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STOPPING POWER AND RANGE OF HEAVY IONS IN SOLIDS: A COMPARATIVE STUDY

G. S. RANDHAWA and H. S. VIRK

Department of Physics, Guru Nanak Dev University, Amritsar-143 005, India

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Abstract—A comparative study of various stopping power and range formulations has been made by comparing the calculated stopping power and range values with corresponding experimental values for different projectiles, viz. H, He, Li, N, O, Al, Si, Xe, Au, Pb, Bi, U, etc. in different targets, e.g. Be, C, Al, Au, Pb, CR-39, Lexan, Mylar, LR-115, CH, $(CH)_n$, TRIFOL-TN, etc. at various low and high energies. A detailed study has been made taking into consideration different target and projectile combinations, e.g. heavy ion–light target, light ion–heavy target and light ion–light target. Overall the Ziegler *et al.* (*The Stopping Power and Range of Ions in Solids*, Vol. 1. Pergamon Press, New York, 1985) formulation (TRIM 95) provides the best agreement with the experimental results for all projectile and target combinations except the heavy ion–light target combination where it underestimates the stopping power data in the limited range of energy of the projectile. Mukherjee and Nayak (*Nucl. Instrum. Meth.* **159**, 421, 1979) formulation totally fails at relativistic and low energies of the projectile, irrespective of the projectile–target combination. Northcliffe and Schilling (*Atom. Data Nucl. Data Tables* **A7**, 233, 1970) formulation does not show any particular trend. Benton and Henke (*Nucl. Instrum. Meth.* **67**, 87, 1969) formulation gives good agreement between experimental and theoretical data within the range of experimental error. The present study has been undertaken in order to determine the best stopping power and range formulation for calibration of solid state nuclear track detectors. Copyright © 1996 Elsevier Science Ltd

1. INTRODUCTION

Theoretical and experimental investigations about the penetration of charged particles in matter have played a very important role in the development of modern physics. Research in many fields, e.g. astrophysics, biophysics, nuclear physics, material science, etc. relies on the experimental techniques utilizing accelerated charged particles and the subsequent interaction processes involved therein (Ahlen, 1980). Particle track detectors (cloud chambers, bubble chambers, nuclear emulsions, etc.) have been directly responsible for the discovery of most of the known elementary particles, and charged particle detectors have at least been indirectly responsible for all of the experimental results in high, medium and low energy physics. Solid state nuclear track detectors, a new class of detectors which came into existence about three decades ago, have now become one of the most important tools in many branches of science and technology (Fleischer *et al*., 1975). In these detectors, the rate of etching of the material along the particle trajectory (V_t) plays an important role in its different applications. This rate directly depends upon the energy loss process of the projectile in the target (stopping power). However, the energy loss phenomenon is complex in nature and no universal energy loss formulation is developed which is valid for all different projectile and target combinations for the whole range of energy. Many review articles and new formulations have been written on the subject of charged particle penetration, among these special mention should be made of those by Benton and Henke (1969), Northcliffe and Schilling (1970), Mukherjee and Nayak (1979), Ahlen (1980), Ziegler *et al.* (1985) and Hubert *et al.* (1989), etc.

In the present work, a comparative study of the different stopping power and range formulations, e.g. Benton and Henke (1969), Northcliffe and Schilling (1970), Mukherjee and Nayak (1979) and Ziegler *et al.* (1985), has been made by comparing the calculated stopping power and range values adopting these formulations with the corresponding experimental stopping power and range data for different projectile and target combinations at various energies. The Northcliffe and Schilling data tables have been used to calculate the stopping power and range data for all heavy ions in the energy range 0.0125–12.0 MeV/u in different elemental and compound targets (using the Bragg additivity rule). The computer code TRIM-95, developed by Ziegler (1995), is used for the stopping power and range calculations from the Ziegler *et al.* formulation. The experimental stopping power and range data of Al-Najjar *et al.* (1981), Andersen *et al.* (1977), Bimbot *et al.* (1980), Fowler *et al.* (1979), Gauvin *et al.* (1987, 1990), Heckman *et al.* (1987), Kiss *et al.*

(1989), Kocsis and Brandt (1993), Laichter *et al.* (1982), Raisanen and Rauhala (1987a, b), Raisanen *et al.* (1994), Rauhala *et al.* (1992), Raju and Dwivedi (1993), Randhawa *et al.* (1996), Saxena and Dwivedi (1988, 1990) and Waddington *et al.* (1986) have been used in the present study.

2. RESULTS AND DISCUSSION

Table 1 presents the stopping power data along with the percentage deviation of theoretical values from experimental values for different heavy ions, viz. U, Pb, Au and Xe in light targets like C, $(CH)_n$, Be, Al, Mylar, etc. It is evident from this table that the Ziegler *et al.* formulation strongly underestimates the stopping power data in comparison to the experimental data. The Mukherjee and Nayak formulation gives satisfactory results in a limited range of energy. An interesting point to be noted here is that for the Au ion in the $(CH)_n$ target, as the energy of the incident ion increases from 15.0 to 150.0 MeV/u, the Ziegler *et al.* formulation starts giving better results in comparison to the Mukherjee and Nayak formulation as it starts underestimating the results above 50 MeV/u. Figure 1 depicts the same behaviour for this heavy ion-light target combination. The results predicted by the Benton and Henke formulation do not show any particular trend. Hubert *et al.*'s (1989) formulation gives the best agreement with the experimental results within a percentage deviation of + 5%. As range has a cummulative effect on stopping power, which can be mathematically written as

$$R(E) = \int_0^E (dE/dX)dE,$$

the range value computed using the TRIM programme based on the Ziegler *et al.* formulation for heavy ion light target combination overestimates the corresponding experimental range values (Randhawa *et al.*, 1996). A similar result is depicted by the range data given in Table 2 for heavy ions U, Bi, Pb, Au, La and Xe in light targets like CR-39, Lexan, Hostaphan, TRIFOL-TN etc. which have C, H, O and N as their main constituents. The Mukherjee and Nayak formulation gives reasonable agreement for these combinations except for the Au (900 MeV/u) ion in C, CH, CH_2 and Al targets where it totally fails to determine the range values. TRIM calculations overestimate the range values. As the energy of the U ion decreases from $\approx$ 16.5 MeV/u to low values in different light targets like CR-39, Lexan, Hostaphan, TRIFOL-TN, the computed values start giving agreement with the experimental values. Similar evidence is given in Figs 2 – 4 for the U ion in CR-39, Hostaphan and TRIFOL-TN targets, respectively. At a relativistic energy of the Au ion in C, CH, CH_2 and Al targets, the Ziegler *et al.* formulation gives good agreement with the experimental values. Benton and Henke in formulation gives satisfactory results within a percentage deviation of $\pm$ 8% in the given energy range.

Table 3 presents a comparison between theoretical and experimental stopping power data (along with the percentage deviation from experimental values in parentheses) for light ions, He and Li, on a heavy target, Au, in the energy range 1.0–4.0 MeV/u. Benton and Henke and Ziegler *et al.*'s formulations show a similar behaviour and give an agreement to the experimental data within a deviation of $\pm$ 4%. The Mukherjee and Nayak formulation in the given energy range for this combination overestimates the experimental data. A similar behaviour is also shown in Fig. 5 for the He ion in an Au target. The Northcliffe and Schilling formulation underestimates the experimental data.

Table 4 presents the stopping power data for light ions, viz. H (0.695–4.322 MeV/u), He (0.289–2.631 MeV/u), Li (0.513–2.446 MeV/u), B (0.547–1.884 MeV/u), C (0.53–1.919 MeV/u), N (0.536–1.649 MeV/u) and O (0.663–1.77 MeV/u) ions in the light target, LR-115. For the H ion, in the given energy range, the Ziegler *et al.* and Benton and Henke formulations give theoretical results in agreement with the experimental stopping power data within a deviation of $\pm$ 5%. Mukherjee and Nayak's formulation underestimates the experimental data between 10 and 30%. In the case of the He ion projectile in a LR-115 target in the given energy range, the Mukherjee and Nayak formulation underestimates the results up to 40% from the experimental ones, whereas Ziegler *et al.* and Benton and Henke formulations give satisfactory results. A similar trend is noted for the Li, B, C, N and O ions in the LR-115 target, where Mukherjee and Nayak's formulation underestimates the experimental data above 15% and Ziegler *et al.* and Benton and Henke predict the results within a percentage deviation of $\pm$ 5%. Figures 6 and 7 depict a similar behaviour for H and O ions in LR-115, respectively.

A similar study has been made for light ions such as H (0.328–2.823 MeV/u), He (0.335–2.544 MeV/u), Li (0.372–2.956 MeV/u), B (0.483–1.896 MeV/u), C (0.565–2.106 MeV/u), N (0.569–1.675 MeV/u), O (0.561–1.782 MeV/u), Na (0.556–0.863), Al (0.646–0.828) and Si (0.665–0.771 MeV/u) in a light target, CR-39. Mukherjee and Nayak's formulation underestimates the experimental data between 12 and 22% up to 0.84 MeV/u energy of an H projectile, above this energy it underestimates below 10%. The results predicted by Ziegler *et al.* and Benton and Henke formulations are deviated up to a maximum of $\pm$ 6% from the experimental results. For the He (Fig. 8) and Li ions, in the given energy range, the Mukherjee and Nayak formulation underestimates the data between 10 and 30%. TRIM calculations based on Ziegler *et al.* and Benton and Henke's formulations predict the results within a deviation of $\pm$ 6% from the experimental ones. For B, C, N, O, Na, Al and Si

Table 1. Comparison between experimental and theoretically calculated stopping power data for different heavy ions in light targets

Ion	Energy (MeV/u)	Target	S_{exp} (MeV/mg/cm^2)*	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*	Hubert *et al.*†
U	3.13	C	156.0 ± 5	140.7(− 10)	149.70(− 4)	127.20(− 18)	154.20(− 1)
U	3.99	Be	200.0 ± 7	142.1(− 29)	162.68(− 19)	124.8(− 38)	200.77(0)
U	4.60	Al	125.0 ± 3	105.4(− 16)	130.88(5)	105.0(− 16)	121.61(− 3)
U	4.74	Mylar	178.0 ± 10	156.0(− 12)	178.77(0)	138.8(− 22)	177.12(0)
U	4.91	Formvar	222.0 ± 25	168.4(− 24)	193.73(− 13)	132.65(− 40)	192.72(− 13)
U	4.94	Hostaphan	181.0 ± 24	159.1(− 12)	182.69(1)	140.28(− 22)	180.99(0)
Pb	3.96	Be	175.0 ± 6	126.2(− 28)	106.24(− 39)	113.0(− 35)	176.79(1)
Pb	4.58	Al	110.0 ± 3	93.6(− 15)	118.10(7)	94.50(− 14)	109.54(0)
Pb	4.70	C	147.0 ± 7	129.4(− 12)	150.37(2)	118.8(− 19)	146.43(0)
Au	15.00	$(CH)_n$	119.0	125.0(5)	123.31(4)	103.42(− 13)	117.25(− 1)
Au	25.00	$(CH)_n$	95.4	100.2(5)	93.66(− 2)	84.88(− 11)	91.12(− 4)
Au	35.00	$(CH)_n$	79.7	83.20(4)	75.60(− 5)	72.45(− 9)	75.64(− 5)
Au	50.00	$(CH)_n$	64.0	66.83(4)	58.97(− 8)	60.4(− 6)	61.31(− 4)
Au	75.00	$(CH)_n$	50.1	51.30(2)	43.59(− 13)	48.09(− 4)	47.80(− 5)
Au	100.00	$(CH)_n$	41.2	42.42(3)	34.88(− 15)	40.53(− 2)	39.93(− 3)
Au	120.00	$(CH)_n$	36.0	37.65(5)	30.19(− 16)	36.33(1)	35.61(− 1)
Au	150.00	$(CH)_n$	30.4	32.62(7)	25.25(− 17)	31.77(5)	30.97(2)
Xe	4.10	Be	103.0 ± 4	83.12(− 19)	67.70(− 34)	74.45(− 28)	101.89(− 1)
Xe	4.58	C	89.0 ± 3	84.48(− 5)	94.29(6)	77.03(− 13)	91.20(2)
Xe	4.66	Al	67.5 ± 2	62.38(− 8)	74.58(10)	61.18(− 9)	68.48(1)
Xe	4.79	Mylar	97.0 ± 6	89.95(− 7)	99.69(3)	80.46(− 17)	96.33(− 1)
Xe	4.99	Hostaphan	94.0 ± 1.7	91.14(− 3)	92.02(− 2)	80.98(− 14)	97.03(3)
Xe	24.07	Be	44.6 ± 0.9	44.59(0)	42.32(− 5)	39.81(− 11)	43.14(− 3)
Xe	26.33	Be	41.2 ± 1.0	42.16(2)	39.79(− 3)	37.92(− 8)	40.75(− 1)

*Bimbot *et al.* (1980), Heckman *et al.* (1987), Gauvin *et al.* (1990).
†Data from Sharma *et al.* (1995).

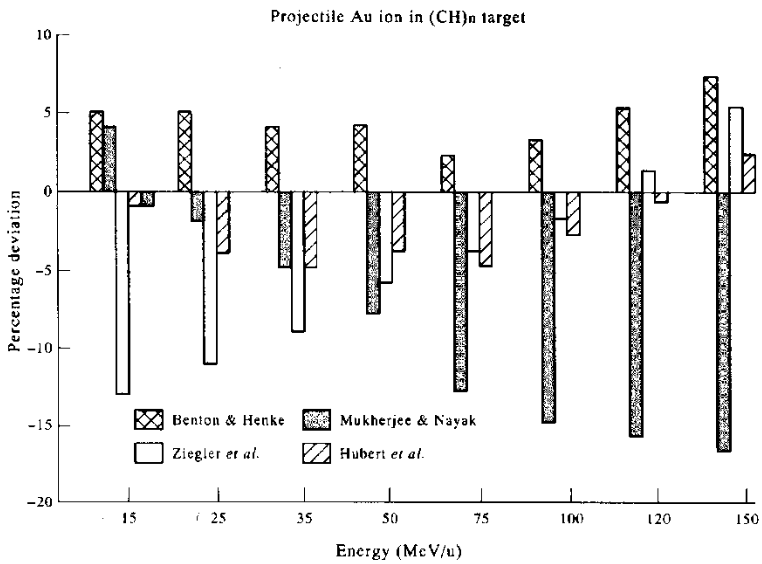

Fig. 1. Percentage deviation of theoretical calculated stopping power data from the experimental data for the Au ion at different energies in a $(CH)_n$ target.

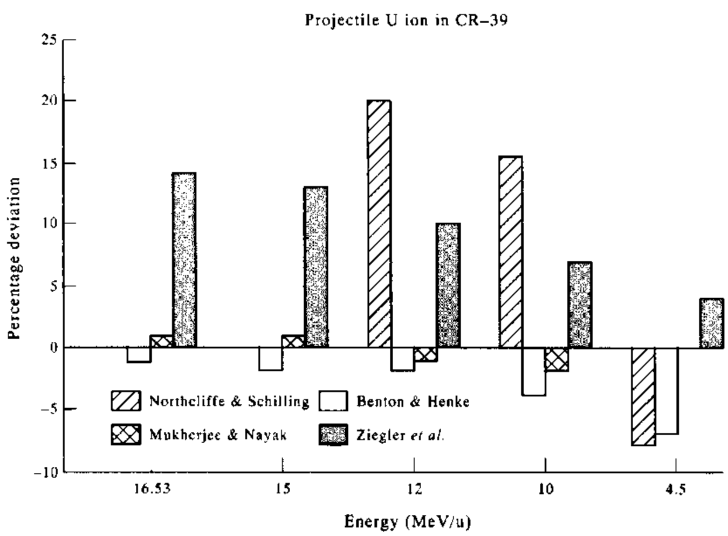

Fig. 2. Percentage deviation of theoretical calculated range data from the experimental data for the U ion at different energies in a CR-39 target.

Table 2. Comparison between experimental and calculated range data for different heavy ions in light targets

Ion	Energy(MeV/u)	Target	R_{exp}* (μm)	Northcliffe and Schilling	Benton and Henke	Mukherjee and Nayak	Ziegler et al.
U	16.53	CR-39	208.00		205.52(1)	209.22(1)	237.22(14)
U	15.00	—	190.00		186.78(− 2)	191.96(1)	214.56(13)
U	12.00	—	155.00	186.06(20)	151.49(− 2)	153.49(− 1)	171.10(10)
U	10.00	—	133.70	154.39(15)	128.88(− 4)	131.50(− 2)	143.23(7)
U	4.50	—	73.00	66.88(− 8)	67.82(− 7)	72.67(0)	76.17(4)
U	16.53	Lexan	227.00		222.01(− 2)	227.00(1)	256.32(13)
U	15.00	—	203.00		201.75(− 1)	205.00(1)	231.22(14)
U	5.90	—	92.00		89.95(− 2)	92.00(0)	95.51(4)
U	16.34	Hostaphan	200.0 ± 2.0		200.00(0)	202.50(1)	241.00(20)
U	14.47	—	173.5 ± 3.0		177.70(2)	179.50(3)	201.69(16)
U	10.12	—	124.6 ± 3.5	140.00(8)	128.40(3)	128.50(3)	141.41(14)
U	7.80	—	100.7 ± 4	118.50(10)	103.16(3)	103.00(2)	110.82(10)
U	4.28	—	63.8 ± 4.5	63.50(0)	64.56(1)	69.00(8)	65.86(3)
U	1.1	—	28.2 ± 4.9	24.50(− 4)	26.48(− 6)	30.00(6)	26.30(6)
U	16.34	Trifol-TN	243.0 ± 2		237.59(− 2)	238.80(− 2)	273.33(13)
U	15.48		216.7 ± 2.4		225.27(4)	225.90(4)	258.18(19)
U	13.14	—	184.7 ± 3		192.69(4)	192.50(4)	218.08(18)
U	9.95	—	146.3 ± 3	162.50(11)	150.22(3)	148.70(2)	165.99(13)
U	7.50	—	121.3 ± 3	124.00(2)	118.47(− 2)	117.80(− 3)	127.67(5)
U	4.67	—	88.6 ± 4	81.50(− 8)	81.67(− 8)	86.00(− 3)	85.21(4)
U	2.65	—	61.7 ± 4	52.50(− 15)	57.85(− 6)	61.7(0)	57.58(− 7)
U	0.83	—	27.7 ± 4	26.00(− 6)	26.46(− 4)	31.10(12.27)	26.51(− 4)
U	1.40	C	20.41 ± 1	19.26(6)	20.33(0)	25.45(20)	20.48(0)
U	1.40	Al	24.42 ± 1	23.36(− 4)	24.13(− 1)	27.97(15)	24.45(0)
U	1.40	Ti	16.15 ± 1	18.39(14)	18.51(14)	21.52(33)	16.47(2)
Bi	13.00	CR-39	158.00		158.52(0)	163.47(3)	179.58(14)
Bi	10.10	—	129.00	154.82(20)	125.42(− 3)	128.63(0)	139.08(8)
Bi	7.30	—	93.00	123.57(33)	94.59(2)	96.91(4)	101.97(10)
Bi	1.30	—	31.00	29.17(− 6)	27.60(− 10)	33.22(7)	32.16(4)
Pb	13.60	—	166.00		166.80(0)	171.23(3)	189.40(14)
Pb	13.60	Lexan	187.00		180.27(− 4)	186.40(0)	204.28(9)
Au	11.40	CR-39	142.00		138.52(− 3)	144.00(1)	155.36(9)
Au	13.42	Lexan	181.00		175.13(− 3)	183.29(1)	198.58(9)
Au	900.00	C	42920.00		44612.20(4)	98917.30(130)	44586.00(4)
Au	900.00	CH	73752.00		78332.70(6)	168044.00(128)	78597.00(7)
Au	900.00	CH_2	98122.00		105404.00(7)	220227.70(124)	106099.00(8)
Au	900.00	Al	39008.00		42128.60 (8)	83222.20(113)	41910.00(7)
La	14.60	Lexan	199.00		195.46(− 2)	208.51(5)	223.25(12)
Xe	14.50	—	206.00		196.87(− 4)	209.94(2)	224.01(9)
Xe	5.90	—	83.00		78.46(− 6)	87.00(5)	86.46(4)
Xe	14.50	CR-39	191.00		182.19(− 5)	195.00(1)	207.55(8)
Xe	13.02	—	169.00		161.48(− 5)	173.43(2)	183.12(8)
Xe	5.90	—	72.00		69.37(− 4)	75.00(4)	76.25(6)

*Laichter *et al.* (1982), Waddington *et al.* (1986), Saxena and Dwivedi (1988), Saxena and Dwivedi (1990), Raju and Dwivedi (1993), Kocsis and Brandt (1993) and Randhawa *et al.* (1996).

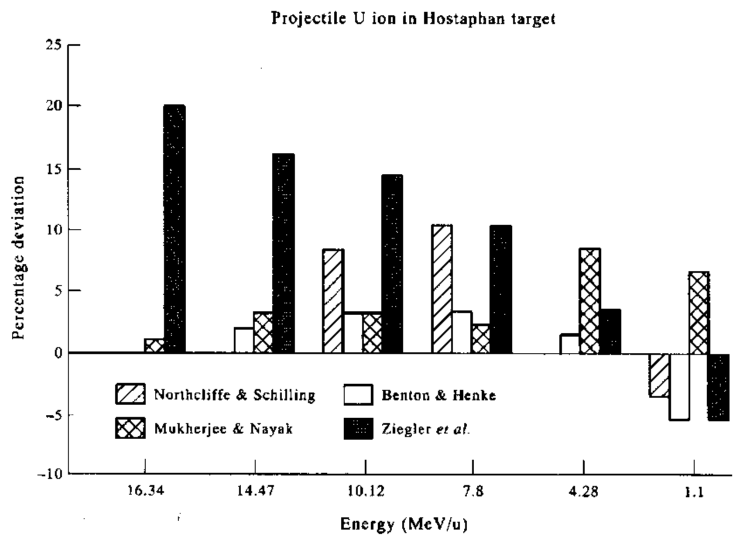

Fig. 3. Percentage deviation of theoretical calculated range data from the experimental data for the U ion at different energies in a Hostaphan target.

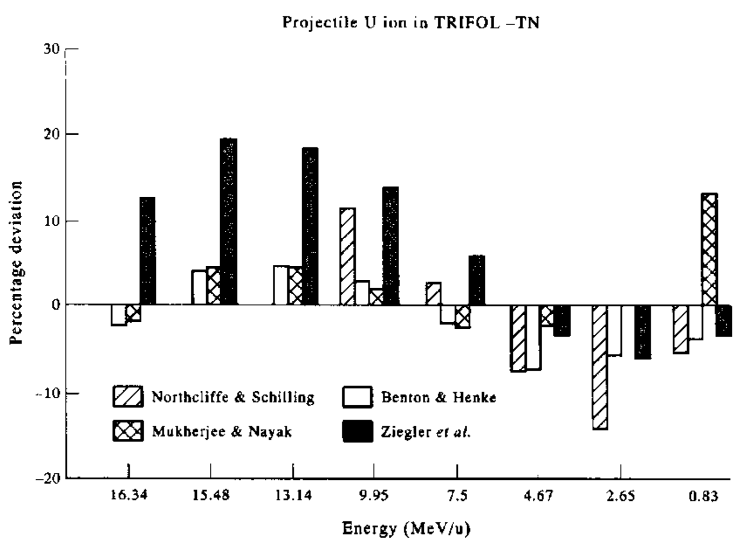

Fig. 4. Percentage deviation of theoretical calculated range data from the experimental data for the U ion at different energies in a TRIFOL-TN target.

Table 3. Comparison between theoretical and experimental stopping power data for He and Li ions in an Au target

Ion	Energy(MeV/u)	S_{exp} (keV/mg/cm^2)*	Northcliffe and Schilling	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*
He	1.0	261.44	250.00(−4)	263.39(1)	282.00(8)	258.50(−1)
He	1.2	241.81	237.75(−2)	249.61(3)	262.51(9)	239.14(−1)
He	1.4	225.83	220.87(−2)	227.19(1)	249.06(10)	221.18(−2)
He	1.6	212.31	204.00(−4)	213.25(0)	234.86(11)	211.66(0)
He	1.8	200.49	192.94(−4)	201.24(0)	223.50(11)	199.98(0)
He	2.0	190.36	183.00(−4)	190.70(0)	211.50(11)	188.30(−1)
He	2.2	181.18	174.16(−4)	181.44(0)	199.50(10)	179.39(−1)
He	2.4	172.92	166.44(−4)	173.15(0)	186.56(8)	171.37(−1)
He	2.6	165.67	156.73(−5)	165.70(0)	176.36(6)	164.80(−1)
He	2.8	158.94	149.30(−6)	158.94(0)	167.67(5)	156.35(−2)
He	3.0	152.88	151.46(−1)	152.79(0)	160.76(5)	151.70(−1)
He	3.2	147.44	142.00(−4)	147.16(0)	155.36(5)	147.16(0)
He	3.4	142.35	136.60(−4)	141.98(0)	152.50(7)	140.86(−1)
He	3.6	137.79	133.50(−3)	137.19(0)	148.00(7)	137.09(−1)
He	3.8	133.6	131.57(−2)	132.76(−1)	144.50(8)	131.64(−1)
He	4.0	129.57	125.00(−4)	128.63(−1)	140.50(8)	128.40(−1)
Li	1.6	478.68	444.00(−7)	479.67(0)	495.60(4)	464.29(−3)
Li	1.8	453.88	423.00(−7)	452.43(0)	494.90(9)	435.51(−4)
Li	2.0	432.29	402.00(−7)	428.22(−1)	475.80(10)	413.30(−4)
Li	2.2	411.44	384.57(−7)	408.25(−1)	447.70(9)	395.45(−4)
Li	2.4	392.68	368.51(−6)	389.59(−1)	453.70(16)	379.06(−3)
Li	2.6	375.43	347.11(−8)	372.83(−1)	392.90(5)	363.30(−3)

*Andersen *et al.* (1977).

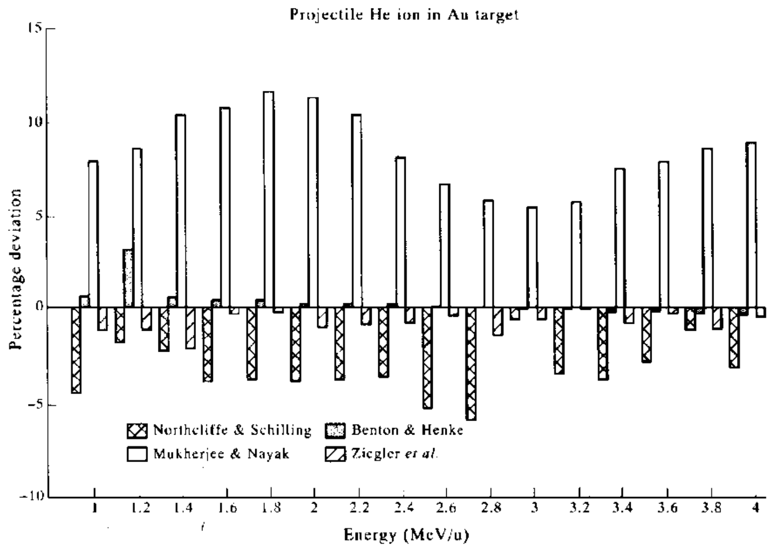

Fig. 5. Percentage deviation of theoretical calculated stopping power data from the experimental data for the He ion at different energies in an Au target.

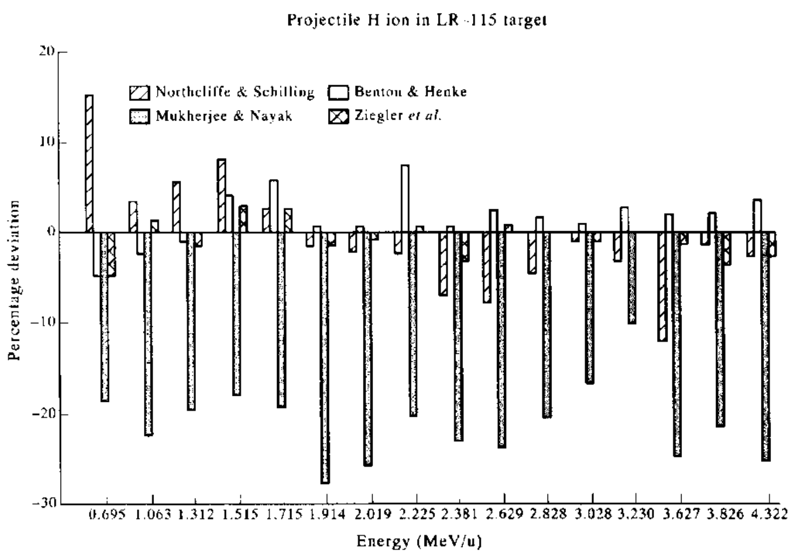

Fig. 6. Percentage deviation of theoretical calculated stopping power data from the experimental data for the H ion at different energies in a LR-115 target.

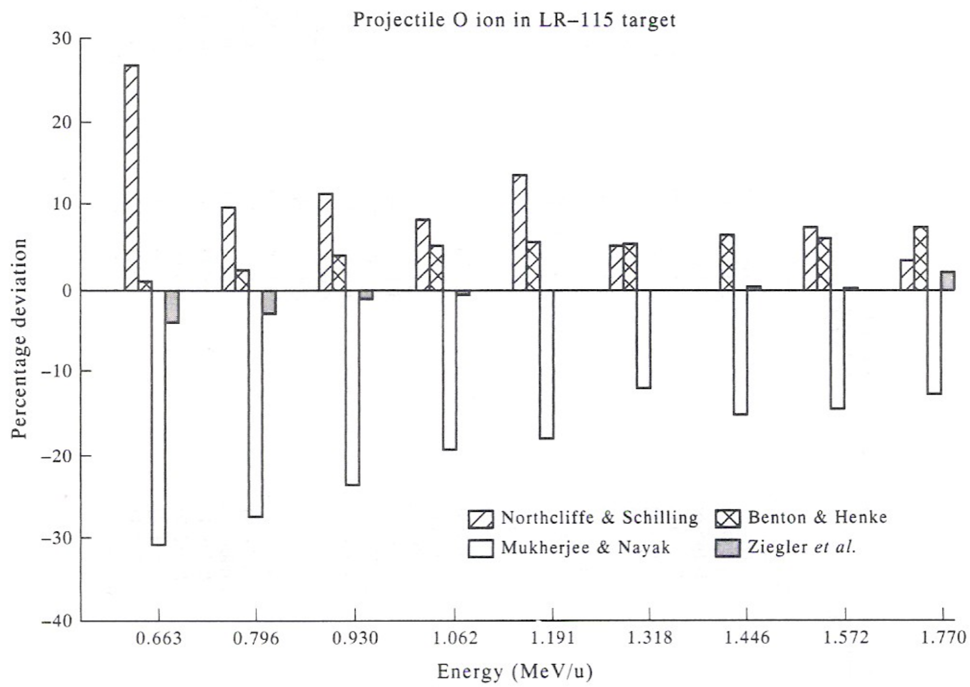

Fig. 7. Percentage deviation of theoretical calculated stopping power data from the experimental data for the O ion at different energies in a LR-115 target.

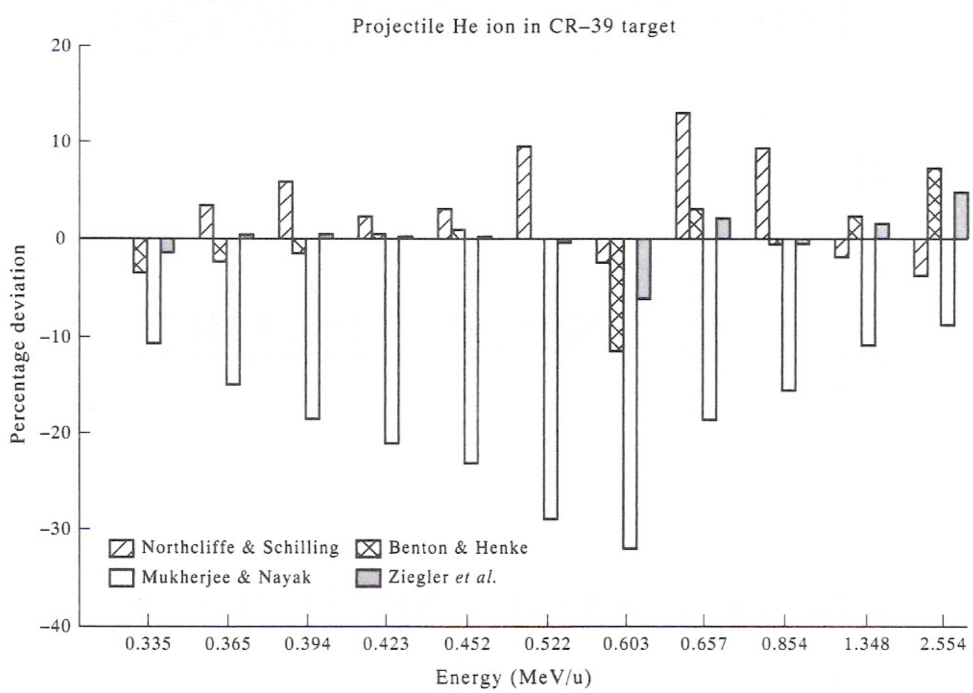

Fig. 8. Percentage deviation of theoretical calculated stopping power data from the experimental data for the He ion at different energies in a CR-39 target.

Table 4. Comparison between theoretical and experimental stopping power data for different heavy ions in LR-115

Ion	Energy (MeV/u)	S_{exp} (MeV/mg^2/cm^2)*	Northcliffe and Schilling	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*
H	0.695	0.313	0.360(15)	0.298(− 5)	0.255(− 18)	0.298(− 5)
H	1.063	0.232	0.240(3)	0.227(− 2)	0.180(− 22)	0.235(1)
H	1.312	0.199	0.210(6)	0.197(− 1)	0.160(− 20)	0.196(− 2)
H	1.515	0.172	0.186(8)	0.179(4)	0.141(− 19)	0.177(3)
H	1.715	0.156	0.160(3)	0.165(6)	0.126(− 19)	0.160(3)
H	1.914	0.152	0.150(− 1)	0.153(1)	0.110(− 28)	0.150(− 1)
H	2.019	0.144	0.141(− 2)	0.145(1)	0.107(− 26)	0.143(1)
H	2.225	0.133	0.130(− 2)	0.143(8)	0.106(− 20)	0.134(1)
H	2.381	0.130	0.121(− 7)	0.131(1)	0.100(− 23)	0.126(− 3)
H	2.629	0.118	0.104(− 8)	0.121(3)	0.090(− 24)	0.119(1)
H	2.828	0.113	0.108(− 4)	0.115(2)	0.090(− 20)	0.113(0)
H	3.028	0.108	0.107(− 1)	0.109(1)	0.090(− 17)	0.107(− 1)
H	3.230	0.100	0.097(− 3)	0.103(3)	0.090(− 10)	0.100(0)
H	3.627	0.093	0.082(12)	0.095(2)	0.070(25)	0.092(− 1)
H	3.826	0.089	0.088(− 1)	0.091(2)	0.070(− 21)	0.086(− 3)
H	4.322	0.080	0.078(− 3)	0.083(4)	0.060(− 25)	0.078(3)
He	0.289	1.850	2.183(18)	1.733(− 6)	1.250(− 32)	1.846(1)
He	0.451	1.590	1.800(13)	1.520(− 4)	1.110(− 30)	1.520(− 4)
He	0.483	1.520	1.794(18)	1.470(− 3)	1.080(− 29)	1.470(− 3)
He	0.586	1.320	1.520(15)	1.320(0)	1.000(− 24)	1.320(0)
He	0.609	1.350	1.437(6)	1.290(4)	0.980(− 27)	1.290(− 4)
He	0.653	1.240	1.410(14)	1.240(0)	0.950(− 23)	1.240(0)
He	0.712	1.210	1.350(12)	1.180(− 2)	0.910(− 25)	1.170(− 3)
He	0.806	1.090	1.234(13)	1.090(0)	0.821(25)	1.085(0)
He	0.856	1.050	1.164(11)	1.040(− 1)	0.645(− 39)	1.040(− 1)
He	1.220	0.824	0.871(6)	0.829(1)	0.570(− 31)	0.828(0)
He	1.476	0.732	0.756(3)	0.732(0)	0.450(− 38)	0.727(0)
He	2.014	0.580	0.582(0)	0.591(2)	0.419(− 28)	0.580(0)
He	2.209	0.546	0.530(− 3)	0.552(1)	0.395(− 28)	0.549(0)
He	2.383	0.536	0.510(− 5)	0.523(− 2)	0.367(32)	0.526(− 2)

He	2.631	0.494	0.460(− 7)	0.486(− 2)	0.328(− 34)	0.480(− 3)
Li	0.513	2.940	3.203(9)	2.730(− 3)	2.136(− 27)	2.790(5)
Li	0.675	2.620	2.880(10)	2.490(− 5)	1.920(27)	2.569(− 2)
Li	0.988	2.090	2.380(14)	2.120(1)	1.580(− 24)	2.141(2)
Li	1.288	1.760	1.740(− 1)	1.800(2)	1.540(− 12)	1.821(3)
Li	1.583	1.520	1.420(− 7)	1.570(3)	1.180(− 22)	1.550(2)
Li	1.872	1.360	1.375(1)	1.400(3)	1.050(− 23)	1.370(1)
Li	2.160	1.220	1.190(− 1)	1.260(3)	0.960(− 21)	1.230(1)
Li	2.303	1.170	1.180(1)	1.210(3)	0.960(− 18)	1.180(1)
Li	2.446	1.110	1.110(0)	1.150(4)	0.860(− 23)	1.120(1)
B	0.547	5.980	5.904(− 2)	5.670(− 5)	4.035(− 33)	5.780(− 3)
B	0.653	5.580	5.669(2)	5.440(− 3)	4.010(28)	5.580(0)
B	0.751	5.360	5.464(2)	5.240(− 2)	3.970(− 26)	5.340(0)
B	0.821	5.170	5.388(4)	5.100(− 1)	3.940(− 24)	5.160(0)
B	0.850	5.910	5.369(− 9)	5.040(− 15)	3.920(− 34)	5.112(− 12)
B	0.913	4.980	5.129(3)	4.930(− 1)	3.890(− 22)	4.940(− 1)
B	0.946	4.930	4.960(1)	4.870(− 1)	3.870(− 22)	4.870(− 1)
B	1.003	4.800	4.933(3)	4.760(− 1)	3.830(− 22)	4.770(− 1)
B	1.043	4.710	4.729(0)	4.690(0)	3.810(− 19)	4.650(− 1)
B	1.091	4.650	4.512(− 3)	4.610(− 1)	3.770(− 19)	4.550(− 2)
B	1.137	4.550	4.330(− 5)	4.530(0)	3.730(− 18)	4.470(− 2)
B	1.179	4.480	4.660(4)	4.470(0)	3.700(− 17)	4.410(− 2)
B	1.232	4.390	4.460(2)	4.390(0)	3.650(− 17)	4.310(2)
B	1.266	4.340	4.350(0)	4.340(0)	3.620(− 17)	4.260(− 2)
B	1.328	4.190	4.150(− 1)	4.260(2)	3.570(− 15)	4.160(1)
B	1.419	4.100	3.890(− 5)	4.140(1)	3.450(− 16)	4.020(− 2)
B	1.513	3.970	4.070(3)	4.020(1)	3.370(− 15)	3.890(− 2)
B	1.606	3.830	3.860(1)	3.910(2)	3.290(− 14)	3.760(− 2)
B	1.699	3.710	3.690(− 1)	3.810(3)	3.090(− 17)	3.640(− 2)
B	1.792	3.590	3.620(1)	3.710(3)	3.080(− 14)	3.534(− 2)
B	1.884	3.490	3.580(1)	3.610(3)	3.060(− 12)	3.440(− 1)

Continued overleaf

Table 4—*Continued*

Ion	Energy (MeV/u)	S_{exp} (MeV/mg^2/cm^2)*	Northcliffe and Schilling	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*
C	0.530	7.250	7.997(10)	7.320(1)	5.040(− 30)	7.250(0)
C	0.620	7.050	7.886(12)	7.130(1)	5.010(− 29)	7.050(0)
C	0.798	6.670	7.330(10)	6.730(1)	4.930(− 26)	7.030(5)
C	0.901	6.380	6.900(8)	6.510(2)	4.889(− 23)	6.310(− 1)
C	0.974	6.290	6.380(1)	6.360(1)	4.850(− 23)	6.280(0)
C	0.981	6.230	6.330(2)	6.340(2)	4.840(− 22)	6.260(0)
C	1.062	6.080	6.180(2)	6.170(1)	4.790(− 21)	6.110(0)
C	1.142	5.910	6.130(4)	6.010(2)	4.730(19)	5.920(0)
C	1.220	5.760	6.050(5)	5.880(2)	4.680(− 19)	5.780(0)
C	1.298	5.640	5.890(4)	5.740(2)	4.620(− 18)	5.660(0)
C	1.324	5.580	5.580(0)	5.700(2)	4.603(− 17)	5.610(0)
C	1.375	5.510	5.550(1)	5.620(2)	4.590(− 17)	5.520(0)
C	1.494	5.340	5.530(4)	5.440(2)	4.470(− 17)	5.320(0)
C	1.584	5.070	5.267(4)	5.310(5)	4.380(− 14)	5.160(2)
C	1.752	4.900	4.990(2)	5.070(3)	4.220(− 14)	4.910(0)
C	1.835	4.820	5.040(5)	4.960(3)	4.140(− 14)	4.790(0)
C	1.919	4.730	4.820(2)	4.860(3)	4.060(− 14)	4.800(1)
N	0.536	8.777	9.941(13)	8.950(2)	6.020(31)	9.170(4)
N	0.691	8.330	9.960(19)	8.630(4)	6.050(− 27)	8.690(4)
N	0.844	7.900	8.850(12)	8.280(5)	5.940(− 25)	8.145(3)
N	0.992	7.610	8.492(12)	7.940(4)	6.000(− 21)	7.764(2)
N	1.142	7.220	7.380(2)	7.600(5)	5.930(− 18)	7.389(2)
N	1.287	7.000	7.410(6)	7.320(5)	5.830(− 17)	7.070(1)
N	1.434	6.690	6.950(4)	7.050(5)	5.680(− 15)	6.772(1)
N	1.578	6.500	6.860(6)	6.790(4)	5.549(− 15)	6.500(0)
N	1.649	6.430	6.560(2)	6.680(4)	5.470(− 15)	6.410(0)
O	0.663	10.290	3.039(27)	0.380(1)	7.130(− 31)	9.883(− 4)
O	0.796	9.870	0.830(10)	0.080(2)	7.180(− 27)	9.573(− 3)
O	0.930	9.410	0.480(11)	9.770(4)	7.190(− 24)	9.290(− 1)
O	1.062	8.990	9.730(8)	9.450(5)	7.267(− 19)	8.940(− 1)
O	1.191	8.670	9.836(13)	9.160(6)	7.110(18)	8.670(0)
O	1.318	8.430	8.880(5)	8.890(5)	7.440(− 12)	8.430(0)
O	1.446	8.100	8.100(0)	8.630(7)	6.880(− 15)	8.130(0)
O	1.572	7.890	8.480(7)	8.380(6)	6.760(− 14)	7.910(0)
O	1.770	7.570	7.840(4)	8.140(8)	6.630(− 12)	7.730(2)

*Rauhala *et al.* (1992).

Table 5. Comparison between theoretical and experimental range data for different heavy ions ($6 \leq Z \leq 29$) in CR-39

Ion	Energy (MeV/u)	R_{exp}*	Northcliffe and Schilling	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*
C	9.6	323	330.97(2)	308.17(− 5)	364.07(13)	314.32(− 3)
N	9.6	276	289.21(5)	268.77(− 3)	313.35(14)	276.24(0)
O	9.6	250	261.71(5)	240.29(− 4)	273.73(9)	248.66(− 1)
Ne	9.6	205	221.95(8)	202.65(− 1)	214.4(5)	210.36(3)
Mg	9.6	180	203.02(13)	178.07(− 1)	191.12(6)	186.41(4)
Al	9.6	179	202.02(13)	175.14(2)	189.14(6)	183.52(3)
P	9.6	153	175.98(15)	147.68(− 3)	161.85(6)	161.07(5)
Ar	9.6	162	186.01(15)	153.08(− 6)	168.96(4)	163.96(1)
Fe	9.6	123	159.38(29)	123.4(0)	137.90(12)	132.86(8)
Cu	9.6	120	156.31(30)	113.18(− 6)	133.13(11)	129.86(8)

*Fowler *et al.* (1979) and Al-Najjar *et al.* (1981).

ions having energy below 1.0 MeV/u, the Mukherjee and Nayak formulation provides results underestimating the experimental results between 10 and 35%, above energy 1.0 MeV/u, the results are under estimated below 10%. The Northcliffe and Schilling formulation does not show any particular trend. The Ziegler *et al.* formulation predicts results for the B, C, N and O ions in a CR-39 target within a percentage deviation of ± 5% and for Na, Al and Si ions, it underestimates the stopping power data between 5 and 9%. Benton and Henke show an almost similar trend to the Ziegler *et al.* formulation. Figure 9 vindicates a similar behaviour of these formulations for the Na ion in a CR-39 target.

Table 5 presents a comparison between theoretical and experimental range data (along with the percentage deviation in parentheses) for C, N, O, Ne, Mg, Al, P, Ar, Fe, and Cu ions having energy 9.6 MeV/u in CR-39 target. Ziegler *et al.* and Benton and Henke formulations give theoretical range values which are in agreement with the experimental values (maximum deviation ± 8%). The Mukherjee and Nayak formulation overestimates the data up to 15% and Northcliffe and Schilling's data tables overestimate the experimental data up to 30% as shown in Fig. 10. The stopping power data for He (0.38 MeV/u–1.74 MeV/u), N (0.62 MeV/u-1.21 MeV/u) and O (0.50 MeV/u 93.10 MeV/u) ions in Mylar target with percentage deviation in parentheses is given in Table 6 (light ion–light target). For the He ion, in the given energy range, Benton and Henke and Ziegler *et al.* formulations predict results which have a maximum deviation of ± 5% from the experimental results. The Mukherjee and Nayak formulation underestimates the results up to 20%. Northcliffe and Schilling's data tables do not show any particular trend. For the N ion, all these four formulations show the same behaviour as for the He ion in a Mylar target. In the case of the O ion, Northcliffe and Schilling's formulation overestimates the experimental results by about 20%. Ziegler *et al.*'s formulation gives the results that are in best agreement with the experimental results within a maximum deviation of ± 3%. Benton and Henke's formulation overestimates the experimental results up to 8%. Mukherjee and Nayak's formulation underestimates the experimental results up to 20% in the low energy range (up to 1.0 MeV/u) of the O ion in the Mylar target. Above 50 MeV/u, it again underestimates the results by 10%. Figure 11 shows the same behaviour of the percentage deviation of the theoretical stopping power data from the experimental data for the O ion in the Mylar target.

In Table 7, the stopping power data for the Au ion at energies of 75.0–150.0 MeV/u (high energy) in $(CH)_n$ and Au targets have been presented. The theoretical results predicted by Benton and Henke and Ziegler *et al.* formulations are in agreement with the experimental results. The Mukherjee and Nayak formulation underestimates the experimental

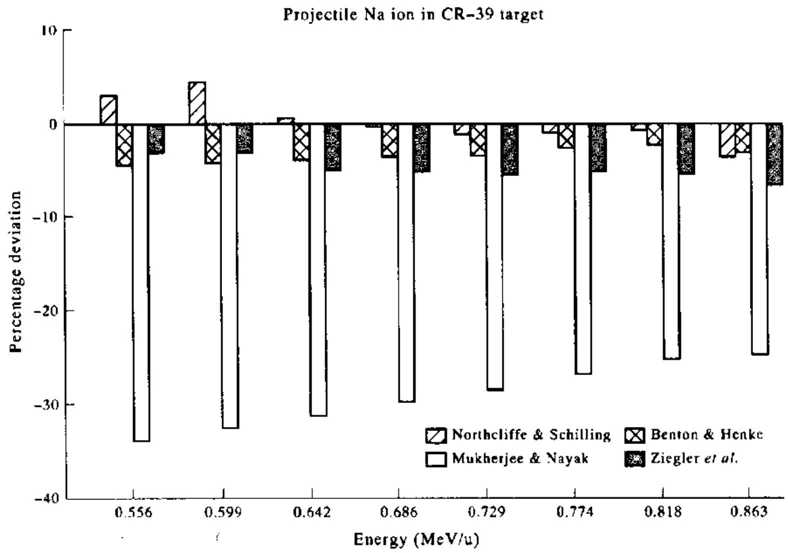

Fig. 9. Percentage deviation of theoretical calculated stopping power data from the experimental data for the Na ion at different energies in a CR-39 target.

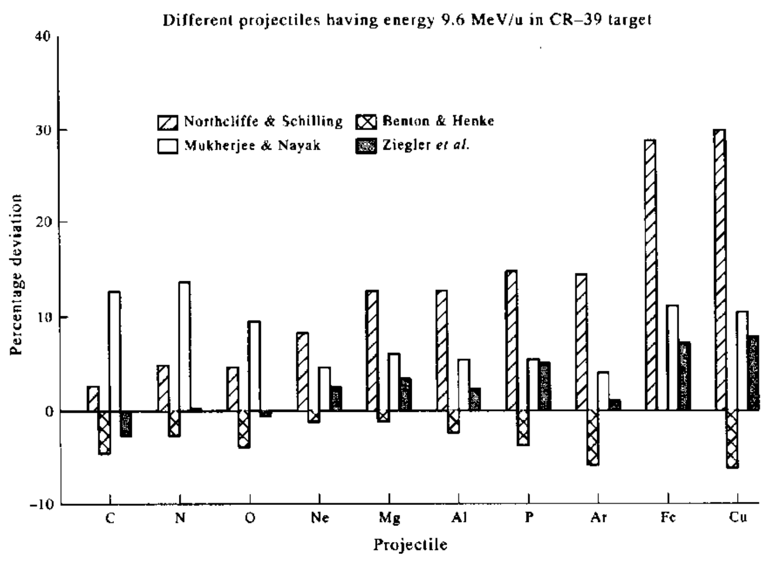

Fig. 10. Percentage deviation of theoretical calculated range data from the experimental data for different light ions having an energy of 9.6 MeV/u in a CR-39 target.

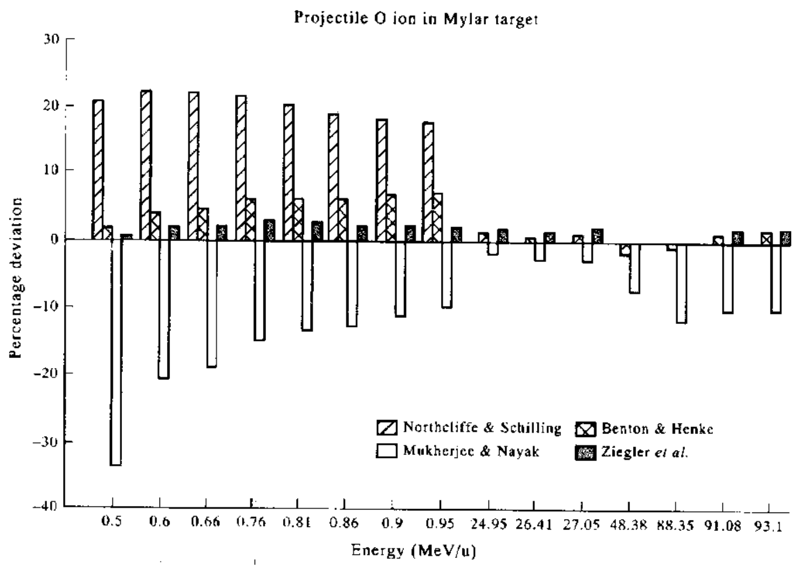

Fig. 11. Percentage deviation of theoretical calculated stopping power data from the experimental data for the [16]O ion at different energies in a Mylar target.

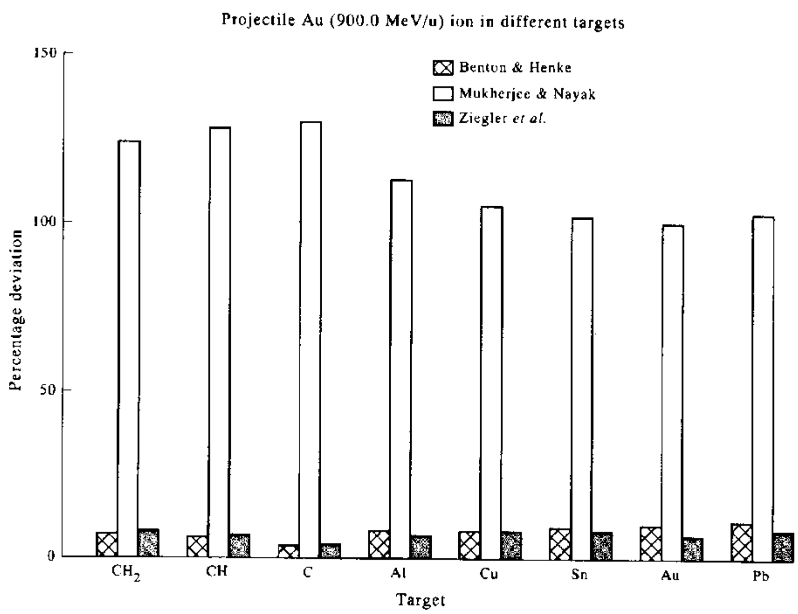

Fig. 12. Percentage deviation of theoretical calculated range data from the experimental data for an Au ion having an energy of 900 MeV/u in different targets.

Table 6. Comparison between theoretical and experimental stopping power data for He, N and O ions in Mylar

Ion	Energy (MeV/u)	S_{exp} (MeV/mg/cm^2)*	Northcliffe and Schilling	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*
He	0.38	1.68	1.84(10)	1.69(1)	1.36(− 20)	1.72(2)
He	0.48	1.53	1.82(19)	1.53(0)	1.24(− 19)	1.52(− 1)
He	0.52	1.45	1.74(20)	1.47(1)	1.21(− 17)	1.45(0)
He	0.58	1.37	1.64(20)	1.38(1)	1.15(− 16)	1.37(0)
He	0.61	1.39	1.57(13)	1.34(− 4)	1.13(− 19)	1.33(− 4)
He	0.66	1.25	1.48(18)	1.27(2)	1.08(− 14)	1.26(1)
He	0.67	1.26	1.48(17)	1.27(1)	1.08(− 14)	1.26(0)
He	0.74	1.15	1.37(19)	1.19(4)	1.02(− 11)	1.18(3)
He	0.74	1.11	1.33(20)	1.16(5)	1.00(− 10)	1.15(4)
He	0.84	1.04	1.24(19)	1.09(5)	0.95(− 9)	1.08(4)
He	0.94	1.00	1.13(20)	1.02(2)	0.88(− 12)	1.01(1)
He	1.21	0.87	0.82(− 6)	0.87(1)	0.73(− 17)	0.86(− 1)
He	1.49	0.74	0.77(4)	0.75(1)	0.64(− 14)	0.74(0)
He	1.74	0.62	0.68(6)	0.67(8)	0.56(− 10)	0.66(6)
N	0.62	8.51	10.68(18)	9.21(3)	7.06(− 20)	9.69(8)
N	0.71	8.93	10.35(16)	8.95(0)	7.11(− 20)	9.18(3)
N	0.76	8.91	10.19(14)	8.82(− 1)	7.13(− 20)	9.07(2)
N	0.82	8.81	10.15(15)	8.67(− 2)	7.14(− 19)	8.86(1)
N	0.88	8.65	9.53(10)	8.54(− 1)	7.14(− 17)	8.58(− 1)
N	0.93	8.46	8.97(6)	8.40(− 1)	7.13(− 16)	8.34(− 1)
N	0.98	8.15	8.98(10)	8.27(1)	7.12(− 13)	8.21(1)
N	1.04	8.08	8.52(5)	8.14(1)	7.10(− 12)	7.98(− 1)
N	1.09	8.08	8.13(1)	8.03(− 1)	7.07(− 13)	7.89(− 2)

N	1.21	7.66	8.27(8)	7.77(1)	6.98(− 9)	7.65(0)
O	0.50	10.93	13.19(21)	11.14(2)	7.25(− 34)	11.00(1)
O	0.55	10.72	13.05(22)	11.06(3)	8.33(− 22)	10.92(2)
O	0.58	10.69	12.96(22)	11.00(3)	8.35(− 22)	10.85(2)
O	0.60	10.55	12.89(22)	10.97(4)	8.37(− 21)	10.76(2)
O	0.63	10.57	12.77(21)	10.90(3)	8.40(− 21)	10.68(1)
O	0.66	10.36	12.68(22)	10.84(5)	8.42(− 19)	10.60(2)
O	0.69	10.43	12.51(20)	10.77(3)	8.45(− 19)	10.50(1)
O	0.71	10.13	12.41(23)	10.72(6)	8.46(− 16)	10.44(3)
O	0.74	10.17	12.25(20)	10.65(5)	8.48(− 17)	10.36(2)
O	0.76	9.98	12.13(22)	10.60(6)	8.49(− 15)	10.29(3)
O	0.80	9.97	11.91(19)	10.50(5)	8.51(− 15)	10.16(2)
O	0.81	9.84	11.84(20)	10.47(6)	8.53(− 13)	10.00(3)
O	0.86	9.73	11.58(19)	10.35(6)	8.50(− 12)	9.97(2)
O	0.90	9.58	11.34(18)	10.25(7)	8.50(− 11)	9.83(3)
O	0.95	9.43	11.12(18)	10.12(7)	8.53(− 9)	9.65(2)
O	1.01	9.26	10.87(17)	9.96(8)	8.52(− 8)	9.44(2)
O	1.15	8.72	10.38(19)	9.63(10)	8.39(− 4)	9.03(3)
O	24.95	1.28		1.30(2)	1.26(− 2)	1.31(2)
O	26.41	1.23		1.24(1)	1.20(− 2)	1.25(2)
O	27.05	1.20		1.22(1)	1.10(− 3)	1.23(3)
O	48.38	0.77		0.76(− 2)	0.71(− 7)	0.77(0)
O	88.35	0.48		0.48(− 1)	0.42(− 11)	0.48(0)
O	91.08	0.46		0.47(1)	0.41(− 10)	0.47(2)
O	93.10	0.45		0.46(2)	0.40(− 10)	0.46(2)

*Raisanen and Rauhala (1987a, b), Gauvin *et al.* (1987) and Kiss *et al.* (1989).

Table 7. Comparison between experimental and theoretically calculated stopping power data for the Au ion in $(CH)_n$ and Au targets

Energy (MeV/u)	Target	S_{exp} (MeV/mg/cm^2)*	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*
75.00	$(CH)_n$	50.1	51.30(2)	43.59(− 13)	48.09(− 4)
100.00	$(CH)_n$	41.2	42.42(3)	34.88(− 15)	40.53(− 2)
120.00	$(CH)_n$	36.0	37.65(5)	30.19(− 16)	36.33(1)
150.00	$(CH)_n$	30.4	32.62(7)	25.25(− 17)	31.77(5)
75.00	Au	23.4	22.85(− 2)	21.29(− 9)	24.00(3)
100.00	Au	20.4	19.76(− 3)	17.55(− 14)	20.55(1)
120.00	Au	18.5	17.99(− 3)	15.45(− 16)	18.60(1)
150.00	Au	16.2	16.01(− 1)	13.17(− 19)	16.46(2)

*Heckman *et al.* (1987).

Table 8. Comparison between theoretical and experimental range data for the Au (900.0 MeV/u) ion in different targets

Ion	Target	R_{exp} (mm)*	Benton and Henke	Mukherjee and Nayak	Ziegler *et al.*
Au	CH_2	98 122	105 404(7)	220 227.7(124)	106 098(8)
Au	CH	73 752	78 332.7(6)	168 044(128)	78 597(7)
Au	C	42 920	44 612.2(4)	98 917.3(130)	44 586(4)
Au	Al	39 008	42 128.6(8)	83 222.2(113)	41 910(7)
Au	Cu	13 565	14 668.5(8)	27 824.75(105)	14 652(8)
Au	Sn	19 198	20 909.7(9)	38 835.53(102)	20 678(8)
Au	Au	8073	8849.85(10)	16 162(100)	8657(7)
Au	Pb	13 862	15 415.8(11)	28 113.9(103)	14 999(8)

*Waddington *et al.* (1986).

stopping power data up to 20%. Table 8 presents the range data for the Au ion having an energy of 900 MeV/u in different targets like CH_2, CH, C, Al, Cu, Sn, Au and Pb. Mukherjee and Nayak's formulation overestimates the experimental range data by more than 100% (Fig. 12). Benton and Henke and Ziegler *et al.*'s formulations predict the results in agreement to the experimental ones.

3. CONCLUSIONS

1. Ziegler *et al.* formulation is in best agreement with the experimental results within a percentage deviation of $\pm 5\%$ for all light ion–light target and light ion heavy target combinations. For heavy projectile and light target combinations this formulation strongly underestimates the stopping power data (overestimating the range data) in the limited range of energy of the projectile. At low (< 2.0 MeV/u) and high energies (> 50 MeV/u) of the projectile this formulation gives reasonable agreement with the experimental results for the heavy ion–light target.

2. Benton and Henke formulation predicts the theoretical results with a maximum deviation of 10% from the experimental ones for all combinations. After Ziegler *et al.* formulation, Benton and Henke formulation provides the stopping power and range data which are in best agreement with the experimental results.

3. Northcliffe and Schilling data tables do not show any particular trend for any of the ion–target combinations in the energy range under study.

4. Mukherjee and Nayak formulation totally fails to predict the results at the relativistic energy of the projectile irrespective of the ion–target combination. For the light ion–light target combination it underestimates the experimental results even up to 40% in the range of energy under study. This formulation only shows agreement with the experimental results at limited points in the case of the heavy ion–light target combination.

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