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Interaction parameters of protons in Aluminum and Iron

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ABSTRACT

The interactions parameters(including ,stopping power with orbital electrons, continues slowing down ranges approximation and square of screening angle)for slow protons(10-500)MeV in aluminum and iron elements were calculated by adopting empirical equations through using Visual Basic Studio program 2016. the present study indicates that the calculated parameters show a linearity with the atomic number (Z) and the proton incident energy of the absorber the comparison with the available pervious experimental work gives a good agreement.

1. Introduction

The proton is the lightest baryon whose existence was inferred as early as 1808 through Dalton's gravimetric weight measurements which implied that the elements were made up of integral constituents, this was followed by Proust's hypothesis in 1815, that all elements were integral multiples of the hydrogen atom, which he had termed as the portly. The proton was recognized as a hydrogen ion through, for example, electrolysis. It was inferred as a nuclear constituent gravimetrically and, to some degree, by Rutherford's interpretation of the results of Geiger's and Marsden's experiment of scattering α-particles from gold foils. The definitive proof of the existence of the proton as a sub nuclear particle can be traced to Rutherford's investigations of the scintillations observed on a zinc sulphide screen at one end of a glass tube and a radium source of α-particles at the other[1].The Interaction parameters of protons have great importance in studying the characteristics of elements material that's used in constructing space shuttles and satellites that resists the cosmic rays as well as a huge applications in Radiotherapy [2] .The study of proton-matter interactions allows to resolve the problems of beam design and doses distributions in human beings [3-5].There are several ways of proton-matter interactions ;first electronic stopping power, secondly scattering and thirdly nuclear interactions, the last two interactions are proceeds via the electromagnetic interaction among the proton – electron or nucleus . While in the stopping power, the proton kinetic energy gradually decreases in each unit path inside the material [5].This subject draw the attention of many theoreticians and experimentalist researchers to use Monte-Carlo Codes. Molina et al [6] applied different algorithms as well as Monte-Carlo Code in estimation the specific energy loss in water for proton beam in energy range (0.50-10) MeV. Paul [7] present outlook of stopping power of positive ions which obtained in the last years, and discuss the recent results of low energetic protons in water and several elements. Ziegler, Biersack, and Littmark [8] present a semi-empirical model named as ZBL model for calculating the stopping power of different ions inside material, on the other hand, many programmers and simulations were developed since 1960[9-14]. Most of these models depend on the dual collision approximation in which the ions transport through matter by a series of independent collisions with electron but without any loss of energy during the collision with atomic nucleus. Eppacher et al [14] measured the energy loss of proton in two elements Rubidium and strontium, their results shows differences up to 30% with results of other researchers[15-16]. Shahad et als [17] investigated the specific energy loss and continue slow down ranges approximation of Carbon by using

slow proton (1.5-295) MeV which were in good agreement with that of Pstar-code .The aim of the present study is to determine the interactions parameters which include stopping power, screening angle and continue slow down range approximation of the proton in energy range (10-500) MeV for iron and aluminum by applying Visual Basic Studio program 2016 and comparing to the available experimental data.

2.Theortical Model

The stopping power of an absorber for a heavy particle can be defined as the energy loss *dE* ***per*** unit path length, *dL***.** The physical picture of this process is that when a charged particle passes through matter, it electromagnetically interacts with a large number of atoms and molecules that it encounters, but only a relatively small number of these will change their energy state. The equation is derived by H.A. Bethe by applying the relativistic quantum mechanics, which is defined as [18]

$$\frac{dE}{dL}=\frac{4\pi r_e m_e c^2 z^2 Z^2 N_A}{\beta^2 A}\left(\ln\frac{2m_e c^2\beta^2}{I(1-\beta^2)}-\beta^2\right) \quad \text{.....(1)}$$

Were r_e electron radius equals to $2.817\times10^{-15}m$, $m_e c^2$ is Electron rest mass energy equals to 0.511MeV.While N_A is the Avogadro's Number $N_A=6.023\times10^{23}\,g/mol$. A and Z are the atomic weight and atomic number of material under study, while I is the mean ionization energy for target material which measured in MeV, given by [18].

$$I=9.1Z(1+1.9Z^{-2/3}) \quad \text{.....(2)}$$

.After substituting the constants in equation (1), we get:

$$\frac{dE}{dL}=0.3072\frac{Z}{A}\frac{1}{\beta^2}\left(\ln\frac{1.022\beta^2}{I(1-\beta^2)}-\beta^2\right) \quad \text{.....(3)}$$

Where the factor β is given by

$$\beta=\frac{v}{c}=\sqrt{1-\frac{m_{proton}c^2}{(m_{proton}c^2+E_p)^2}} \quad \text{.....(4)}$$

v: proton velocity .

c:velocity of light in vacuum .

The screening angle represents the least angle, which the single scattering angle begins to level off(divergence from Rutherford's equation)due to screening effect of the nuclear charge by orbital electrons .The square of screening angle is given by [4].

$$\chi^2_{screening}=\chi_0^2(\alpha^2+1.13) \quad \text{.....(5)}$$

$$\chi_0^2=\frac{k_1}{(pc)^2} \quad \text{.....(6)}$$

The energy amount (*pc*) calculated by

$$(pc)^2=(1876.54E_p+0.999E_p^2) \quad \text{.....(7)}$$

Where E_p is the kinetic energy of incident proton, and born parameter (α) is given by

$$\alpha^2=\frac{k_2}{\beta^2} \quad \text{.....(8)}$$

While the k_1 and k_2 are defined by

$$k_1=\left[\frac{m_e c^2}{0.885}\left(\frac{e^2}{\hbar c}\right)Z^{\frac{1}{3}}\right]^2 \quad \text{.....(9)}$$

$$k_2=\left[\left(\frac{e^2}{\hbar c}\right)Zz\right]^2 \quad \text{.....(10)}$$

The continuous slow down range approximation R_{CSDA} for a charged particles with a kinetic energy E_p, represent the path distance in target material , in which the velocity of incident proton reduced to zero , in the present study , we depends upon the empirical constants method[19]:

$$R_{CSDA}(cm)=\frac{10^{\alpha+\beta x+\gamma x^2}}{\rho} \quad \text{.....(11)}$$

Where

$$x=\log_{10}E_p \quad \text{.....(12)}$$

Where ρ is the target density and the empirical constants α, β, γ for aluminum and iron are given in the table (1).

Table 1: The empirical constant values of elements [19].

Element	α	β	γ
Aluminum	-2.3829	1.3494	0.19670
Iron	-2.2262	1.2467	0.22281

After insert the empirical constant values of elements under study , eq.(11), becomes

$$R_{CSDA-Al}(cm)=\frac{10^{-2.3829+1.3494x+0.1967x^2}}{\rho_{Al}} \quad \text{.....(13)}$$

$$R_{CSDA-Fe}(cm)=\frac{10^{-2.2262+1.2467x+0.22281x^2}}{\rho_{Fe}} \quad \text{.....(14)}$$

All these equations are written by employing Visual Basic Studio program 2016.The present calculation model is shown in fig.(1).

3.Results and discussion

Tables (2-3)and figures 1- 2, illustrate the comparison results of proton stopping power in energy range (10-500) MeV in the aluminum $^{27}_{13}Al$ and iron $^{56}_{27}Fe$ by using equations (1-4) the dE/dL results compared with ICRU. In these tables, we found that at low velocities this term inside the bracket of equation (2) increases with the velocity(incident proton kinetic energy), but very slowly, especially in energy region (10-100)MeV, where the values $\frac{dE}{dL}$ are for Al (34.55-2.185) $\frac{MeV.cm^2}{g}$ and for Fe element(29.30-1.96) $\frac{MeV.cm^2}{g}$, this due to many interactions with the orbitals electron render them to lost their kinetic energy .

Table 2: The comparison values of dE/dL with results ICRU 49 of aluminum

E_p(MeV)	dE/dL (MeV.cm^2)/g	ICRU49
10	34.55648	33.75
20	19.97815	19.68
25	16.73004	16.51
30	14.4743	14.3
40	11.52855	11.41
50	9.677974	9.6
60	8.401449	8.33
70	7.464952	7.405
80	6.747188	6.7
90	6.178775	6.133
100	5.717061	5.676
110	5.334327	5.297
120	5.011755	4.977
140	4.497783	4.467
150	4.28966	4.261
160	4.106326	4.08
180	3.79819	3.773
200	3.549367	3.525
250	3.09664	3.075
300	2.792123	2.772
330	2.653399	2.634
360	2.53789	2.518
400	2.411215	2.392
450	2.285381	2.266
500	2.185776	2.166

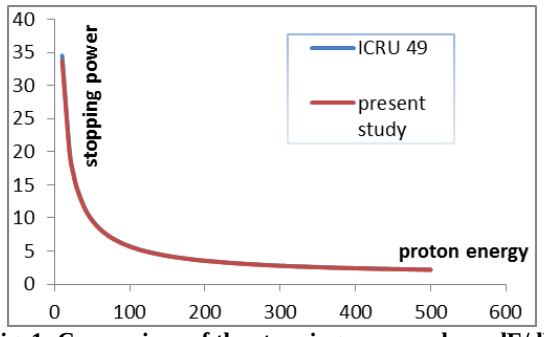

Fig. 1: Comparison of the stopping power values dE/dL for Aluminum.

Table 3: The comparison values of dE/dL with results ICRU49of iron.

E_p(MeV)	dE/dL (MeV.cm^2)/g	ICRU49
10	29.30073	28.54
20	17.22205	16.97
25	14.4857	14.31
30	12.57435	12.45
40	10.06355	9.99
50	8.476867	8.43
60	7.377765	7.346
70	6.568853	6.545
80	5.947301	5.929
90	5.454061	5.44
100	5.052714	5.0411
110	4.719532	4.71
120	4.438367	4.43
140	3.989677	3.982
150	3.807738	3.8
160	3.647348	3.64
180	3.377515	3.37
200	3.159384	3.152
250	2.761959	2.753
300	2.494278	2.484
330	2.372256	2.361
360	2.270627	2.26
400	2.15916	2.146
450	2.048441	2.034
500	1.960832	1.945

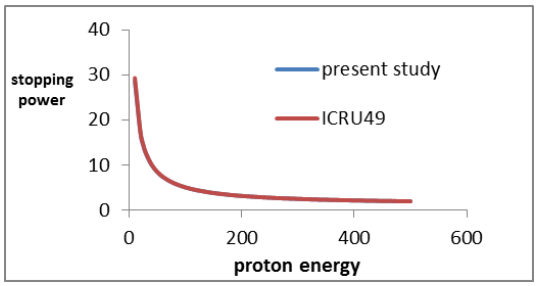

Fig. 2: Comparison of the stopping power values dE/dL for iron.

The interpretation of these results is that at low energy, the protons spend more interactions time with the orbital electron, thus the probability of the collisional energy loss (and production of Bremsstrahlung) increasing and continuously as the proton incident energy increases, the amount of energy losses depends mainly on the atomic number in two ways, firstly on the electron density $n_{ele} \propto \frac{Z}{A}$, secondly through the mean ionization energy (equation 2). The differences in dE/dL values between present study and ICRU49 [13 due to chemical bonding effects have been established to be of order of 1 %. Also the insufficient knowledge of mean ionization energy I is one of the sources of error in calculating the stopping power. Table (4) and fig(3) represent the screening angles $\chi_{screening}$ of Al and Fe obtained by applying equations (5 to 10), the obtained results interpreted that in the manner of the stopping power function and this is due to the screening of the orbitals electrons by the incident

protons . Fig.(3) shows the incident protons suffering from the screening effect in aluminum more than iron due to the electron density for the latest element is lesser .

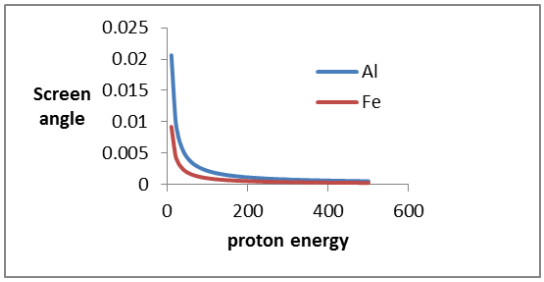

Fig. 3: Comparison of the square screen angle for aluminum and iron.

Table 4: The calculated values of screening angles of aluminum and iron.

E_{proton}(MeV)	Screening angles Al	Screening angles Fe
10	0.0092146	0.0206317
20	0.004647	0.0103785
25	0.0037333	0.0083277
30	0.003124	0.0069603
40	0.0023623	0.0052508
50	0.001905	0.0042248
60	0.0015999	0.0035406
70	0.0013818	0.0030517
80	0.0012182	0.0026848
90	0.0010907	0.0023993
100	0.0009887	0.0021708
110	0.0009051	0.0019837
120	0.0008354	0.0018277
140	0.0007256	0.0015822
150	0.0006816	0.0014839
160	0.000643	0.0013979
180	0.0005786	0.0012542
200	0.0005269	0.0011391
250	0.0004334	0.000931
300	0.0003704	0.0007915
330	0.0003415	0.0007278
360	0.0003173	0.0006744
400	0.0002905	0.0006155
450	0.0002634	0.0005561
500	0.0002415	0.0005082

Table (5) and fig (4) represent the ranges R_{CSDA} of proton in Al and Fe elements by applying equations (13 and 14), the obtained results of proton CSDA-ranges in elements under the study are influenced by the following factors:1. Energy, as the proton energy increases, the CSDA-ranges increase inside material.

2. Density of the medium: The denser the medium (for aluminum $\rho_{Al} = 2.7 g/cm^3$ and $\rho_{Fe} = 7.874 g/cm^3$) is, the shorter is the range of the proton .For examples at E_{proton} 150MeV, the values of $R_{CSDA} = 11.3$ and $R_{CSDA} = 4.422 cm$ for aluminum and iron respectively .All he calculation's are summarized through the flow chart fig (5).

Table 5: The calculated values of proton ranges in Aluminum and iron.

E_{proton} (MeV)	Proton ranges Al (cm)	Proton ranges Fe(cm)
10	0.0540	0.02225
20	0.187	0.075
25	0.286	0.1138
30	0.4053	0.1604
40	0.70944	0.2772
50	1.1066	0.4336
60	1.60925	0.62922
70	2.2111	0.8638
80	2.882	1.1243
90	3.744	1.462
100	4.69	1.83
110	5.74	2.24116
120	6.9722	2.72211
140	9.711	3.771
150	11.30	4.422
160	13.0378	4.999
180	16.933	6.639
200	21.366	8.3922
250	36.08	15.2665
300	54.318	21.5244
330	67.733	25.95
360	80.47	33.169
400	105.625	42.216
450	138.95	55.75
500	181.2	72.992

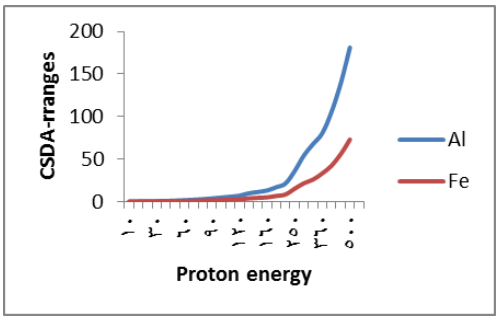

Fig. 4: Comparison of continuous slow down ranges CSDA for aluminum and iron

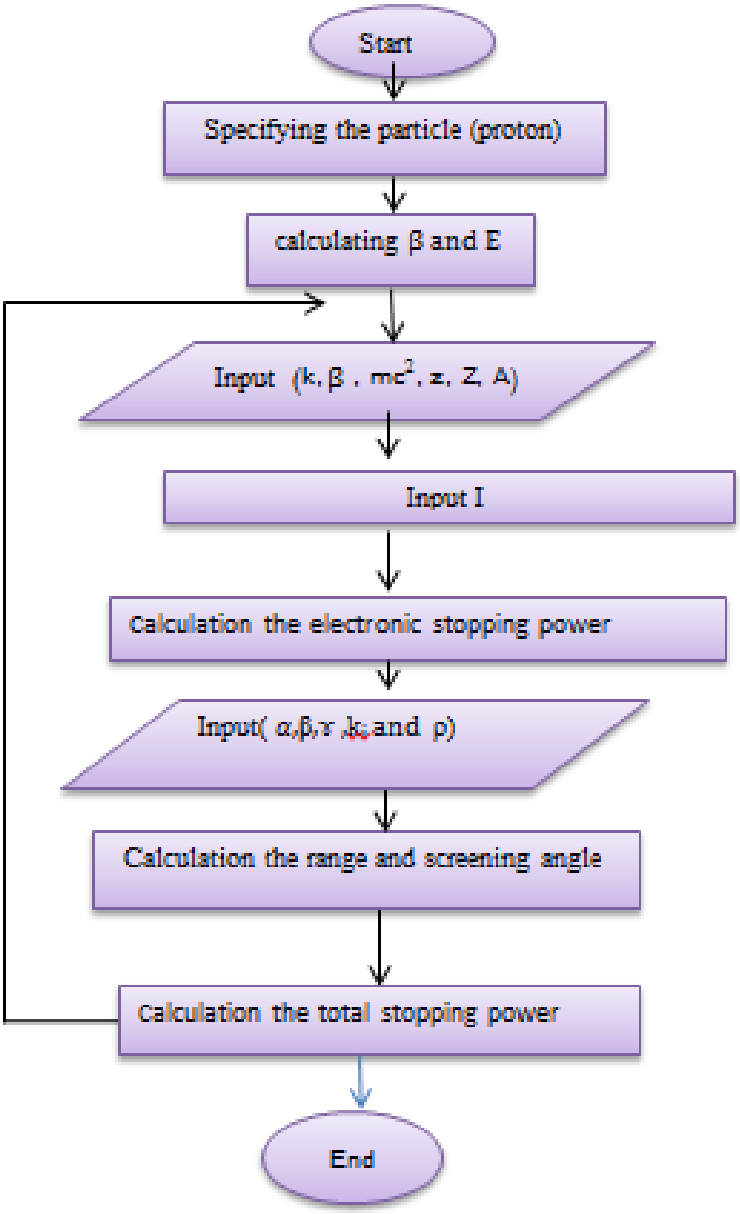

Fig. 5: Flow chart of the calculations model

4. Conclusion

The interactions parameters of the slow protons depend on the atomic number and incident proton energy; the present study suggests that the aluminum is most suitable as a cosmic rays shield than iron due to a property of dispersive energy loss power, while the continuous slow down range approximation for aluminum are bigger which can be overcoming by increasing the
Shield thickness as well as due to its light weight in comparison to iron, which is a huge challenge facing the space industry.

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معاملات التفاعل للبروتونات في عنصري الالمنيوم والحديد

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الملخص

معاملات التفاعل والتي تتضمن (قدرة الايقاف مع الكترونات المدارية ،وتقريب المدى التباطؤي المستمر و زاوية حجب) للبروتونات البطيئة ذات الطاقات MeV(10−500) في عنصري الالمنيوم و الحديد قد تم حسابها باستخدام المعادلات التجريبية باستخدام برنامج Visual Basic Studio 2016. تشير نتائج الدراسة الحالية الى ان معاملات التفاعل تتصرف خطيا مع العدد الذري Z لمادة الهدف وطاقة البروتونات الساقطة وبمقارنة النتائج الحالية مع ما متوفر من الدراسات العملية السابقة وجد انها في تطابق جيد.