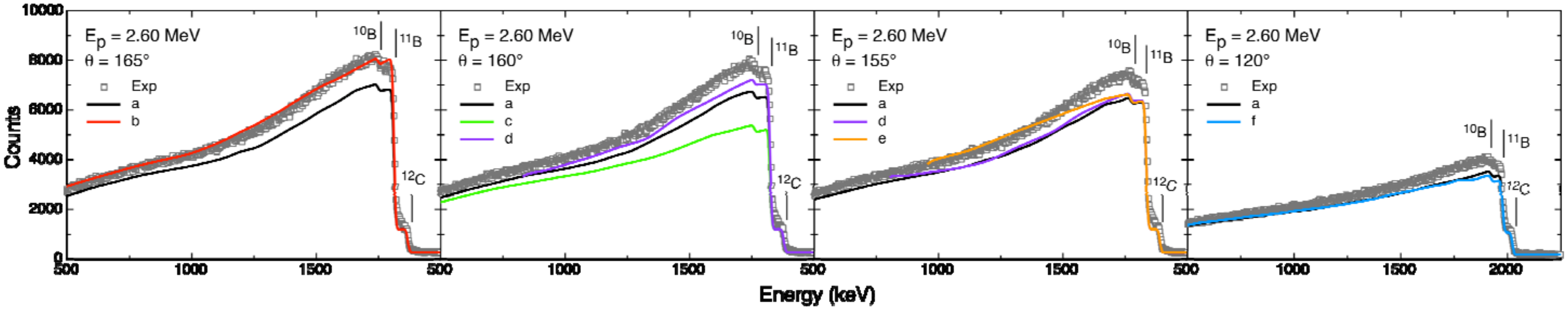
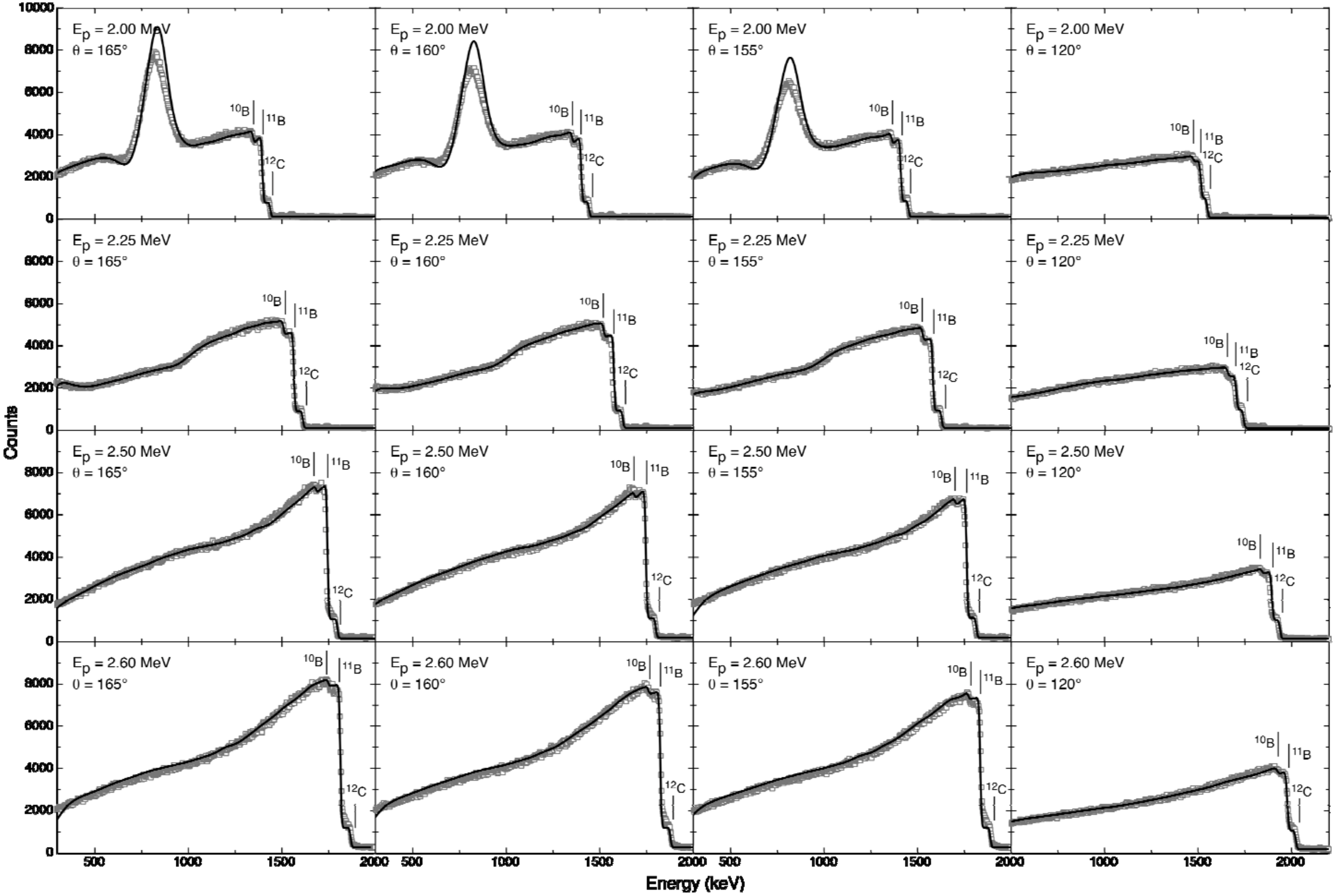

Ep = 2.60 MeV
θ = 165°
Exp
a
b
Ep = 2.60 MeV
θ = 160°
Exp
a
c
d
Ep = 2.60 MeV
θ = 155°
Exp
a
d
e
Ep = 2.60 MeV
θ = 120°
Exp
a
f
10B
11B
12C
Counts
0
2000
4000
6000
8000
10000
500
1000
1500
2000
Energy (keV)

FIGURE 3



Counts
Energy (keV)
10000
8000
6000
4000
2000
0
500
1000
1500
2000
E_p = 2.00 MeV
θ = 165°
θ = 160°
θ = 155°
θ = 120°
E_p = 2.25 MeV
E_p = 2.50 MeV
E_p = 2.60 MeV
^{10}B
^{11}B
^{12}C

FIGURE 4

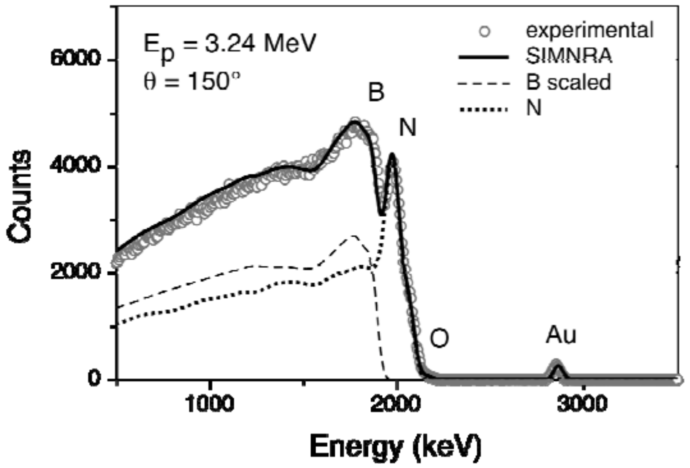

E_p = 3.24 MeV
θ = 150°
experimental
SIMNRA
B scaled
N
B
N
O
Au
Counts
0
2000
4000
6000
1000
2000
3000
Energy (keV)

FIGURE 5