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Study of Proton Stopping Power in Be, C, Al and Cu with Energy (1-12) MeV

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Abstract: ***In this research, a theoretical study for calculation of electronic stopping power with energy (1-12MeV) when passing in some atomic media (Be, C, Al and Cu). The electronic stopping power were calculated using Bethe equation and SRIM 2012 program and also by fitting, and then a semi empirical equation we got for calculating the value of stopping power and after that a comparison where made with the theoretical results of Bichsel and Getachew. The maximum difference between the the semi empirical calculation and with all results we found using the statistical test (kstest2) in Matlab program.***

Keyword: Stopping power, stopping number, ionization, excitation.

1. Introduction

The Stopping power and energy dissipation of charged particles through matter has been a subject of great interest for 100 years [1] because of its wide areas of application, such as ion implantation, fundamental particle physics, nuclear physics, radiation damage, radiology [2,3]. Heavy charged particles traversing matter lose energy primarily through the ionization and excitation of atoms [4].The **stopping power** is defined as the mean energy loss per unit path length–*dE*/*dx*. It depends on the charge and velocity of the projectile and, of course, the target material [5,6]. Early investigation of the energy loss of charged particles traversing matter arrive at a general stopping power formula [6]:

$$-\frac{dE}{dx}=\frac{4\pi e^4 NZ_2}{m_e v^2}Z_1{}^2 B \quad \text{..... (1)}$$

Where N is the target density, Z_2 the target atomic number, m_e the electron mass, v and Z_1 the projectile velocity and charge respectively and B called "stopping number'' [6]. Here the negative sign signifies the fact that the particles lose energy as they pass through the material. For most practical purposes, the physics of the energy loss phenomena is complex, and will be not covered in detail [7]. If an ion beam penetrates through matter it loses energy due to collisions with electrons (electronic stopping) and target nuclei (nuclear stopping) [8].The total stopping power is then just the sum of the stopping powers due to electronic and nuclear interactions [9,7]. At low energies the total energy loss is usually described in terms of electronic stopping power [10]. The nuclear component of the stopping power can also be ignored [7]. The possible phenomena contributing to the electronic stopping in the velocity region well below the light velocity are [9]:

1. Momentum Exchange in a Collision between the Ion and a Free Electron in the Target Material.
2. Ionization of the Ion.
3. The Ion Captures An Electron.
4. Excitation of the Ion.
5. Excitation of A Target Atom.
6. Ionization of A Target Atom.
7. Collective Effects Such As the Polarization or the Plasmon Excitation.

The first quantum mechanical study of stopping power was done by Bethe. Bethe theory of stopping is valid when the projectile's velocity is higher than the Bohr velocity. In Bethe theory, the target is assumed as an elemental material [2]. Bethe's treatment of the energy loss is based on the Born approximation applied to the collisions between the heavy particle and the atomic electrons. In this theory, the projectile heavy particle is assumed to be structure less, and the target nucleus is assumed infinitely massive. The differential cross section for a process in which the heavy particle transfers a given momentum to the atomic electrons is given by the square of the matrix element of the Coulomb interaction between appropriate initial and final states [5]. The expression used for the calculation of the stopping power of particles, consisting of M nucleons, with charge Z_1, speed v, and kinetic energy E is [11] :

$$S=-\frac{dE}{dx}=K\frac{Z_1^2}{A\beta^2}Z_2 B \quad \text{..... (2)}$$

With $x=t\rho$ the surface density of the absorber (g/cm^2), ρ its density (g/cm^3), t its thickness (cm), $k=4\pi e^4 N_\circ/mc^2=0.307075 MeV cm^2$, $\beta=v/c$,e the electron charge m its rest mass (mc^2=510999eV), c the speed of light, $r_o=e^2/mc^2$ =2.817941×10^{-13}cm the classical electron radius, N_o =-6.022134×10^{23}atoms/mol, (Avogadro's number), $Z_2$the atomic number of the absorber, A its atomic weight, B stopping number (L in some papers). M_o the rest mass of the partical (protons: M_oc^2 =938.2723 MeV, α particale :3727.316 MeV). As will be seen, this function is valid for $T\geq$0.5MeVfor protons,$T/M \geq$ (Z_1-1.5)MeV for $Z_1\geq$2. For particales heavier than electrons, Bethe gave the stopping number B in the form [11] :

$$B=\ln\frac{2m_e c^2\beta^2\gamma^2}{I}-\beta^2 \quad \text{..... (3)}$$

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Where $\gamma^2 = \frac{1}{1-\beta^2}$, I is the mean excitation energy of the absorber $I = \hbar\omega$. One of the difficult parameters to evaluate in the above expression is the ionization potential I of the medium. For this a number of empirical formulas have been [7]:

$I = 12 + 7,\ Z_2 < 13$ ….. (4)
$I = 9.76Z_2 + 5.58Z_2^{-0.19}, Z_2 \geq 13$ ….. (5)

With the inclusion the corection terms B is now written as [11]:

$B(Z_1) = B_\circ + Z_1L_1 + L_2(Z_1) + [G(Z_1,\beta) - \delta(\beta)]/2$ ….. (6)

Where
$B_\circ(\beta) = f(\beta) - lnI - \frac{C(\beta)}{Z_2}$ ….. (7)

Where $C(\beta)$ is the total shell correction, $G(Z_1, \beta)$ the mott correction, δ the correction for the density effect, $L_1$the Barkas correction term, and L_2 the Bloch correction term [11].Many experimental as well as theoretical studies have been made with the object of establishing standard range energy relations.The subject has been reviewed in last two decades by several authors such as Taylor, Bethe and Askin, Allision and Warshaw, Uehling and by Barkas and Berger. Most of the experimental data has been compiled by Whaling and Bichsel in the form of tables. 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 semiempirical formulas derived from the Bethe-Bloch expression of stopping power or on entirely empirical formulas extracted from the experimental information. The old empirical formulas are in great error due. To lack of correct experimental information at that time. Moreover some relations are valid only for specific values of Z and in a small energy region. A. K. Chaubey and H. V. Gupta arrived at the following empirical relation for the stopping power of protons [12]:

$-\frac{dE}{\rho dx} = \frac{a}{A_2}E^{-b}Z_2^{clogE+d}$ ….. (8)

The appropriate values of the constants a, b, c, and d are a = 915.0, b = 0.85, c = 0.145, d = 0.635.Here ρ, A and Z_2 denote the density, atomic weight and atomic number of the stopping material while E is the kinetic energy of the particle in MeV/amu. The eq. (8) is found to be valid in the energy region 0.7 to 12 MeV/amu. The stopping power is in MeVcm^2/gm. The constants c and d are found to be independent of particle type and were obtained by fitting Northcliffe and Schilling (here after referred to as NS) stopping power values by the least squares method while the constants a and b were extracted using the experimental data of Whaling and Anderson et al. and also NS data towards lower energies. The stopping power for the ions heavier than protons can be found by the expressions given by Pierce and Blann [12,13]:

$\left(-\frac{dE}{\rho dx}\right)_H = \frac{z_{eff}^2}{\gamma_P^2}\left(-\frac{dE}{\rho dx}\right)_P$ ….. (9)

Where
$Z_{eff}^2 = \gamma^2 Z^2$

2. Results and Discussion

By using Bethe formula which represented in equation (2). We calculate the stopping power of protons with energy (1-12MeV) when passing in the atomic media (Be, C, Al and Cu) and we have arrived at the following semi empirical relation for the stopping power of protons for that four atomic media:

$S_e = abE^{-1}$ ….. (10)

Where

$a = 96\ \frac{Z_2}{A} + 3lnE$
$b = ln\left(104 \times 10^2 \times \frac{E}{I}\right)$

We programming this equation depended on Matlab program. As well as we using the SRIM2012 program to calculate the stopping power of protons in this atomic media and by using coincidence tool (curve fitting tool), we achieved finding equation (11) with its constants in any medium of four element :

Table 1: The equation which represent the stopping power of protons in (Be, C, Al and Cu)

Energy		Function	Element	Constant
1-12MeV	Power2	$f(x) = ax^b + c$ $S_e = aE^b + c$ …… (11)	Be	a = 229.2 b = -0.7113 c = -6.795
			C	a = 242.1 b = -0.6641 c = -11.53
			Al	a = 185.9 b = -0.6197 c = -10.77
			Cu	a = 132.8 b = -0.5135 c = -13.71

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The figures (1- 4) are plots of the stopping power versus the incident proton energy from (1 - 12Mev) for the elements Be, C, Al and Cu by using Matlab Language. These figures represented comparison among the stopping power calculated from equation (2), the corresponding values obtained from SRIM-2012 program, theoretical values of Getachew and Bichsel and the fitting results to the SRIM-2012 results for the same elements. From figures (1,2,3) we note the semi empirical formula agree with all results we achieved compare with it, but from figure (4) we noticed there is no good agreement between, the present semi empirical results and all results at energy leas than 8MeV for protons incident on Cobalt. this show, the semi empirical equation don't availed at energy leas than 8MeV because the stopping power depend on atomic mass of the stopping element. To show The maximum difference between the curves we use the statistical test k (kstest2Two-sample test) by using Matlab program. The maximum difference between the present semi empirical results (equations (10)) and all results for figure (1,2,3) which for Be, C and Al gave k = 0.0833 but, in the case of Cu from figure (4), we got The maximum difference among the present semi empirical and the results for SRIM-2012, fitting, theoretical values of Getachew and Bichsel gave k=0.1667 but with Bethe gave k=0.0833.

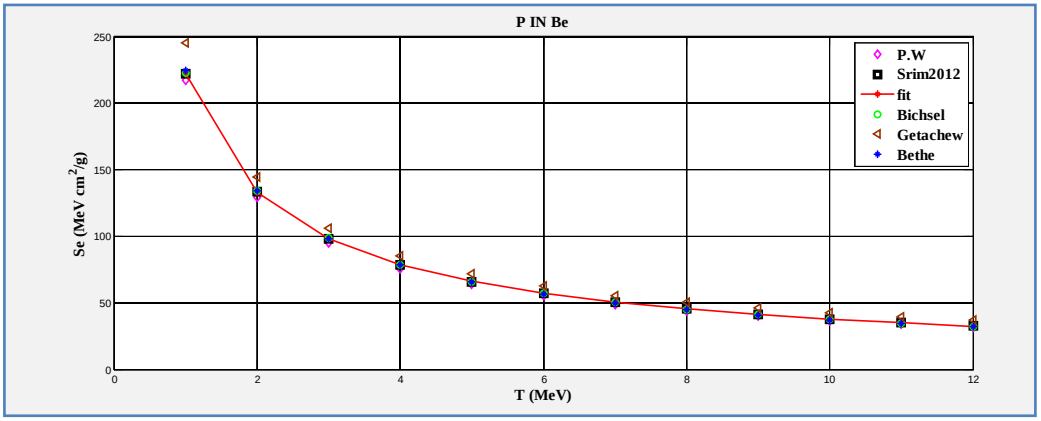


Figure 1: Stopping power of proton versus energy in Beryllium with others workers value

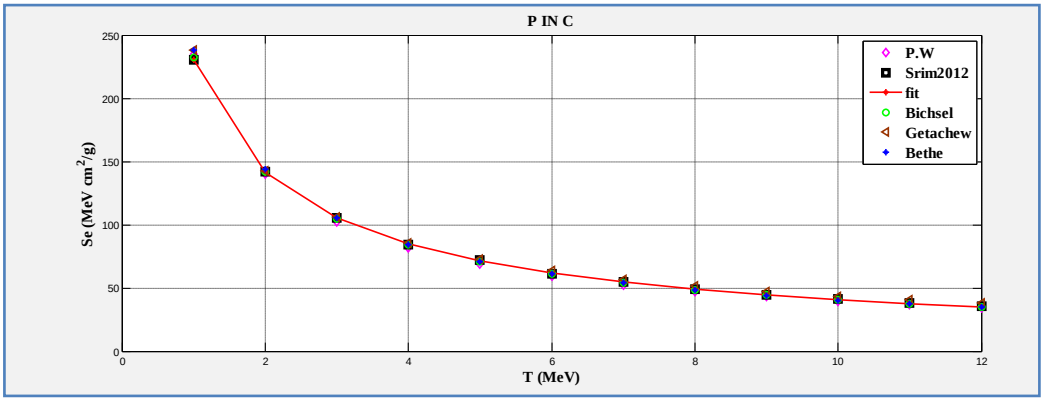


Figure 2: Stopping power of proton versus energy in Carbon with others workers value.

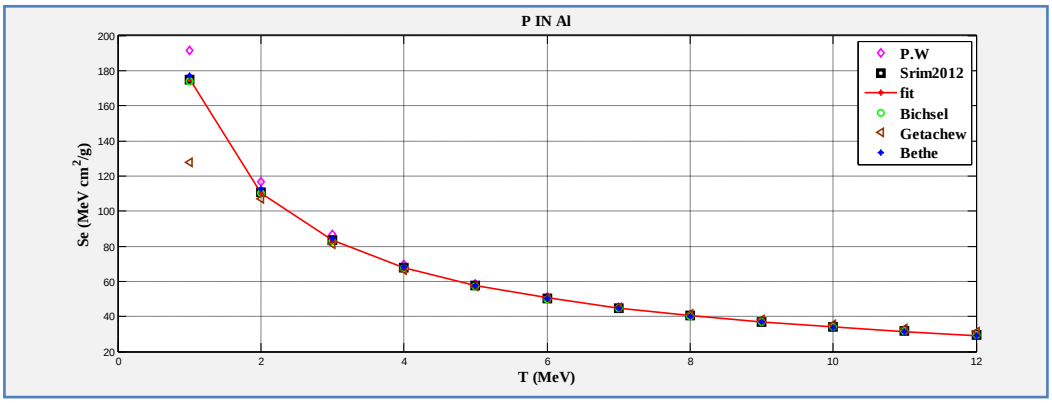


Figure 3: Stopping power of proton versus energy in Aluminum with others workers value.

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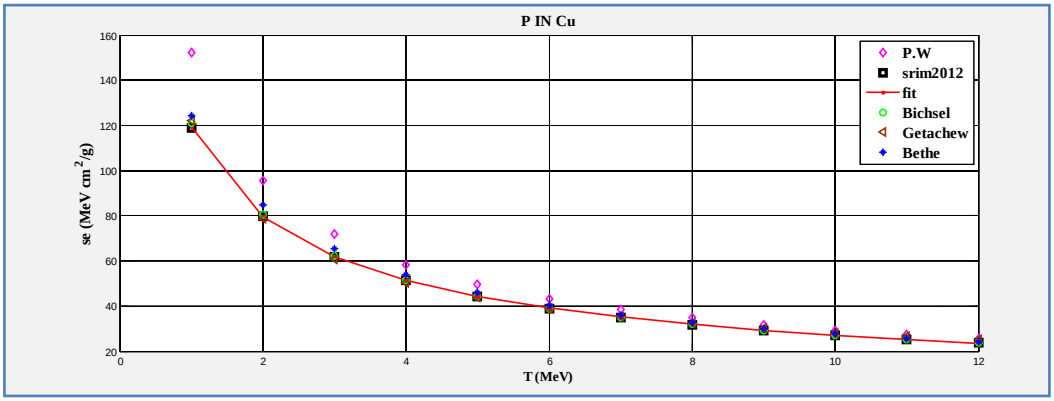


Figure 4: Stopping power of proton versus energy in Copper with others workers value.

3. Conclusions

From this research we can conclude several conclosion as follows:

1. The maximum value of stopping power occurs of lower energies of protons.
2. From the calculation of stopping power for proton using mathematical formulas (Bethe and semi empirical) we conclude that the stopping power inversely proportional with energy.
3. From the statistical test k, it can be concluded that the semi empirical relation do not agreed with the result of other ways of stopping compare with it of protons incident on Cu.

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