STOPPING POWER AND RANGE OF PROTONS OF VARIOUS ENERGIES IN DIFFERENT MATERIALS

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Abstract

An empirical formula based on Bohr’s classical approach has been obtained to predict the stopping power for proton with energies 1-12Mev/amu in elemental targets. The range formula is determined by directly integrating the stopping power formula of proton. These relations are also used to find the stopping power for compound targets by using the Bragg’s additivity rule.

The results are compared with experimental data and tabulated values of Bichsel and Sternheimer, and discussed at various energies of proton.

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0.1 Introduction

The knowledge of the features of the transmission and absorption of low, intermediate and high energy proton in elemental materials is of great importance for the experimental methods in nuclear and atomic physics. It is also useful in understanding the various interactions of these particles with matter.

The knowledge of the ranges of this particle in matter has useful applications for the study of biological effects, radiation damage dosoge-rates and energy dissipation at various depths of an absorber. It has also useful applications in the design of detection systems, radiation technology, semi-conductor detectors, shielding and choosing the proper thickness of the target.

Many experimental as well as the theoretical studies have been made with the object of establishing standard range-energy relations. The subject has been reviewed over the years by several authors such as Bohr, Bethe and Askin, Bichsel, sternheimer ,etc. Most of the experimental data has been compiled by whaling and Bichsel [1] in the form of table. There have been several discussions and compilations on the energy loss and range of heavy charged particles. Most of the work either depends on the use of fairly complicated semi-empirical formulas derived from the Bethe-Bloch expression of stopping power or on entirely empirical formulas extracted from the experimental information.

Easy empirical formulas are very helpful in the study of energy straggling, target foil thickness estimation and in particle identification studies. The important aspect of such problem is to know the energy loss incurred by the charged particle during the course of their passage in the absorber.

Chapter 1

INTERACTION OF PROTON WITH MATTER

1.1 Nature of interaction

Heavy charged particles such as proton, interact with matter primarily through coulomb forces between their positive charge, and negative charge of the orbital electrons with in the absorber atoms. Interaction of the particle with nuclei (as in Rutherford scattering) [2] is also possible. The collision with electron and with nuclear have different consequences.

The light electron can take up large amount of energy from the incident particle with out causing significant deflections of the heavy particle. Whereas the massive nuclei absorbs very little energy but because of their greater charge cause scattering of the incident particle.

The deflection of the particle from its incident direction results from essentially elastic collisions with the atomic nuclei. The scattering is confined to rather small angles so that a heavy particle keeps more or less straight line path while losing energy until it nears the end of its range

1.2 Energy loss mechanism

When a proton enters to a medium it immediately interacts simultaneously with many electrons. In any one encounter the electron feels an impulse from the attractive coulomb forces as the particle passes its vicinity. This impulse may be sufficient either to raise the electron to a higher level shell with in the absorber atom (excitation) or to remove completely the electron from the atom (ionsiation). The energy that is transferred to the electron must come at the expense of the charged particle, and its velocity is therefore, decreased as a result of inelastic collision.

The maximum energy that can be transferred from a charged particle of mass m with kinetic energy E to an electron of mass m_e in a single collision is $\frac{4Em_e}{m}$. Because, this is a small fraction of the total energy, the primarily particle must lose its energy in many such interactions during its passage through matter. At any given time the particle is interacting with many electrons, so the net effect is to decrease its velocity continuously until the particle is stopped.

1.3 Energy loss characteristics

1.3.1 The Bragg curve

A plot of the specific energy loss along the track of a heavy charged particle such as that shown in figure 1.1 is known as Bragg curve. The general appearance of the heavy particle Bragg curve can be explained from principles developed in chapter 2. The increase in ionization near the end of the path occurs because the ionization loss is inversely related to the square of the particle speed. Thus ionization density rises as the particle slows, of course, the ionization must drop to zero when the energy of the incident particles has been dissipated and near the end of the track, the charge is reduced through electron pickup and the curve falls off.

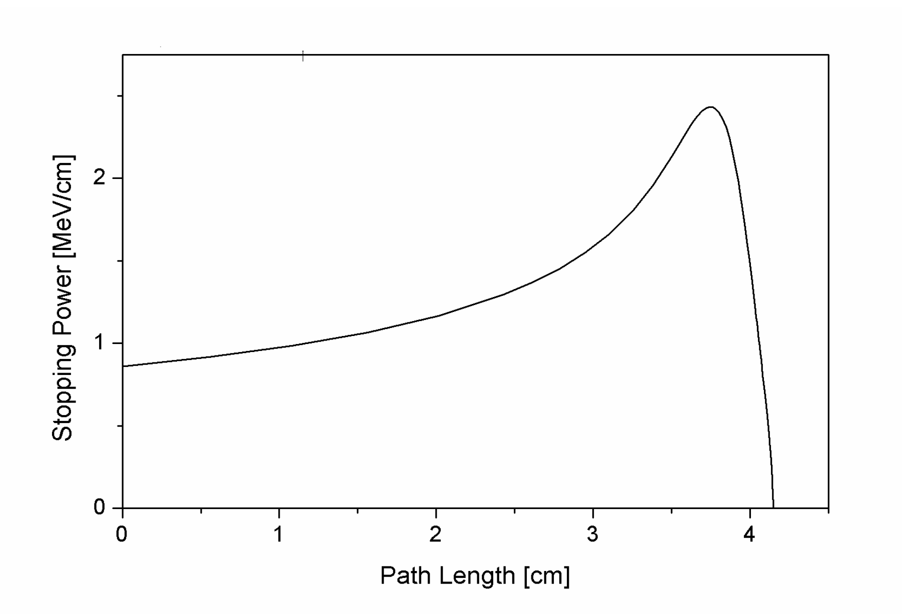

Fig 1.1 A diagram showing ionization loss versus distance from the sources for a beam of heavy charged particles in air at STP [3]

Chapter 2

STOPPING POWER

2.1 Stopping power Definition

In passing through matter, fast charged particles ionize the atom or molecule which they encounter. Thus, the fast particles gradually lose energy in many small steps. By stopping power we mean the average energy loss of the particle per unit path length designated by $\frac{-dE}{dx}$ and measured, for example in $\frac{Mev}{cm}$.

The stopping power depends on the type and energy of the particle and on the properties of the material it passes. Since the production of an ion pair (usually a positive ion and a negative ion (electron) requires a fixed amount of energy, the density of ionization along the path is proportional to the stopping power of the material. Stopping power refers to the property of the material while energy loss per unit path length describes what happens to the particle. But numerical values and units are identical for both quantities.

2.2 Calculations of stopping power

2.2.1 Niels Bohr formula

In 1913, Niels Bohr derived an explicit formula for the stopping power of heavy charged particles. Bohr calculated the energy loss of a heavy charged particle in a collision with an electron then averaged over all possible distances and energies. The nonrelativistic formula that Bohr obtained gave the correct physical features of stopping power. Bohr derived the formula based on the following assumptions:

•The particle move rapidly compared with the electron.

•For maximum energy transfer the collision is head on.

•The energy transferred is large compared with the binding energy of the electron.

•The electron is considered to be free and at rest and the collision is elastic.

The Bohr formula for heavier particle is given by:

$$-\frac{dE}{dX} = \frac{4\pi n z^2 k_0^2 e^4}{mv^2} \ln\left(\frac{2mv^2}{I}\right) \tag{2.1}$$

n= number of electrons per unit volume in the stopping material.

m= electron rest mass.

v=velocity of the particle.

Z=charge of the particle.

e= electron charge

$k_o = \frac{1}{4\pi\epsilon_o}$

I=mean excitation energy of the medium and is normally treated as an experimentally determined parameter for each element.

2.2.2 The Bethe- Bloch formula

Using relativistic quantum mechanics Bethe derived the following expression for the stopping power of a heavy charged particle.

$$-\frac{dE}{dx} = \frac{4\pi n z^2 k_o^2 e^4}{mv^2}\left[\ln\frac{2mv^2}{I} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right] \tag{2.2}$$

2.3 Dependence of stopping power on particle Energy

2.3.1 Stopping power at low Energies

The Bethe-Bloch formula is not valid at low proton energy because in this region the charged particle captures and loses electrons as it moves, thus reducing its net charge and stopping power. More over the term $\ln\frac{2mv^2}{I}$ eventually becomes negative giving a negative value for the stopping power.Electron capture becomes important when the speed v of the proton is comparable to or less than the speed that an electron needs in order to orbit the nucleus. If the proton loses its energy by picking up electrons in its passage through matter, the coulomb interaction and the rate of energy loss will diminish.

For low energies, where the velocity of the proton is less than the velocity of the atomic electron (Tp<25kev) Fermi and Teller [4] have obtained the following expression for the energy loss.

$$-\frac{dE}{dx} = \frac{4R_y mv}{3\pi\hbar}\ln\left(\frac{\hbar v_m}{e^2}\right) \tag{2.3}$$

Where Ry is the Rydberg unit,v is the velocity of proton and v_m is the maximum velocity of the electrons of the substance. Equation 2.3 shows that the energy loss increases with increasing velocity of proton. fig.2.1 [5]

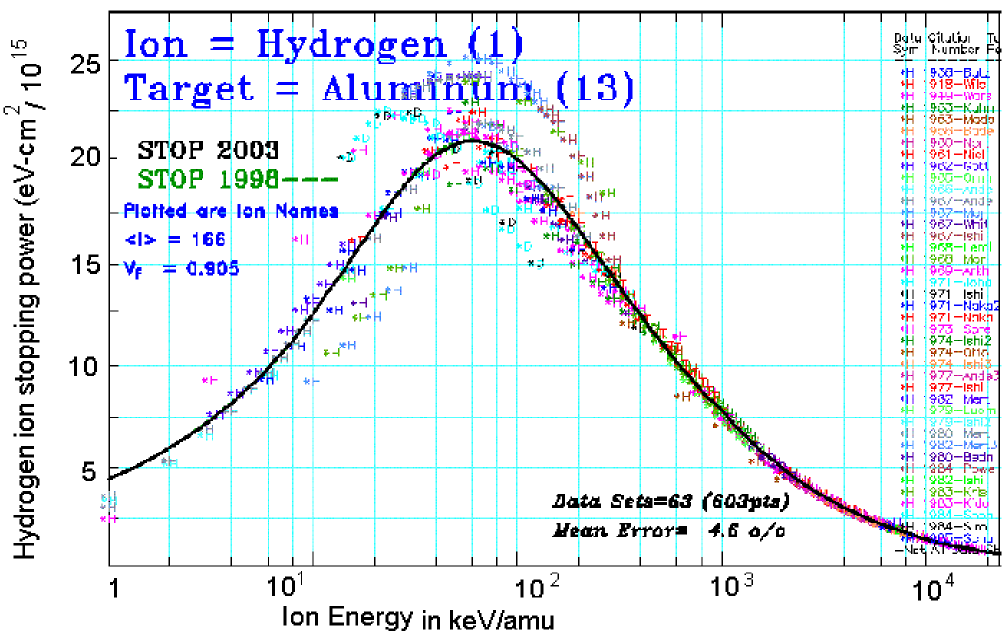

Fig.2.1 Stopping power versus energy of hydrogen ion (protons) in aluminium target.

Experimentally good evidence has been obtained for the increase of the stopping power with increasing velocity at low energies. Warshaw [4] has made careful measurements of $\frac{dE}{dx}$for proton in Be, Al, Cu, Ag and Au in the energy range from 50 to 400kev. For all cases, he obtained a maximum of $\frac{dE}{dx}$ in the neighborhood of Tp= 100kev.

For higher energies above 100kev Bohr has given an approximate theory based on the Thomas Fermi model of the atom, and has obtained the following expression for the energy loss [4].

$$\frac{-dE}{dx} = \frac{16\pi n Z^{\frac{1}{3}}\hbar e^2}{mv} \tag{2.4}$$

Where Z is atomic number of the medium.

In this region the stopping power decrease as$\frac{1}{v}$ warshaw has also obtained reasonable agreement of equation 2.4 with stopping power data for cu, Ag and Au in the range from Tp=350 to 550kev.

2.3.2 Intermediate Energies Stopping Power

In this energy region the rate of energy loss decreases inversely with the square of the velocity of proton. This is a consequence of the diminished time of interaction between the charged particle and the atomic electrons. If the velocity of particle is v the time that the particle spends with in a given distance from the atom is proportional to 1/v, hence the impulse on the electrons in the atom, or the momentum transfer, is also proportional to 1/v, since the energy transfer to the electron in the atom is equal to the energy loss by the particle and is proportional to the square of the momentum transfer, it is evident that the rate of energy loss must have a term inversely proportional to v 2 or inversely proportional to E,the energy of the particle. This is a cause of the rapid decrease in stopping power seen at relatively low energy fig.2.1.

From equation 2.1, the velocity in the logarithm term has very small effect on dE/dx . The stopping power is dependent on $1/v^2$ outside the logarithm term. For a given ion:

$$\frac{dE}{dx} \alpha \frac{1}{v^2}$$

2.3.3 Stopping Power Theory at High Energies

For either Bohr's or Bethe formula, with increasing particle energy, the stopping power first decreases very rapidly (in inverse proportion to the energy), but the decrease becomes slower as the particle velocity approaches the velocity of light. At a certain values of energy, stopping power attains its lowest value. This means that the denominator in equation 2.2 contains a nearly constant quantity ($V^2 \,\tilde{}\, C^2$). However,an examination of the term in the bracket shows that starting from a certain energy the magnitude of $\frac{dE}{dx}$ again starts increasing slowly (logarithmically) and reaches a certain plateau (Fig 2.2). The data of figure 2.2 is taken from Sternheimer[4].

When the velocity of the particle is comparable with speed of light, the normal spherical field becomes distorted. In the direction of motion of the particle expanding laterally and in the perpendicular direction shrinking. This leads to higher energy loss at higher energies.

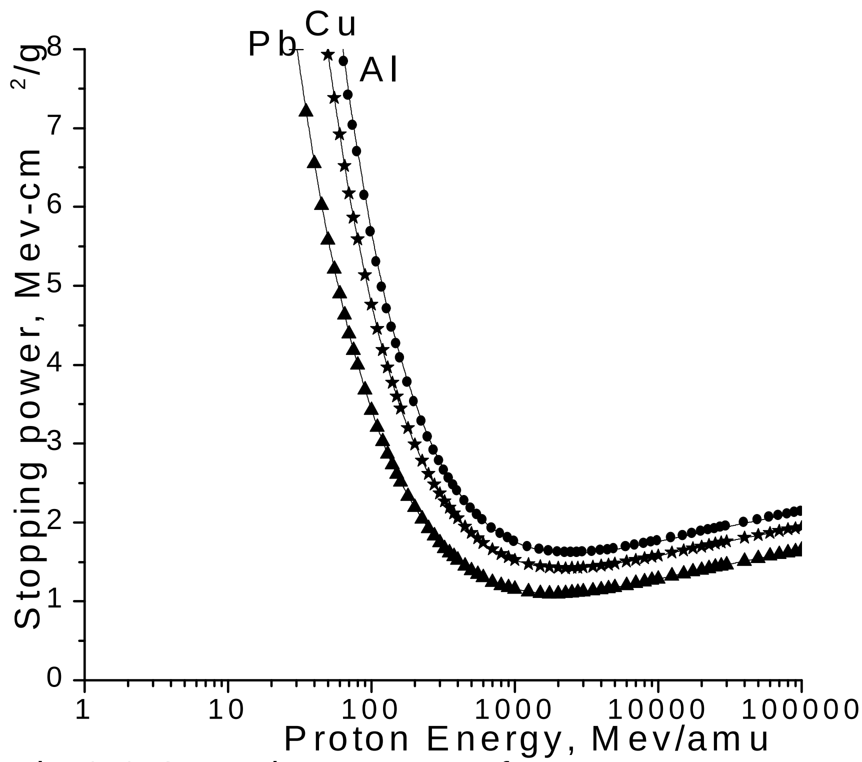

Fig.2.2 Stopping power of proton versus energy for Al,Cu,and Pb

2.4 Mass Stopping Power

The mass stopping power of a material is obtained by dividing the stopping power by the density of the material. Common units for mass stopping power, is $\frac{Mev-cm^2}{g}$.

The mass stopping power is a useful quantity because it express the rate of energy loss of the charged particle per $\frac{g}{cm^2}$ of the medium traversed. In a gas, for example, $\frac{-dE}{dx}$ depends on pressure, but $\frac{-dE}{\rho dx}$ does not, because dividing by density exactly compensates for the pressure.

Chapter 3

RANGE- ENERGY RELATIONS

3.1 Definition of Range

The range R(T_o) of a proton of initial kinetic energy T_o, mass m, is mean distance it travels before it stop The range depends upon the type of the particle,its initial energy and the material it traverses. A theoretical approach to the determination of charged particle range utilizes stopping power expression. The value found is often called the CSDA range (continuous slowing Down Approximation). Since range is an average value, fluctuations can be ignored and losses are assumed to be continuous. The CSDA range is calculated by integrating the reciprocal of the total stopping power.

$$R = \int_0^R dx = \int_{T_o}^0 \frac{-dE}{\frac{-dE}{dx}} = \int_0^T \frac{dE}{S} = \int_{T_1}^{T_o} \frac{dE}{S} + R_1(T_1) \tag{3.1}$$

Where dx is the path length variable of integration, S is the stopping power, and T_o is the initial kinetic energy of the charged particles, T_1 is Some lower limit of energy below which the calculations can not be performed because of the poor knowledge of the stopping power. The last part of the path length is usually not accurately calculated when an analytical expression is used for the stopping power. Most such expressions are inaccurate at low energies. Because of this, a finite lower limit can be utilized, and R_1 (E_1) can be estimated from experimental results. The range is expressed in $\frac{g}{cm^2}$; that is the range in cm multiplied by the density of the substance.

3.2 Range of proton

Range- energy relations for protons have been obtained by several authers, such as Livingston and Bethe, Sternheiner, Bichsel, etc. Sternheimer has carried out calculations [7] to determine range energy relations for some of the commonly used materials Aluminum, copper, Carbon, Beryllium and lead for proton energy from 2 Mev to 100Gev. Bichsel has also obtained range energy relation for the same substances from 1Mev to 100Mev [1].

3.3 Range straggling

When protons and similar heavy particles lose energy by ionization, all of the particles do not come to the end of their range and stop after traversing the same thickness of material. Instead there is a distribution of the ionization loss process. This variation is known as straggling. The number of particles, which survive as a function of the thickness traversed is shown in figure 3.1.

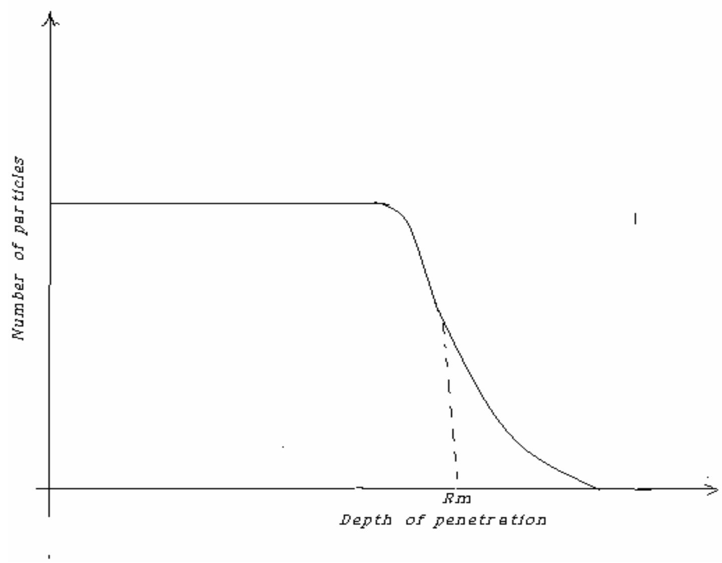

Fig. (3.1) A diagram showing number of particles left versus depth in to an absorber.

The energy losses that bring the particle to rest consists of large number of individual energy transfer events of varying magnitudes, most of them relatively small. Thus there are variations in both the number of events occurring per unit path length and the energy transfer per event with a few events involving large amounts of energy transfer.

The range of the particle in the absorber material can be determined from this curve in several ways. The mean range (R_m) is defined as the absorber thickness that reduces the particle count to exactly one- half of its initial value (value in the absence of the absorber). This definition is most commonly used in tables of numerical range values.

Chapter 4

EMPIRICAL RELATION FOR STOPPING POWER AND RANGE OF PROTON

4.1 Empirical relation for Mass stopping power

In the medium energy region the stopping power is inversely proportional to the square of the velocity of the particle. From expression 2.2 ,Bethe formula ,the logarithm is a slowly varying function, the energy loss is due to $\frac{1}{v^2}$.

In the energy region 1Mev/amu to 12Mev/amu an empirical relation of the following form is obtained.

$$\frac{-dE}{\rho dx} = \frac{a}{A} E^{-b} Z^{c \log E + d} \tag{4.1}$$

The appropriate values of the constants a,b,c, and d are a= 915.0, b=0.85, C= 0.145 and d=0.635 . Here ρ, A and Z denote the density ,atomic weight and atomic number of the stopping material while E is the kinetic energy of the proton in Mev/amu, the stopping power is in Mev-cm^2/g.The constants c and d are obtained by fitting Bichsel [1] stopping power values by the least squares method while constants a and b are extracted using the experimental data of Srim and Bichsel data towards lower energies.

4.2 Range

The range of a proton is computed by numerical integration of the stopping power. The range R in the continuous slowing down approximation (CSDA) is given as

$$R = \int_{E_{\min}}^{E_{\max}} \left(\frac{-dE}{\rho dx} \right)^{-1} dE + R\left(E_{\min}\right) \tag{4.2}$$

Where R $(E_{\min})$ is the measured range at energy E_{min} which is added to the integral equation and treated as a constant for a particle and material. For the calculations of ranges for proton E_{min} is taken to be as 1Mev as much data is available at 1Mev. Substituting equation 4.1. into equation 4.2 and converting energy units from Mev to $\frac{Mev}{amu}$ we get

$$R_p = \int_{E_1}^{E} m_p \left(\frac{a}{A} E^{-b} Z^{c \log E + d} \right)^{-1} dE + R_1(E_1) \tag{4.3}$$

Here m_p is the mass of the proton.

After integration and putting the values of the constants we get:

$$R_p = m_p \left(\frac{A}{915 \times 1.85 Z^{0.635} \left(1 - \frac{0.145 \log Z}{1.85}\right)} \right) \times \left(E^{1.85} Z^{-0.145 \log E} - E_1^{1.85} Z^{-0.145 \log E_1} \right) + R_1\left(E_1\right) \tag{4.4}$$

Let

$$G_p = \left(\frac{A}{915 \times 1.85 Z^{0.635} \left(1 - \frac{0.145 \log Z}{1.8} \right)} \right) \tag{4.5}$$

$$R_p = m_p G_p E^{1.85} Z^{-0.145 \log E} - m_p G_p E_1^{1.85} Z^{-0.145 \log E_1} + R_1 (E_1) \tag{4.6}$$

$R_1 (E_1)$ is the experimental range of the proton at energy E_1.The second term of equation 4.6 can be combined with R_1 (E_1) and we may define a correction term Fp to the range in a Specific medium as:

$$F_p = R_1 (E_1) - m_p G_p E_1^{1.85} Z^{-0.145 \log E_1} \tag{4.7}$$

Therefore equation 4.6 is reduced to

$$R_p = m_p G_p E^{1.85} Z^{-0.145 \log E} + F_p \tag{4.8}$$

This equation gives the range of proton in $\frac{g}{cm^2}$ in solid medium in the energy region 1Mev/amu to 12Mev/amu.

4.3 Stopping power for compound Targets

For compounds Bragg's additivity [8] rule is found to hold quite well. The rule says the mass stopping power for the substance containing several elements is taken to be equal to the weighted sum of the mass stopping power of the constituent atoms.Thus

$$\left(\frac{-dE}{\rho dx} \right)_{compound} = \frac{1}{M} \sum N_i A_i \left(\frac{-dE}{\rho dx} \right)_i \tag{4.9}$$

Where M is the molecular weight of the compound medium containing Ni atoms of atomic weight Ai .For example for the compound CdTe the stopping power can be given as

$$\frac{-dE}{\rho dx} = \frac{1}{M}\left(N_{cd}A_{cd}\left(\frac{-dE}{\rho dx}\right)_{cd} + N_{Te}A_{Te}\left(\frac{-dE}{\rho dx}\right)_{Te}\right)$$

$$\frac{-dE}{\rho dx} = \frac{1}{240}\left(112.4\left(\frac{-dE}{\rho dx}\right)_{cd} + 127.6\left(\frac{-dE}{\rho dx}\right)_{Te}\right)$$

4.4 Range for compound Targets

The range of a charged particle in a compound material can be calculated provided its range is known in all the constituent element using the following formula [8].

$$Rc = \frac{Mc}{\sum n_i\left(\frac{A_i}{R_i}\right)} \tag{4.10}$$

Where $R_i$is the range in i element, n_i is the number of atoms of element i, in the molecule , A_i is the atomic weight of the element i and Mc is the molecular weight of the compound .This formula has also been used by different authors while presenting the table for range of proton in several compound materials.

Example: Equation 4.10 can be written for the compound CdTe as:

$$Rc = \frac{240.02}{\frac{112.41}{R(cd)} + \frac{127.61}{R(Te)}}$$

$$Rc = \frac{R\left(cd\right)R\left(Te\right)}{0.4684R\left(Te\right) + 0.5316R\left(cd\right)}$$

Chapter 5

RESULTS AND DISCUSSION

5.1 Stopping power calculation

Using the empirical relation given in equation 4.1 stopping powers are calculated from 1Mev to 12Mev proton energy for Al, Cu, Pb, C, Be,Cd,Te and for a compound CdTe. The results of stopping power calculated by the empirical formula are tabulated in table 5.1 and 5.2, and plotted in fig. 5.1 to 5.8 along with available theoretical values,Bichsel and Sternheimer tabulated values(here after referrd to as BS).

Table 5.1 Mass Stopping power in Mev-cm^2/g for Al ,Cu and Pb for proton energy 1Mev to 12MeV.

Energy in MeV	Aluminium			Copper			Lead		
	Empi	Bich	Ster	Emp	Bich	Ster	Emp	Bich	Ster
1	127.74	174.0		122.25	121.0		72.56	62.9	
2	107.19	110.0	110.0	78.56	80.5	78.93	48.79	44.8	41.14
3	81.08	83.1	83.6	60.65	62.2	61.83	38.68	35.9	34.62
4	66.51	67.5	67.44	50.48	51.5	51.27	32.81	30.6	29.85
5	57.04	57.2	57.19	43.78	44.3	44.08	28.87	26.9	26.36
6	50.31	50.0	49.84	38.98	39.0	38.73	26.01	24.1	23.65
7	45.24	44.5	44.38	35.32	35.0	34.71	23.81	22.0	21.54
8	41.27	40.2	40.09	32.44	31.9	31.50	22.06	20.2	19.81
9	38.05	36.7	36.67	30.09	29.3	28.94	20.62	18.8	18.4
10	35.39	33.9	33.80	28.13	27.1	26.77	19.41	17.5	17.18
11	33.14	31.7		26.47	25.3		18.38	16.5	
12	31.21	29.4	29.35	25.04	23.8	23.38	17.49	15.3	15.23

Table 5.2Mass Stopping power in Mev-cm^2/g for C,Be,Cd ,Te and CdTe for proton energy 1Mev to 12MeV.

Energy in MeV	Carbon			Beryllium			Cadmium	Tellurium	CdTe
	Emp	Bich	Ster	Emp	Bich	Ster	Emp	Emp	Emp
1	237.88	232.6		245.18	223.0		95.1	83.78	89.08
2	142.71	141.0	140.6	144.5	134.0	131.9	62.48	58.1	60.15
3	105.82	105.0	104.4	106.06	98.5	97.45	48.86	45.54	47.09
4	85.61	84.0	83.97	85.17	78.7	78.06	41.04	38.3	39.58
5	72.62	70.7	70.74	71.84	66.0	65.59	35.85	33.49	34.59
6	63.49	61.3	61.29	62.51	57.0	56.69	32.1	30.02	30.99
7	56.67	54.3	54.28	55.58	50.4	50.15	29.23	27.36	28.23
8	51.36	48.3	48.81	50.19	45.2	45.03	26.96	25.25	26.05
9	47.1	44.5	44.47	45.88	41.1	40.99	25.1	23.52	24.25
10	43.57	40.9	40.87	42.34	37.7	37.63	23.55	22.08	22.76
11	40.61	37.7		39.37	34.8		22.22	20.85	21.49
12	38.09	35.1	35.29	36.84	32.1	32.44	21.08	19.79	20.39

5.1.1 Stopping power-Energy plots

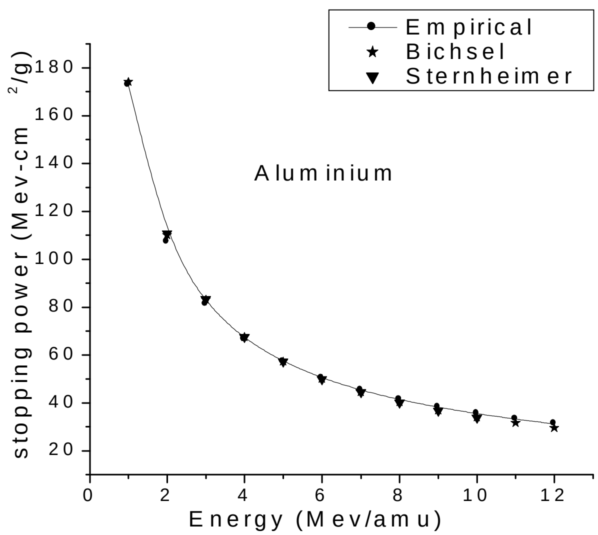

Fig.5.1 Stopping power of proton versus energy in Aluminium with other workers value

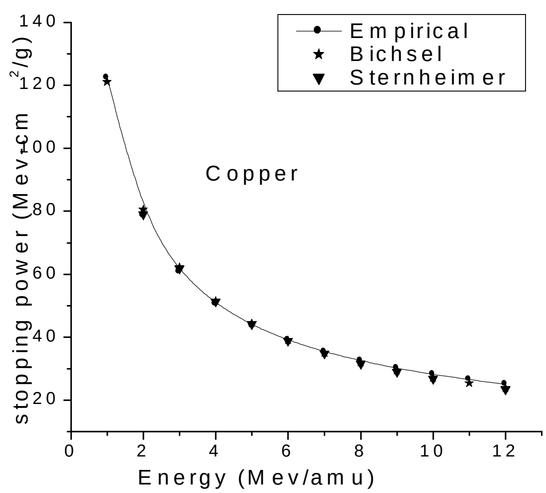

Fig.5.2 Stopping power of proton versus energy in Copper with other workers value

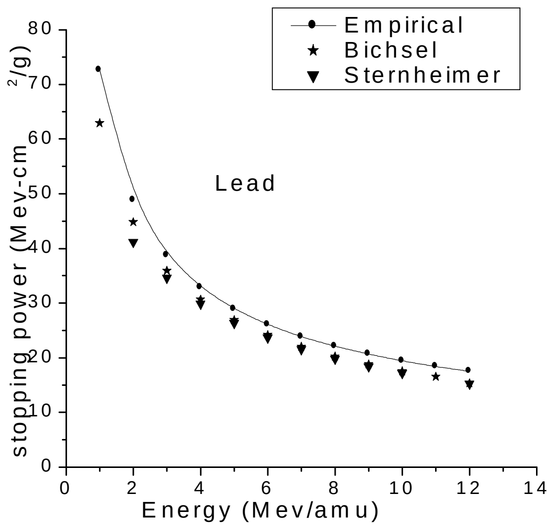

Fig.5.3 Stopping power of proton versus energy in Lead with others workers value

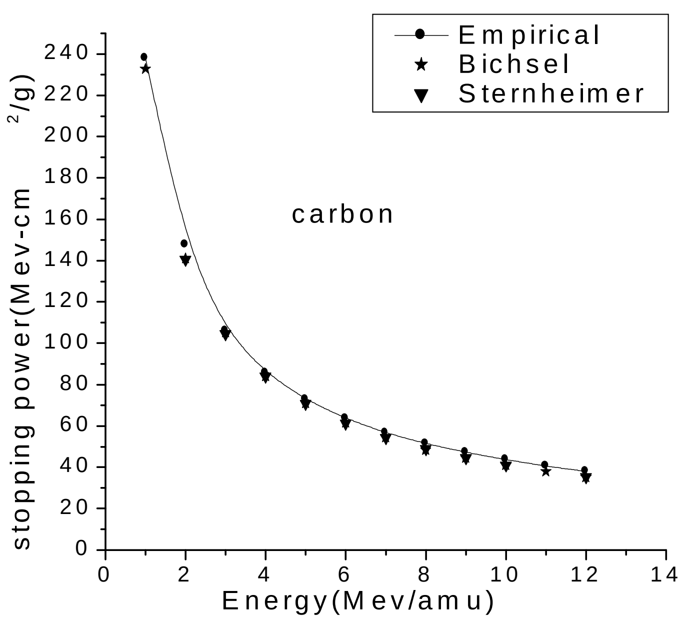

Fig.5.4 Stopping power of proton versus energy in carbon with others workers value

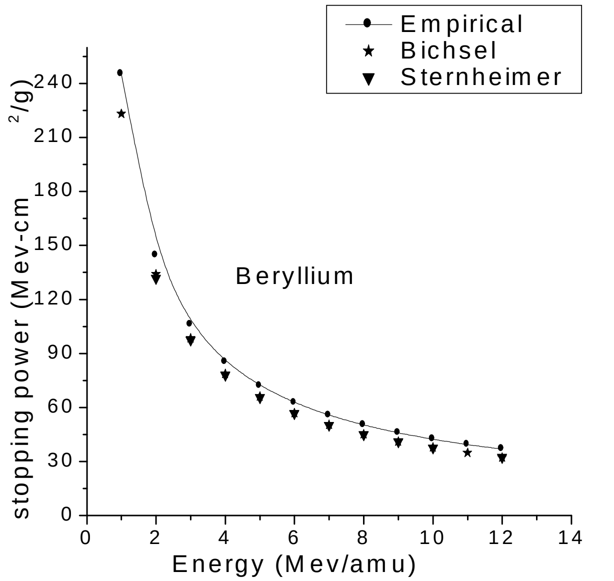

Fig.5.5 Stopping power of proton versus energy in Beryllium with others workers value

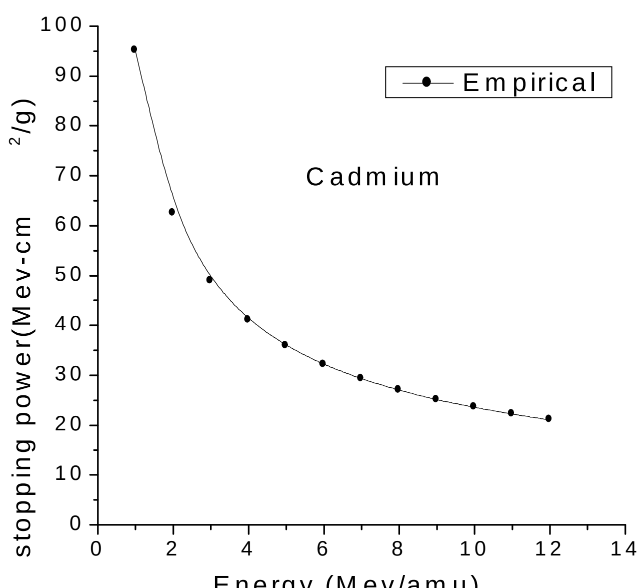

Fig.5.6 Stopping power of proton versus energy in Cadmium

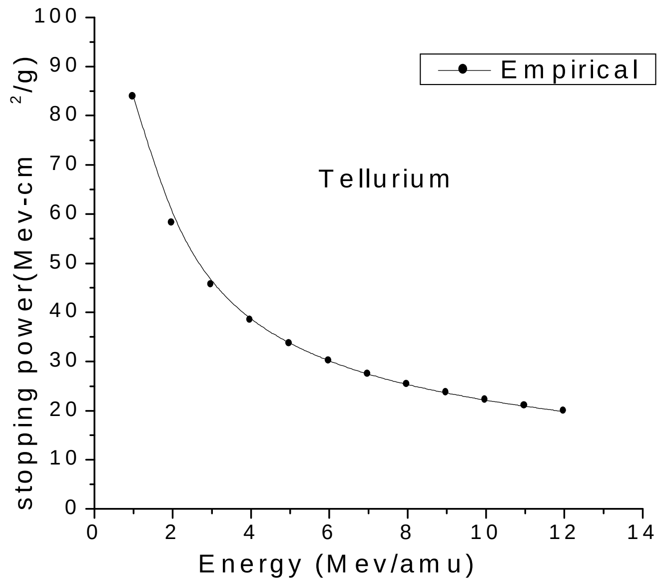

Fig.5.7 Stopping power of proton versus energy in Tellurium

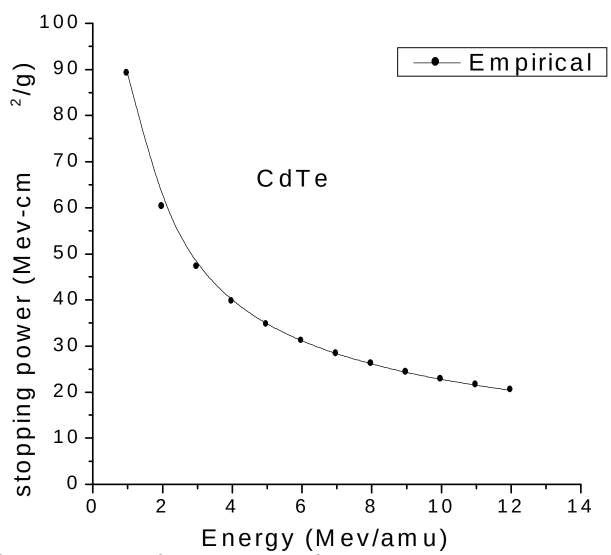

Fig.5.8 Stopping power of proton versus energy in CdTe

5.2 Range calculations

The ranges for Al, Cu, C, Pb and Be are calculated using the empirical relation 4.8 ,and for the coumpond CdTe equation 4.10 is used. In this calculations values of starting ranges are taken from the literature and these are tabulated in table 5.3 .

Table 5.3 Range of 1Mev proton in mg/cm^2

Element	Range
Al	3.96
Cu	6.12
C	3.85
Pb	11.0
Be	2.76
Cd	8.326
Te	9.103

The empirical results calculated by the range formula 4.8 are tabulated in table 5.5 and 5-6 and plotted in figure 5.9 to 5.16 along with BS values. The values of Gp and Fp for a given substance are given in table 5.4.

Table 5.4 Fp and Gp values

Element	F_p	G_p
Al	0.544	3.423
Cu	1.121	4.999
C	1.48	2.42
Pb	2.836	8.764
Be	0.59	2.31
Cd	1.78	6.546
Te	2.017	7.086

Table 5.5 Range in mg/cm^2 for Al, Cu, and Pb for proton energy 1-12MeV

Energy	Aluminium			Copper			Lead		
(MeV)	Emp	Bich	Ster	Emp	Bich	Ster	Emp	Bich	Ster
1	3.96	4.1		6.12	6.1		11.0	11.6	
2	11.57	11.6	11.5	16.67	16.5	19.0	28.9	30.8	41.0
3	22.42	22.2	22.1	31.34	30.8	33.5	52.15	56.0	67.6
4	36.1	35.6	35.5	49.54	48.6	51.3	80.36	86.3	98.8
5	52.37	51.8	51.7	70.90	69.6	72.4	112.94	121.0	134.5
6	71.06	70.5	70.4	95.19	93.7	96.7	149.5	161.0	174.6
7	92.02	91.8	91.7	122.21	121.0	124.0	189.74	204.0	219.0
8	115.16	116.0	115.5	151.81	151.0	154.2	233.41	252.0	267.4
9	140.38	142.0	141.6	183.88	183.0	187.4	280.32	303.0	319.8
10	167.6	170.0	170.0	218.3	295.1	223.4	330.3	358.0	376.1
11	196.77	198.3		255.0	256.6		383.27	411.3	
12	227.83	232.8	233.7	293.89	295.1	303.5	439.06	465.7	500.0

Table 5.6 Range in Beryllium,Carbon,Cd,Te and CdTe for proton energy 1-12MeV.

Energy	Beryllium			Carbon			Cd	Te	CdTe
(MeV)	Emp	Bich	Ster	Emp	Bich	Ster	Emp	Emp	Emp
1	2.76	2.9		3.85	3.9		8.326	9.103	8.71
2	8.43	8.9	9.1	9.55	9.7	8.4	21.71	23.51	22.63
3	16.6	17.7	18.0	17.79	18.0	16.8	40.0	43.16	41.62
4	27.18	29.1	29.6	28.37	28.7	27.5	62.45	63.71	63.11
5	40.0	43.1	43.6	41.1	41.8	40.6	88.61	95.25	92.02
6	54.94	59.4	60.1	55.88	57.0	55.8	118.18	126.85	122.62
7	71.91	78.1	78.9	72.58	74.4	73.2	150.84	161.8	156.47
8	90.8	99.1	99.9	91.14	93.8	92.6	186.51	199.9	193.3
9	11.67	122.0	123.2	111.5	115.0	114.1	224.98	240.97	233.2
10	137.34	148.0	148.7	133.6	139.0	137.6	266.14	284.88	275.78
11	158.8	184.6		157.4	164.7		309.87	331.51	321.0
12	185.04	205.4	206.1	182.84	193.2	190.4	356.08	380.77	368.79

5.2.1 Plots of range versus energy

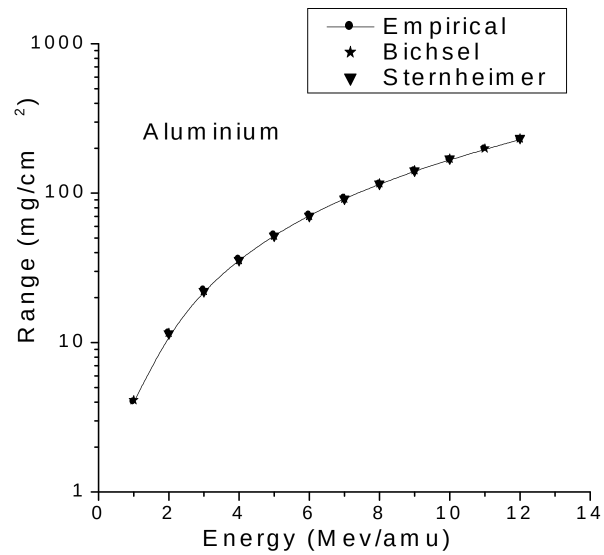

Fig.5.9 Empirical values for proton ranges versus energy in Aluminium with other workers value

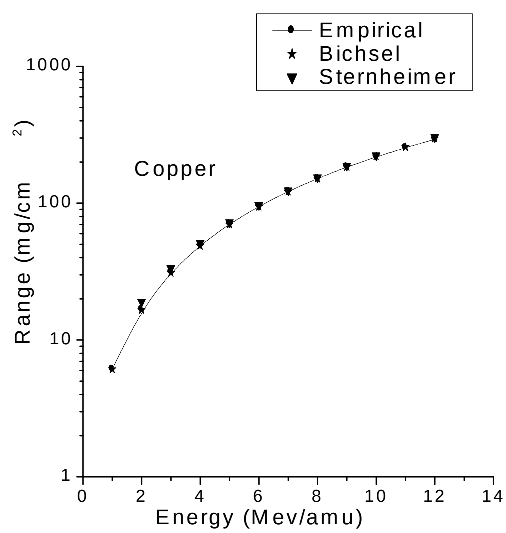

Fig.5.10 Empirical values for proton ranges versu energy in Copper with other workers value

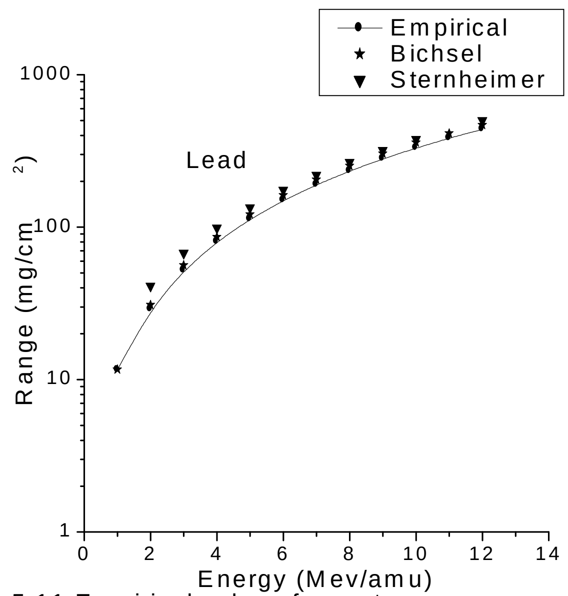

Fig.5.11 Empirical values for proton rangesversus energy in Lead with others workers value

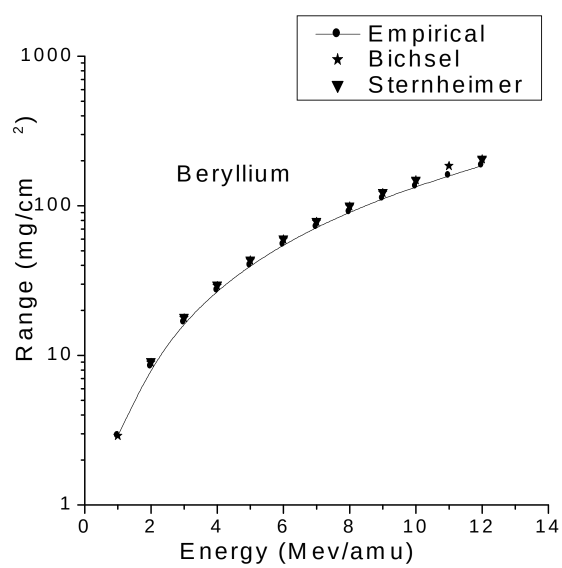

Fig.5.12 Empirical values for proton ranges versus energy in Beryllium with others workers value

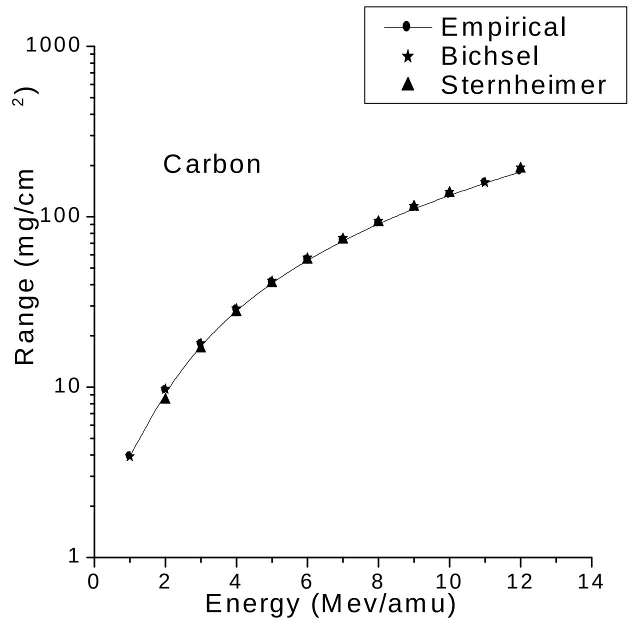

Fig.5.13 Empirical values for proton ranges versus energy in Carbon with others workers value

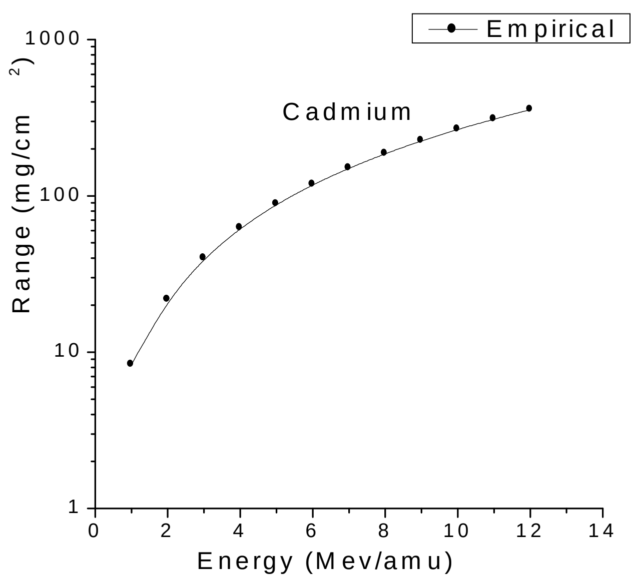

Fig.5.14 Empirical values for proton ranges versus energy in Cadmium

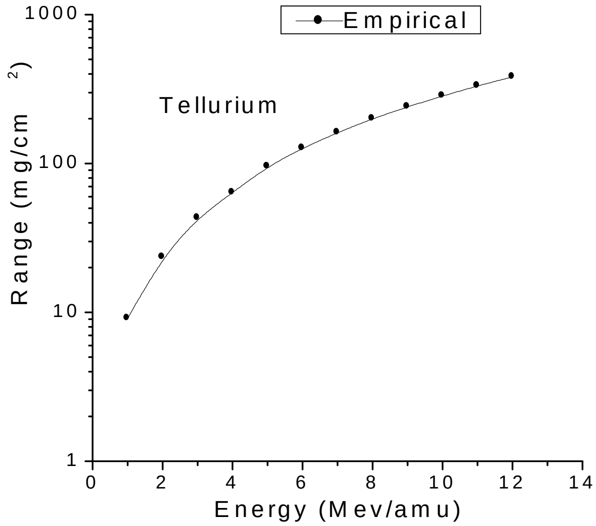

Fig.5.15 Empirical values for proton ranges versus energy in Tellurium

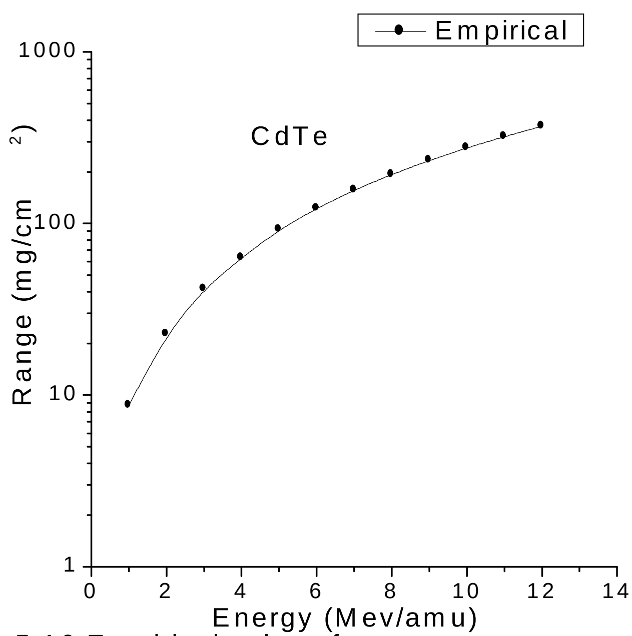

Fig.5.16 Empirical values for proton ranges versus energy in CdTe

5.3 Percentage difference of empirical stopping power values from BS values

The percentage difference between the stopping power calculated from equation 4.1 and the corresponding values obtained from Bichsel [1] and Sternheimer [4] tables are tabulated in table 5.7 and 5.8,and plotted in figure 5.17 and fig 5.18 for Al, Cu, C, Pb and Be.

Table 5.7 Percentage difference of empirical stopping power values from Bichsel values

Energy [MeV]	1	2	3	4	5	6	7	8	9	10	11	12
Al	0.72	2.55	2.42	1.46	0.28	-0.62	-1.66	-2.66	-3.67	-4.4	-5.2	-6.18
Cu	-1.03	2.41	2.49	1.98	1.17	0.05	-0.91	-1.69	-2.69	-3.8	-4.6	-5.2
Pb	-15.3	-8.9	-7.74	-7.2	-7.3	-7.9	-8.22	-9.2	-9.68	-10.9	-11.4	-14.3
C	-2.26	-1.21	-0.78	-1.9	-2.7	-3.57	-4.36	-6.33	-5.84	-6.5	-7.7	-8.5
Be	-9.9	-7.8	-7.67	-8.2	-8.8	-9.6	-10.2	-11	-11.6	-12.3	-13.1	-14.7

Table 5.8 Percentage difference of empirical stopping power values from sternheimer value

Energy (Mev)	1	2	3	4	5	6	7	8	9	10	11	12
Al		3.24	2.5	1.37	0.26	-0.94	-1.93	-2.94	-3.76	-4.7		-6.37
Cu		0.46	1.9	1.54	0.68	-0.64	-1.75	-2.98	-3.97	-5.1		-7.1
Pb		-18.6	-11.7	-9.9	-9.5	-9.97	-10.5	-11.35	-12	-12.9		-14.8
C		-1.49	-1.34	-1.94	-2.65	-0.35	-4.4	-5.22	-5.89	-6.6		-7.9
Be		-9.5	-8.8	-9.1	-9.5	-10.2	-10.8	-11.45	-11.9	-12.5		-13.56

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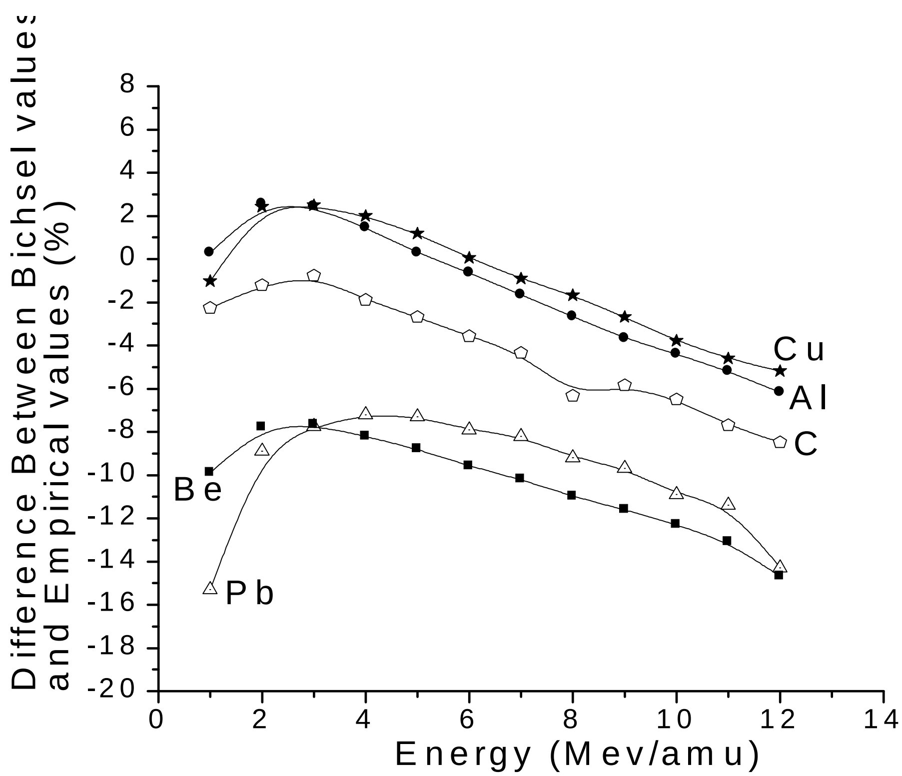

Fig 5.17 Percentage difference between Bichser and empirical values of stopping power versus energy of protons

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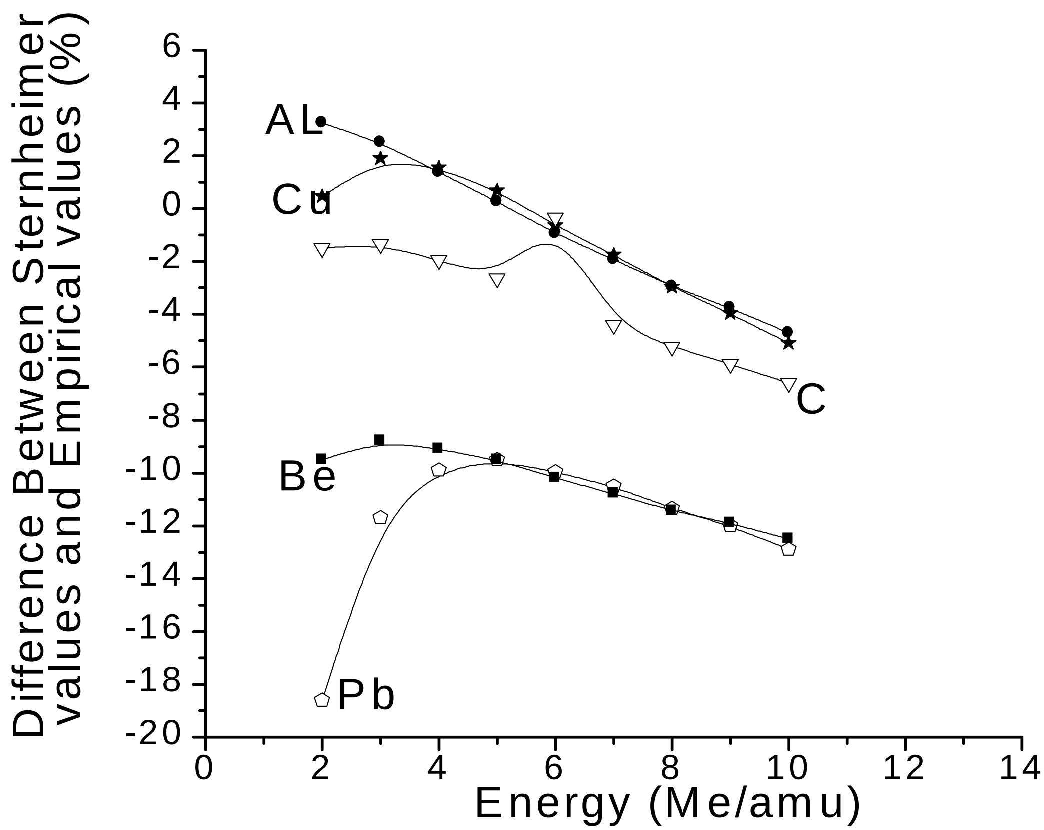

Fig 5.18 Percentage difference between Sternheimer and empirical values of stopping power versus energy of protons.

5.4 Percentage difference of empirical Range values from BS values

The percentage difference between the range calculated from equation 4.8 and the corresponding values obtained from BS tables are plotted in figure 5.19 and 5.20 for Al,Cu,C,Pb and Be.

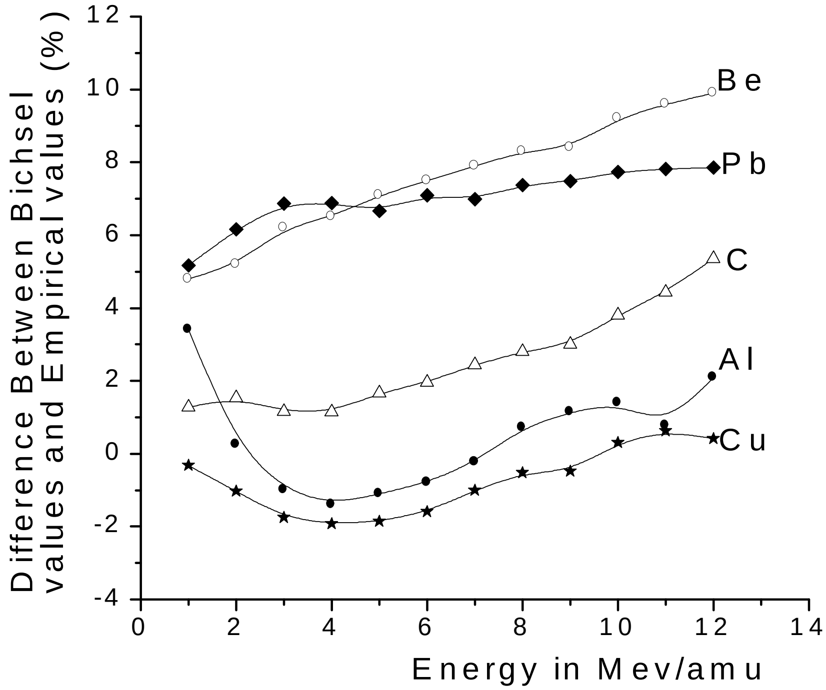

Fig.5.19 Percentage difference between Bichsel and empirical values of Range versus energy of proton.

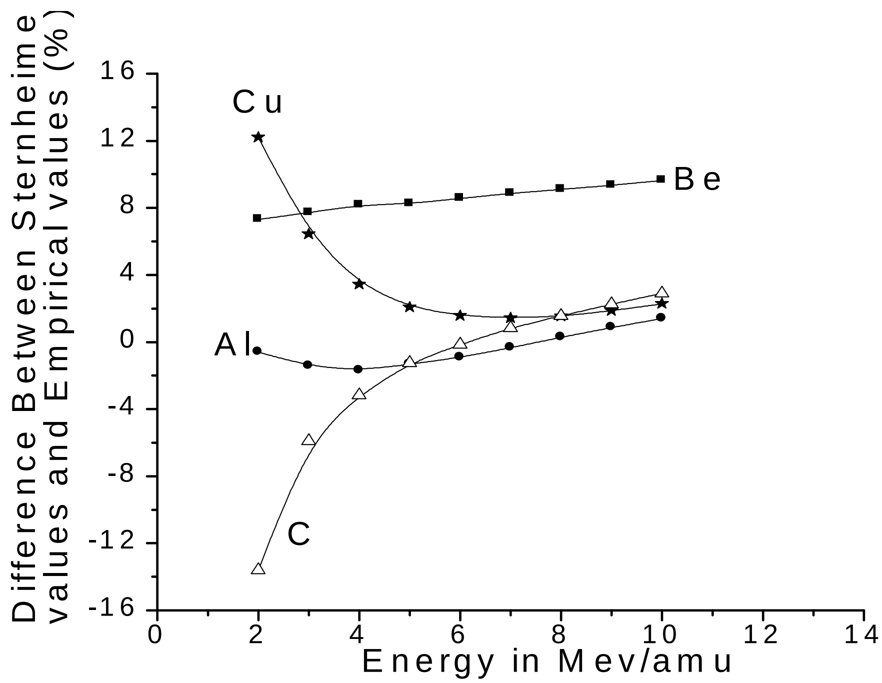

Fig.5.20 percentage difference between Sternheimer and empirical values of Range versus energy of proton

5.5 Comparison with BS results

5.5.1 Proton Stopping Power

The percentage difference between the stopping power calculated from equation 4.1 and the corresponding values obtained from BS are shown in figure 5.17 and 5.18 for Al, Cu, Pb, C and Be.It is evident from the figure that the empirical values for Al, Cu and C are in good agreement with BS values. Aluminum has a maximum difference of

6.2% with Bichsel values and 6.4% difference with Sternheimer values from 1Mev to 12Mev. Copper has 5.2% difference with Bichsel values and 7.1% difference with Sternheimer values. It can be noticed from figure 5.17 that the empirical results of stopping power for Al and Cu for proton energy 1Mev to 8Mev is in excellent agreement with Bichsel results with a maximum deviation of 3%. In this energy interval copper has a maximum deviation of 3% with Sternheimer results. From 1Mev to 9Mev proton energy Aluminum has 4% maximum difference from Sternheimer values.

The comparison between empirical results and results of Bichser for carbon is with in an accuracy of 3% from 1Mev to 5Mev proton energy. From 1Mev to 6Mev the deviation is 3% with Sternheimer values. Carbon has a maximum difference of 8.6% with BS values from 1Mev to 12Mev.The empirical results of stopping power for lead and Beryllium are poor compared to BS results. The deviation goes up to 14.7% for Beryllium and 15.3% for lead.

From the curves shown in figure 5.17 and 5.18, one can infer that the percentage difference shows a systematic behavior with energy as well as with atomic number. For both elements under consideration the percentage deviation from BS values increases with energy of proton.More over, for high atomic numbers like lead and small atomic numbers like Beryllium, the empirical formula gives a poor result

I also tried to compare the empirical results with Srim [5] stopping power values that is plotted for different elements. But it is difficult to read the stopping power values for the corresponding proton energy from the plot because the proton energy is indicated in logarithm scale. I could not get Srim tabulated data's. However I tried to read few values from the plot and compared with my empirical values. The percentage difference of the empirical values from Srim values is less than 8% for Aluminum and Copper. For carbon it goes up to 10%. For Pb and Be the deviation is between 7% to 18%.

For the compound CdTe I could not get data's for comparison

5.5.2 Proton Range

The proton ranges calculated from equation 4.8 are plotted against energy in figures 5.9 to 5.16. The percentage difference from BS results is plotted in figures 5.19 and 5.20 for Al,Cu,C,pb and Beryllium. For Al and Cu the ranges calculated by the empirical formula are very close to the range given by Bichsel. Al and Cu have a maximum difference of 2.11% from Bichsel results in the interval 2 to 12Mev/amu. Carbon has less than 2% deviation from Bichsel values in the energy range 1-6Mev/amu.Higher than this value the difference is from 2% to 5%.

The empirical values of Pb and Be have poor agreement with BS values. Specially ,Pb has a poor agreement with Sternheimer values. Al is in good agreement with Sternheimer results, the maximum disagreement is 2.52%. For Cu and C, 5-11Mev/amu energy region the maximum deviation is 3%.

5.6 Conclusion

By using the empirical formula 4.1 and 4.8,the stopping power of various elements and the corresponding range for proton energy 1Mev to 12Mev is calculated and compared with available tabulated data obtained from literature. From the result one can notice that the error increases with increasing of proton energy and atomic mass of the stopping element. For lower atomic masses also such as Be the error is large.

Equation 4.1 and 4.8 give good results for Al,Cu,C,Pb and Be in 1Mev-12Mev. Above this energy and for higher atomic masses the values of a,b,c and d should be changed or another parameter is required to decrease the error.

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