PHYSICAL REVIEW B
CONDENSED MATTER AND MATERIALS PHYSICS

THIRD SERIES, VOLUME 57, NUMBER 17 1 MAY 1998-I

BRIEF REPORTS

Brief Reports are accounts of completed research which, while meeting the usual **Physical Review B** *standards of scientific quality, do not warrant regular articles. A Brief Report may be no longer than four printed pages and must be accompanied by an abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Measured stopping power for ^{11}B ions in $Z=6-47$ targets

Zheng Tao, Lu Xiting, Xia Zonghuang, and Shen Dingyu
Department of Technical Physics and Institute of Heavy Ion Physics, Peking University, Beijing 100871, China
(Received 17 July 1997; revised manuscript received 29 December 1997)

The stopping powers for 0.5–5.2 MeV ^{11}B ions in the C, Al, Ti, Cu, Nb, and Ag targets have been measured using a transmission technique. The experimental error is about 3%. The results are compared to the TRIM-91 calculation and fitted to an empirical formula. Our measurements for ^{11}B in the Al target are reasonably consistent with Ziegler's compilation. However, for the other five stoppers, significant deviation is found. The effective charge deduced from our experimental measurements appears to have a clear dependence on the stopping medium. The electronic stopping power at low energies exhibits a strong Z_2 oscillation, which becomes weaker with increasing energy of boron ions. [S0163-1829(98)01517-3]

I. INTRODUCTION

The knowledge of stopping powers for heavy ions in various materials is of significant importance in applications involving heavy ions and in the development of theoretical approaches. However, the experimental information on low-velocity stopping of heavy ions is still scarce.

This study is an investigation of the stopping powers for 0.5–5.2 MeV ^{11}B ions in C, Al, Ti, Cu, Nb, and Ag foils using a transmission technique. It is a continuation of our systematic study of stopping powers in various solids.[1–4] In the present energy region, no previous experimental stopping data exist to our knowledge for boron ions in these foils. In this paper, our results are compared to the Ziegler-Biersack-Littmark (ZBL) model calculations[5] and differences are observed. The present stopping data can be fitted to an empirical formula.

II. EXPERIMENT

The experimental arrangement was similar to that described in a previous paper.[3] The boron ion beams were obtained from the 1.7 MV tandem accelerator at Peking University. For measuring boron-ion energy loss in C, Al, Cu, and Ag, a 150 nm thick gold layer on a silicon substrate was used to scatter the ions incident from the accelerator. For measurements in Ti and Nb, the scatterer was a thin gold layer of 4 nm. The foil under investigation was placed in front of the silicon surface barrier detector, positioned at a scattering angle of 160°. In this way the ion flux could be reduced to a reasonable level and direct beam exposure of the foils was avoided. The energy loss of the ions transmitted through the foil could then be determined by the shift of the leading edge of the energy spectra for the thick gold layer and by the change of the spectrum peak position for the thin gold layer. The energy calibration of the detector system was carried out by using scattered boron ion beams of known energies, as defined by the magnetic field of the accelerator analyzing magnet. In this way, corrections include effects due to detector window thickness, pulse height defect, and any nonlinear energy response of the detector system for boron-ion beams.

To extract stopping powers from the energy loss data, the area densities of the foils were determined from the energy loss of 3.6–4.2 MeV α particles in the foils. The α energy loss was measured by using the same geometry and at the same spot on the foils as the boron-ion energy loss. For Cu, Ag, and Al, the α-stopping data given by Anderson *et al.*[6] were used; the error of the data was less than 1%. For C, Ti, and Nb, the α-stopping data were taken from the Ziegler-Biersack-Littmark calculations[5] which had high accuracy in the higher energy region; the error of the data was less than

TABLE I. A Stopping powers for ^{11}B ions in C, Al, Ti, Cu, Nb, and Ag (MeV cm^2/mg).

Carbon			Aluminum			Titanium		
E (MeV)	Se	Se-ZBL	*E* (MeV)	Se	Se-ZBL	*E* (MeV)	Se	Se-ZBL
5.20	5.59	5.39	5.20	3.69	3.76	5.11	3.86	3.32
4.88	5.56	5.45	4.88	3.63	3.76	4.78	3.90	3.34
4.54	5.87	5.52	4.55	3.73	3.76	4.46	3.94	3.36
4.22	5.87	5.58	4.24	3.67	3.76	4.13	3.91	3.37
3.89	5.92	5.64	3.91	3.69	3.74	3.73	3.96	3.38
3.56	5.89	5.72	3.57	3.71	3.73	3.49	3.91	3.39
3.32	5.97	5.78	3.34	3.69	3.73	3.24	3.92	3.41
3.08	5.90	5.85	3.10	3.62	3.72	3.00	3.87	3.41
2.84	5.93	5.90	2.87	3.62	3.71	2.77	3.84	3.41
2.59	5.89	5.95	2.62	3.55	3.69	2.53	3.75	3.40
2.36	5.78	5.97	2.38	3.54	3.66	2.29	3.71	3.38
2.12	5.69	5.97	2.14	3.53	3.63	2.06	3.60	3.33
1.88	5.66	5.92	1.90	3.50	3.58	1.82	3.52	3.26
1.64	5.50	5.81	1.66	3.48	3.52	1.59	3.38	3.16
1.41	5.36	5.62	1.41	3.49	3.43	1.44	3.30	3.08
1.18	5.18	5.32	1.18	3.35	3.32	1.29	3.20	2.97
1.03	4.88	5.05	1.02	3.26	3.20	1.13	3.10	2.82
0.88	4.60	4.71	0.88	3.04	3.07	0.99	2.96	2.66
0.73	4.24	4.29	0.73	2.84	2.89	0.84	2.80	2.46
0.60	3.72	3.86	0.59	2.56	2.67	0.70	2.60	2.23
0.48	3.07	3.40	0.48	2.09	2.45	0.56	2.36	1.97
						0.43	2.07	1.69
Copper			Niobium			Silver		
E (MeV)	Se	Se-ZBL	*E* (MeV)	Se	Se-ZBL	*E* (MeV)	Se	Se-ZBL
5.03	2.63	2.42	5.04	2.65	2.45	5.03	2.38	2.04
4.71	2.59	2.41	4.71	2.68	2.46	4.72	2.32	2.04
4.40	2.58	2.39	4.39	2.67	2.46	4.40	2.30	2.04
4.08	2.54	2.37	4.06	2.66	2.46	4.08	2.27	2.04
3.69	2.48	2.33	3.66	2.69	2.45	3.68	2.24	2.02
3.45	2.41	2.31	3.42	2.66	2.45	3.44	2.20	2.02
3.21	2.42	2.29	3.18	2.64	2.44	3.22	2.16	2.00
2.97	2.35	2.26	2.94	2.60	2.43	2.97	2.12	1.98
2.75	2.29	2.23	2.70	2.56	2.42	2.74	2.09	1.95
2.50	2.27	2.19	2.46	2.54	2.39	2.51	2.04	1.92
2.28	2.20	2.14	2.22	2.51	2.36	2.27	2.00	1.88
2.04	2.10	2.08	1.99	2.44	2.32	2.04	1.89	1.82
1.83	2.01	2.01	1.77	2.33	2.27	1.83	1.81	1.76
1.59	1.94	1.91	1.54	2.24	2.19	1.60	1.73	1.67
1.45	1.82	1.84	1.39	2.18	2.13	1.45	1.62	1.60
1.29	1.79	1.75	1.24	2.07	2.05	1.30	1.57	1.53
1.16	1.62	1.66	1.10	1.98	1.97	1.16	1.46	1.45
			0.96	1.82	1.86			
			0.82	1.72	1.74			
			0.69	1.56	1.60			
			0.55	1.40	1.43			
			0.43	1.20	1.26			

3%. The foils studied were analyzed by using 2 MeV α Rutherford backscattering spectroscopy and 3.05 MeV α resonance scattering. No obvious impurities were found in the foils.

III. RESULTS AND DISCUSSION

A. Stopping power

The stopping power is usually treated as the sum of the independent components, the nuclear part and the electronic part. So the experimental stopping power S_{exp} can be written as follows:

$$S_{\mathrm{exp}}=S_n+S_e\,. \tag{1}$$

The ratio of nuclear S_n to electronic S_e stopping value S_n/S_e is small and always less than 1% for 0.5 MeV boron ions passing through the Ag target and is smaller in all other cases. In order to compare experimental results with theoretical calculations, the experimental S_{exp} values were corrected to give S_e. For this correction, the nuclear S_n values were taken from ZBL.

The present stopping power results are shown in Table I and Fig. 1. Each value is given at the average energy, i.e., the initial energy minus half the observed energy shift. The uncertainty of our stopping data is about 3%, which mainly consists of the error of determining the thickness of foils and the energy shift of the backscattering spectra from the gold layer. For comparison, the ZBL calculations[5] are also shown.

From Fig. 1 we can see that for ^{11}B ions in Al, the present measurements are generally consistent with the ZBL calculations. However, for the other five stoppers, significant differences are found. The present results are systematically higher than the ZBL semiempirical values for Ag, Nb, and Cu materials at energies above 2 MeV and for the Ti stopper in the whole energy region. For the carbon foil, and energies from 1.0 to 2.5 MeV the ZBL values are higher than ours, while at higher energies between 3.5–5.2 MeV the ZBL predictions are lower. It should be noted that in our energy range, no previous experimental data exist to our knowledge for boron ions in these six stoppers.

To quantify the energy dependence of the measured stopping powers, the experimental electronic stopping data have been adjusted to the following empirical formula

$$S_e=\frac{1}{a_1E^{-b_1}+a_2+a_3E^{b_2}}, \tag{2}$$

where a_1, a_2, a_3, b_1, and b_2 are the fitted coefficients, which are listed in Table II. The unit of MeV cm^2/mg is taken for S_e and that of MeV for E. The fitted curves are shown in Fig. 1 as well.

B. Effective charge

ZBL semiempirical stopping values for heavy ions are based on a scaling law that relates the electronic stopping power of heavy ions S_{HI} to that of protons S_p at the same ion velocity:

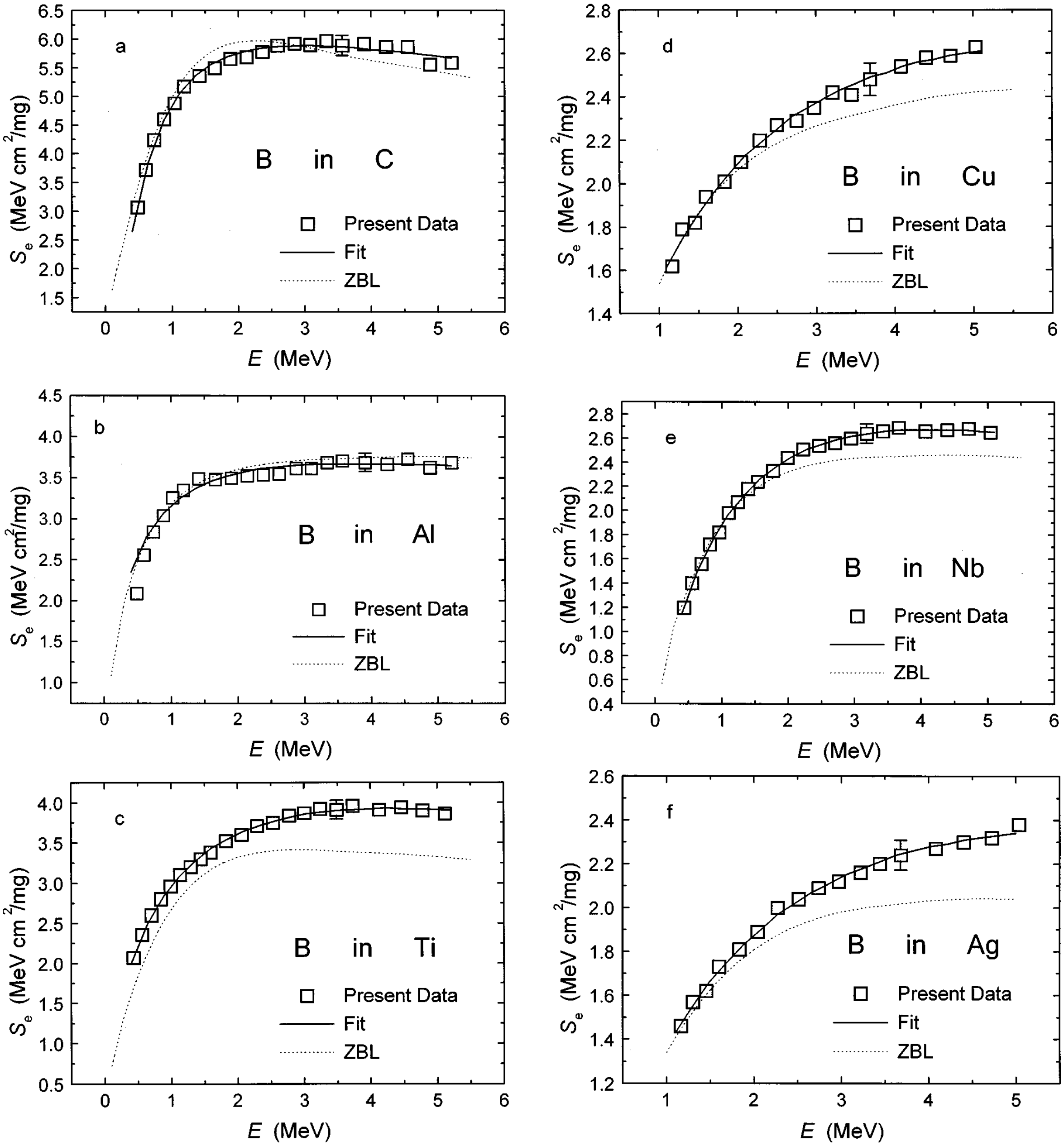

FIG. 1. Stopping power for ^{11}B in C (a), Al (b), Ti (c), Cu (d), Nb (e), and Ag (f).

$$S_{\mathrm{HI}}=(Z_{\mathrm{HI}}e/Z_p e)^2 S_p = Z_{\mathrm{HI}}^{*\,2} S_p \tag{3}$$

where $Z_{\mathrm{HI}}^{*}e$ represents the effective charge of the heavy ion as it slows down in the stopping medium, and $Z_p e$ is the charge of a proton. In this approach, it is assumed that effective charge is independent of the stopping medium, and dependent only on the boron-ion energy. The curve for effective charge versus energy of boron ions from the ZBL predictions are compared with our experimental results in Fig. 2. Clearly our measurements of the effective charge for boron ions depends on the stopping medium. This is similar to the results that Santry and Werner[7–9] observed for the stopping powers of ^{7}Li, ^{12}C, ^{14}N, ^{16}O, and ^{19}F ions.

C. Z_2 oscillation

The dependence of the present electronic stopping data on the target atomic number Z_2 is depicted in Fig. 3 and compared with the ZBL calculations. Our data display a strong Z_2 oscillation at low energies that becomes weaker for higher energy boron ions. At lower energy, the ZBL predictions reproduce the experimental results rather well. At higher energies the ZBL calculations lie below our data for higher Z_2 values.

TABLE II. Fitted coefficients of ^{11}B electronic stopping power.

Sample	b_1	b_2	a_1	a_2	a_3	fitting range (MeV)
C	1.5	1.0	0.0592	0.1411	0.0058	0.48–5.20
Al	0.6	0.1	0.2060	−0.3737	0.4842	0.48–5.20
Ti	0.7	1.0	0.1854	0.1411	0.0109	0.43–5.11
Tu	0.5	0.1	0.9248	−1.6878	1.4114	1.16–5.03
Nb	0.6	0.3	0.5596	−0.3383	0.3094	0.43–5.04
Ag	0.5	0.1	1.1562	−2.3246	1.9029	1.16–5.03

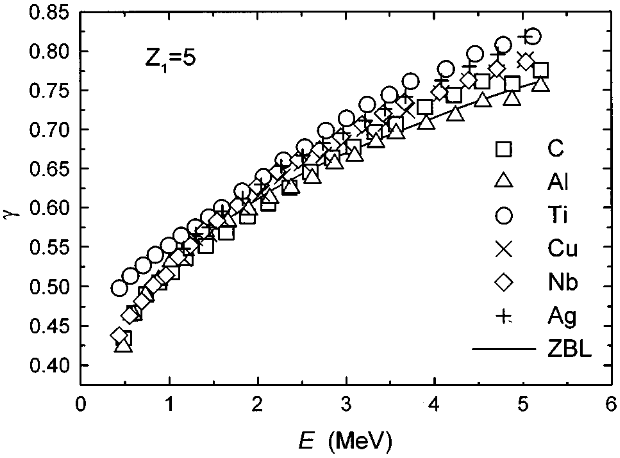

FIG. 2. Comparison of effective charge versus energy between present data and ZBL approaches.

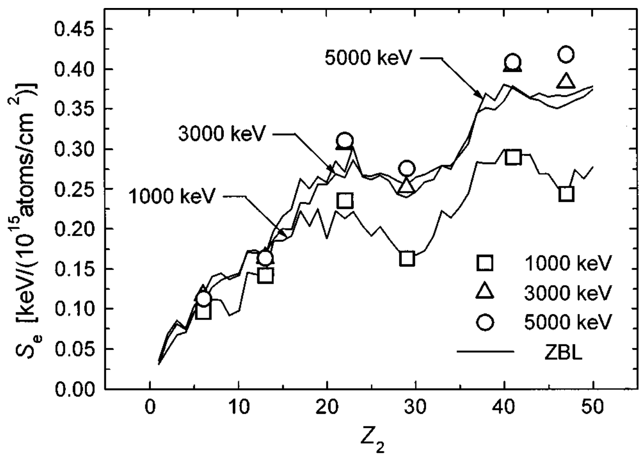

FIG. 3. Dependence of ^{11}B S_e on Z_2.

In conclusion, we present stopping power data for MeV boron ions in six targets with Z_2 between 6 and 47. The data are compared with the predictions of the ZBL semiempirical model. Better agreement was observed for the Al target, while the data failed to match for C, Ti, Cu, Nb, and Ag stopping media. The effective charge of boron ions is dependent on the stopping material. A strong Z_2 oscillation has been shown in a lower energy and the oscillation behavior becomes weaker for higher energy boron ions.

ACKNOWLEDGMENTS

We would like to thank Xu Guoji for preparing the high quality foils and Wang Xuemei and Zhao Qiang for operating the accelerator.

[1] Lu Xiting, Xia Zonghuang, Shen Dingyu, Mao Lian, and Wang Xuemei, Nucl. Instrum. Methods Phys. Res. B **36**, 390 (1989).

[2] Lu Xiting, Xia Zonghuang, Zhou Kungang, Jin Changwen, Yang Xihong, Liu Hongtao, Jiang Dongxing, and Ye Yanlin, Nucl. Instrum. Methods Phys. Res. B **58**, 280 (1991).

[3] Jin Changwen, Lu Xiting, Huang Xiaoqing, Ye Yanlin, Xia Zonghuang, Liu Hongtao, and Jiang Dongxing, Phys. Rev. B **48**, 6858 (1993).

[4] Wu Zeqing, Lu Xiting, Jin Changwen, Zheng Tao, Xia Zonghuang, Liu Hongtao, Jiang Dongxing, and Ye Yanlin, Chin. Phys. **11**, 537 (1994).

[5] J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon, New York, 1985), Vol. 1; J. F. Ziegler, *The Transport of Ions in Matter*, TRIM-91 (IBM Research, Yorktown, New York).

[6] H. H. Andersen, J. F Bak, H. Knudsen, and B. R. Nielsen, Phys. Rev. A **16**, 1929 (1977).

[7] D. C. Santry and R. D. Werner, Nucl. Instrum. Methods Phys. Res. B **5**, 449 (1984).

[8] D. C. Santry and R. D. Werner, Nucl. Instrum. Methods Phys. Res. B **35**, 7 (1991).

[9] D. C. Santry and R. D. Werner, Nucl. Instrum. Methods Phys. Res. B **69**, 167 (1992).