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A Theoretical Study of Range for Energy (1MeV/amu to 12MeV/amu) Protons In Aluminum, Gold , Copper and Germanium Solid Materials

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Abstract: To evaluate the effects of radiation, the range of protons in the target material is an important variable for this purpose. For this study, the range of protons with energy from 1MeV/amu to 12MeV/amu which represent Within the low energy range of protons, which are of particular importance in surface applications, some are medically and technically simple. that interacts with some elements (Al,Au,Cu,and Ge) was calculated using a semi-empirical equation and compare it with SRIM2012 data ,PASTR data which they are advanced simulation tools then we use two methods of fitting : used MATLAB's polyfit function to carry out a polynomial regression and fitting the data with a 7th-degree polynomial. The results of both methods were well agreed. Our proton range values show good agreement with SRIM2012 data and PASTR data.

Keywords: Stopping power, Range , SRIM, PASTR, MATLAB Simulation, Semi-Empirical Formula , Polynomial Fitting, polyfit, polyval ,cftool , Correlation Coefficient, Standard Deviation.

I. Background

Energy loss study is important for measuring and evaluating radiation effects. When protons and charged particles move through a medium, they will interacting with the atomic electrons and atomic nuclei of the medium by Coulomb forces. Each atom has many electrons with different ionization and excitation potentials. Thus, the interaction of the moving charged particle with an estimated number of millions of electrons certainly results from this . Each interaction has its own possibility for incidence and a certain energy loss [1]. The ability to stop electrons considered the importance of measuring radiation and the model of electron flow in the material in applications and the ability of the medium to stop electrons is one of the properties of the medium. Knowing this physical property is critical in radiotherapy and dose estimation.[2]. Ionizing radiation levels may worsen due to human activities [3]. Human events, such as waste disposal, be inclined to negatively impact the environment and public health.[3] To knowing a material's ability to stop an electron there are many fields which can benefit from it ,such as Radiation physics, chemistry, medicine , and biology [2By studying individual collisions it is impossible to calculate the energy loss. The average energy loss per unit distance traveled is calculated instead. This is known as the stopping power. (S = -dE/dx) [1,4,5]. That is, in any absorbing medium, its stopping power for charged particles can be described as the result of dividing the differential energy loss of the body within the material by its differential path [6,7] . During the progress of the particle , the ability to stop along the path along which the particle moves is called the loss of specific energyWhile the stopping power increases with decreasing particle velocity for particles with a specific charge state. To explain the loss of specific power, the classical formula, which is Lebeth's formula, is written as follows:

$$-\frac{dE}{dx}=\frac{4\pi e^4 z^2}{m_0 v^2}NB \dots\dots\dots (1)$$

Where $B = Z\left[\ln\frac{mc^2\tau\sqrt{\tau+2}}{I\sqrt{2}} + F^{\pm}(\beta)\right]$ The total stopping cross-section can be divided into two parts:

1-The energy transferred from the incident ions to the target electrons which is called elastic energy loss or electronic stopping.

2- The energy transferred to the target nuclei from incident ions, which is called elastic energy loss or nuclear stopping. [1,4,5].

$$-\frac{dE}{dx}=S_{electronic} + S_{nuclear} \dots\dots..(2)$$

Contributions resulting from nuclear reactions and relativistic corrections are taken into account at high energies (>10 MeV/amu) [8,9]. Since the speed of the incident particles used in this research (protons) is less than the speed of light, they can be neglected. As a result of interactions between the charged particle and both the electrons and nuclei of the material through which it moves, this charged particle loses its kinetic energy .Finally, the falling charged particle becomes neutral after stopping and picks up the required number of electrons from the surrounding material. The total distance from its entry into the material until it stops is called the path length. In other words, we can say that any body with kinetic energy, mass, and charge, when it cuts a thickness of matter and this particle stops in the matter, this thickness is called the particle's range (r), and this range indicates the distance that this particle travels before it loses a large part of its energy. [1,8], which is calculated as follows:

$$R = \int \frac{dE}{f(E)}, \left(-\frac{dE}{dx} = f(E)\right) \dots \dots \dots (3)$$

Range can be defined as the average length of the path that a charged particle is supposed to travel through a target material before reaching its stable state. Therefore, when a proton passes through a medium, it immediately interacts with many electrons in that medium at the same time. What happens in any collision is a pulse of Coulombic force of attraction to each electron when any particle passes close to its surroundings. Sometimes this pulse is not sufficient to make the electron rise to a high shell level in the target atoms (excitation of the atoms) or to remove the electron from the target atoms finally (ionization of the atoms) [11,12]. The factors that affect this distance are different, and they are the type of interactions that occur with the atoms of the material that the particles penetrate, the interactions that occur with the atoms of the material, and the energy of the falling particle[13]. The charged particle range is calculated by take stopping power numerical integration, and the range is given in which it the continual deceleration approximation by the following equation: [11,14]:

$$R = \int_{E_{min}}^{E_{max}} \left(-\frac{dE}{\rho dx}\right)^{-1} dx + R(E_{min}) \dots \dots \dots (4)$$

$R(E_{min})$ is the range of the falling particle when the energy of the falling particle is E_{min} (the least energy used) and is added to the integral equation (3). It is also a specific and constant energy for each particle used and a specific material, meaning that the stopping power of protons is [15] :

$$-\frac{dE}{\rho dX} = \frac{a}{A} E^{-b} Z^{c\,\log E + d} \quad \dots \dots \dots \ (5)$$

Equation (5) is an empirical relationship for the proton stopping power as established by CHAUBEY and GUPTA [8, 10] where the values of the constants a, b, c and d are as follows: a = 915.0, b = 0.85, c = 0.145, d = 0.635 while ρ, A and Z are the density, atomic weight and atomic number of the medium while E is the kinetic energy of the falling particle in MeV/amu. Substituting the value of $-\frac{dE}{\rho dX}$ from Equation (4) into Equation (3) and converting the energy units from MeV to MeV/amu, it becomes:

$$R_p = \int_{E_1}^{E} m_p \left[\frac{a}{A} E^{-b} Z^{c\log E + d}\right]^{-1} dE + R_1\,(E_1) \dots \dots \dots (6)$$

After integrating the above equation and using the rate constants, the equation becomes:

$$R_p = m_p \left[\frac{A}{915 \times 1.85 Z^{0.635\left(1 - \frac{0.145\log Z}{1.85}\right)}}\right] \times \left[E^{1.85} Z^{-0.145\log E} - E_1^{1.85} Z^{-0.145\log E_1}\right] + R_1\,(E_1) \dots \dots \dots (7)$$

The $R_1\,(E_1)$ is the experimental proton range at energy E_1, which varies depending on the type of incoming particle when calculating the corresponding energy of the incoming particle and the type of target used. [6,8,12]. Therefore, the second term of the second bracket in Equation (6) can be related to $R_1\,(E_1)$ and the correction term F_p for the range if the medium is defined by the following formula: $F_p = R_1\,(E_1) - m_p G_p E_1^{1.85} Z^{-0.145\log E_1} \dots \dots \dots (8)$

$$G_p = \left[\frac{A}{915 \times 1.85 Z^{0.635\left(1 - \frac{0.145\log Z}{1.85}\right)}}\right] \dots \dots \dots (9)$$

Therefore, eq. (7) reduces to

$$R_p = m_p G_p E^{1.85} Z^{-0.145\log E} + F_p \dots \dots \dots (10)$$

This equation gives the range of protons in gm/cm^2 if the target is a solid medium and the energy of the incident particle is (0.7 - 12.0) MeV/amu[14,16].

II. Results and Discussion

The range of proton in some element (Al,Au,Cu,and Ge) can get it as a function of its energy from 1MeV/amu to 12MeV/amu by using the equation (10) then compered it with SRIM2012 data ,PASTR data, To analyzes the relationship between the range – energy of protons ,we used MATLAB's polyfit function to carry out a polynomial regression, fitting the data with a 7th-degree polynomial. Then the fitted model rated by using polyval . It allows us to compare predicted values with experimental and theoretical data. Thus, we find that there is a clear and good agreement between the results of this study and the theoretical and experimental data.. All results in the tables below are calculated and represented in shapes that were programmed and drawn in MATLAB-2014 program to obtain an accurate understanding and correct comparison between these results. They are represented by the relationship between the energy **(1-12KeV)** of the incident proton on Al,Au,Cu and Ge.

Table 1. Table of proton range in Al .

E[KeV]	Range of protons by **P.W** $[mg/cm^2]$	Range of protons by SRIM $[mg/cm^2]$	Range of protons by PASTR $[mg/cm^2]$	Fitting of P.W by Power Fit (cftool) $[mg/cm^2]$	Fitting of P.W by **Polynomial Fit (Polyfit)** $[mg/cm^2]$
1	3.92746534450235	3.885476	3.87	3.9275	3.92737533768497
2	11.5995967779025	11.248426	11.34	11.5959573136369	11.6001107817744
3	22.5338093549488	21.718676	21.93	22.5222885323984	22.5327444097729
4	36.3281451913395	35.047642	35.4	36.3044718776570	36.3288873377762
5	52.7329191055920	51.062396	51.57	52.6928278638162	52.7333417456014
6	71.5709206079838	69.65756	70.33	71.5101727126836	71.5702797590813
7	92.7068285664984	90.74667	91.58	92.6212191827569	92.7064752854161
8	116.032346291644	114.235156	115.3	115.917706585857	116.032927308551
9	141.457913976048	140.087892	141.3	141.310111131623	141.458213151552
10	168.907645609906	168.256242	169.7	168.722581934679	168.906910212950
11	198.316025094117	198.69157	200.3	198.089636743520	198.316424684014
12	229.625639847636	231.356048	233.2	229.353895409894	229.625565753945

Table 1. Table of proton range in Au.

E[KeV]	Range of protons by **P.W** $[mg/cm^2]$	Range of protons by SRIM $[mg/cm^2]$	Range of protons by PASTR $[mg/cm^2]$	Fitting of P.W by Power Fit (cftool) $[mg/cm^2]$	Fitting of P.W by **Polynomial Fit (Polyfit)** $[mg/cm^2]$
1	10.6343	10.6343	10.77	10.635	10.6340532214461
2	27.5091037262933	28.4482	28.75	27.5129594560946	27.5105137095445
3	50.2110750003496	51.6854	52.19	50.2209780386640	50.2081507942115
4	77.7796997367769	79.7669	80.45	77.7983911065801	77.7817449361530
5	109.643655484955	112.3067	113.2	109.673752510266	109.644804243700
6	145.409619768468	149.0925	150.1	145.453638135831	145.407861399661
7	184.784287119455	189.8927	191	184.844657158903	184.783328119775
8	227.537460729969	234.5336	235.8	227.616539612831	227.539051161640
9	273.481902190950	282.9187	284.3	273.581983317575	273.482713902990
10	322.461234226471	334.9515	336.5	322.584554636756	322.459227508215
11	374.342164236432	390.5355	392.2	374.490910589103	374.343255701990
12	429.009219648095	449.5935	451.3	429.185533135778	429.009017168890

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Table 1. Table of proton range in Cu.

E[KeV]	Range of protons by **P.W** $[mg/cm^2]$	Range of protons by SRIM $[mg/cm^2]$	Range of protons by PASTR $[mg/cm^2]$	Fitting of P.W by Power Fit (cftool) $[mg/cm^2]$	Fitting of P.W by **Polynomial Fit (Polyfit)** $[mg/cm^2]$
1	6.0031776	6.0031776	6.008	6.003	6.00303863434819
2	16.5578545934407	16.3926055	16.38	16.5583665089897	16.5586483632152
3	31.2199660722456	30.5786859	30.54	31.2217907788033	31.2183207590428
4	49.4065191230786	48.2040868	48.14	49.4102633640073	49.4076675665579
5	70.7622750985201	69.0454757	68.97	70.7685290780327	70.7629251182434
6	95.0384964505446	92.9777864	92.86	95.0478356115471	95.0375066827274
7	122.047234706687	119.884886	119.7	122.060221466067	122.046691676215
8	151.639374003551	149.6417083	149.4	151.656559222475	151.640270415405
9	183.692503333145	182.2035868	181.9	183.714427534204	183.692963090324
10	218.103564641507	217.4990551	217.2	218.130759018534	218.102431635522
11	254.784087268439	255.4834467	255.1	254.817074531906	254.784703178072
12	293.656937969318	296.0942285	295.6	293.696233061625	293.656823740804

Table 1. Table of proton range in Ge

E[KeV]	Range of protons by **P.W** $[mg/cm^2]$	Range of protons by SRIM $[mg/cm^2]$	Range of protons by PASTR $[mg/cm^2]$	Fitting of P.W by Power Fit (cftool) $[mg/cm^2]$	Fitting of P.W by **Polynomial Fit (Polyfit)** $[mg/cm^2]$
1	6.11576	6.11576	6.121	6.1157	6.11560942628097
2	17.4142762987818	16.95368	17.25	17.4168979054129	17.4151363969615
3	33.0604028601750	31.76336	32.42	33.0686978665972	33.0586199654849
4	52.4271769247635	50.15352	51.22	52.4440988012230	52.4284216461777
5	75.1334699775623	71.89904	73.41	75.1619130036290	75.1341739609179
6	100.912859468290	96.84984	98.84	100.955658921664	100.911786979780
7	129.564294359541	124.888	127.4	129.624230632024	129.563706288951
8	160.928433003585	155.88488	158.9	161.008236237291	160.929404208348
9	194.874588204873	189.79224	193.4	194.976942620951	194.875086081376
10	231.292820788535	226.53504	230.7	231.420368529942	231.291593459252
11	270.088818781792	266.05968	270.8	270.244163274483	270.089486002330
12	311.180407668825	308.31256	313.7	311.366116554915	311.180283920865

To more understand the agreement between the results The coefficient of determination (R) was calculated using the following code in matlab program for both experimental models, SRIM and PASTR by using , to compare their fit with the calculated theoretical values.

```
R1 = corrcoef(Rp, Rsrim);
R2_SRIM = R1(1,20)^2

R2 = corrcoef(Rp, Rpstar);
R2_PASTR = R2(1,20)^2
```

Where Rp is the values of Range of protons by P.W **in** $[\mathbf{mg/cm^2}]$ from eq.() , Rsrim and Rpstar are the values of Range of protons by SRIM and PASTR in $[\mathbf{mg/cm^2}]$ respectively in the tables 1,2,3 and 4. The results showed that both models demonstrated excellent fit with the theoretical data, with an R value of 0.9999 for each, as shown in Table (5)

Table 5. Table Correlation Coefficient (R) of P.W with SRIM and PASTR

Elements	Correlation Coefficient (R) of P.W with SRIM	Correlation Coefficient (R) of P.W with PASTR
Al	0.9998	0.9999
Au	0.9999	0.9999
Cu	0.9998	0.9998
Ge	0.9998	0.9999

This indicates that the models explain approximately 99.99% of the variance in the data, demonstrating that both SRIM and PASTR accurately represent the theoretical model. This high coefficient of determination value reflects a very high degree of agreement between the theoretical values (R) and the experimental data. These results confirm that both SRIM and PASTR are accurate and effective tools for simulating and interpreting experimental data in the context of this study. From the results obtained, it can be concluded that these models provide a reliable representation of theoretical performance and have a high ability to predict. At we use two method to fit the range of protons in Al,Au,Cu and Ge which get from eq.( ) we get a good agreement by these two methods of fitting as shown in the figures (1,2,3 and 4) and above tables(1,2,3 and 4) but to know which one of them is more agree with the present work from eq() we can use Standard Deviation of both method of fitting by use the following code in matlab program for both fitting methods :

```
std_Rf = std(Rp - Rf)
std_f = std(Rp - f)
```

where Rf, f are Fitting of P.W by Power Fit (cftool) and Fitting of P.W by Polynomial Fit (Polyfit) in $[\mathrm{mg/cm^2}]$

Table 6. Table Standard Deviation of P.W

z	Std_Deviation_Rp_Rf	Std_Deviation_Rp_f
Al	0.0922	5.8809e-04
Au	0.0595	0.0016
Cu	0.0134	9.0772e-04
Ge	0.0630	9.8350e-04

From table (6) Since the Fitting of P.W by Polynomial Fit (Polyfit) produces the lowest standard deviation in all cases, it minimizes the spread of errors, indicating higher precision in estimating the proton range. Thus, Fitting of P.W by Polynomial Fit (Polyfit)is the better approach based on standard deviation analysis.in addition that the differences in standard deviation across elements may be influenced by their physical properties, such as atomic number and density, which affect proton range. Below figures show the summary of the results:

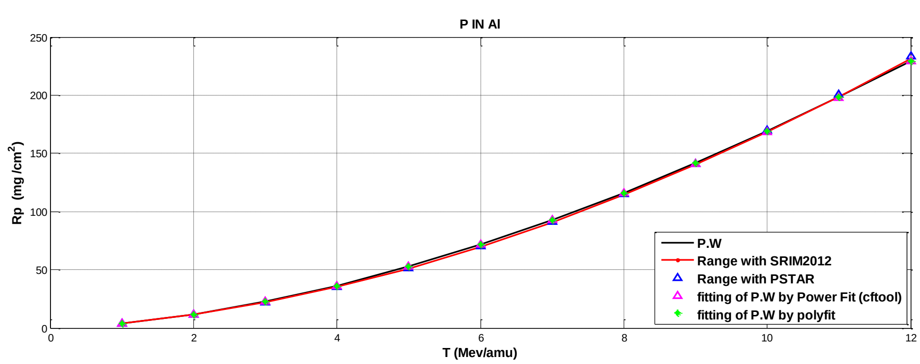

FIGURE.1 Range of proton versus the energy of proton which incident on **Al** , with other Range values.

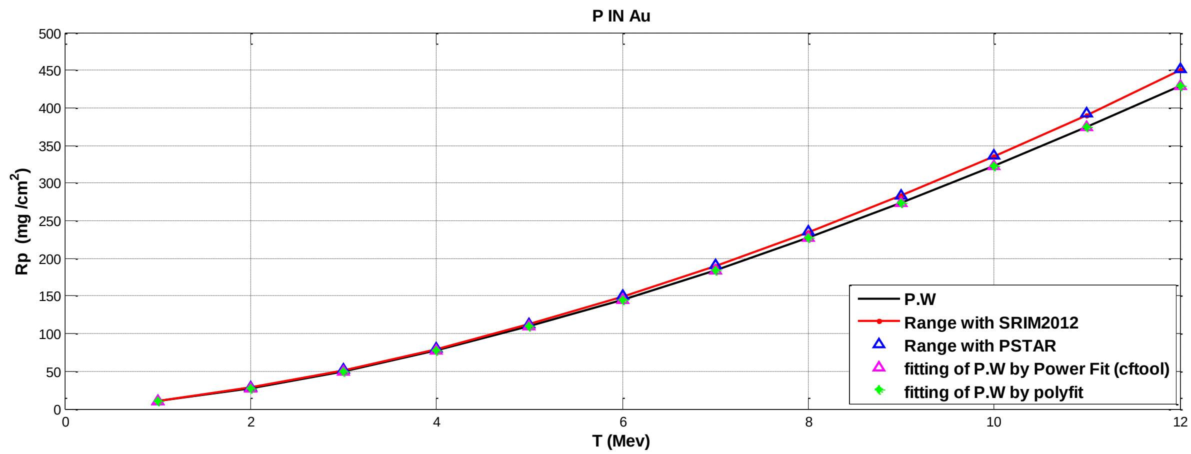

FIGURE.2 Range of proton versus the energy of proton which incident on **Au** , with other Range values.

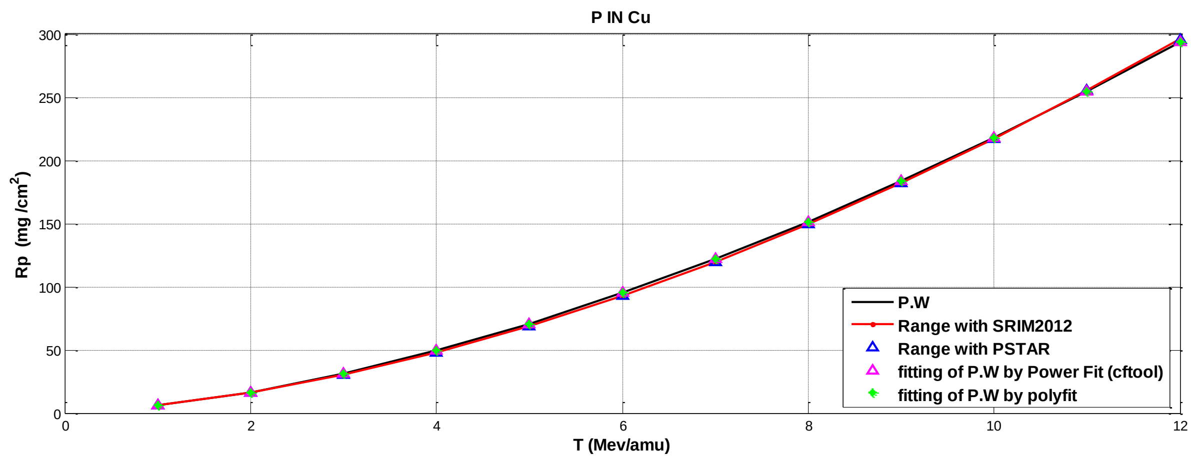

FIGURE.3 Range of proton versus the energy of proton which incident on **Cu** , with other Range values.

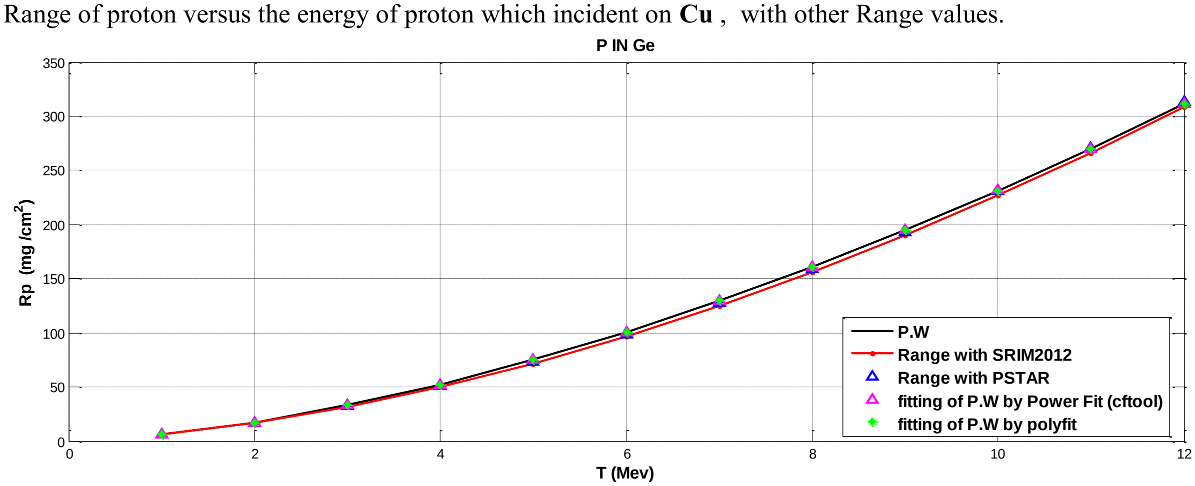

FIGURE.4 Range of proton versus the energy of proton which incident on **Ge** , with other Range values.

III. Conclusions:

In this study, the results of calculating the range of protons falling with energy from 1 MeV/amu to 12 MeV/amu on the following elements are shown: Al, Au, Cu and Ge. It can be concluded from this comparative analysis which was between the values of range of protons in these element by present work and compere them with SRIM2012 data ,PASTR data .The analysis showed an excellent agreement, with correlation coefficients (R) ranging from **0.9998 to 0.9999**, reflecting a highly consistent relationship across all examined elements.Additionally, the standard deviations of the projected range differences, both in terms of Standard Deviation of both method of fitting by use the code in matlab program for both fitting methods were found to be very small. For instance, the standard deviation of present work from Fitting of P.W by Power Fit (cftool) which refere it by (Std_Deviation_Rp_Rf) from **0.0134** (Cu) to **0.0922** (Al), while deviation values the standard deviation of present work from Fitting of P.W by Polynomial Fit (Polyfit) which refere it by (Std_Deviation_Rp_f) were on the order of **10^{-3} to 10^{-4}**, further affirming the precision of the methodology. The results from the study show that the method executed could develop accurate forecast of proton ranges in substance. The conformity with the established sources of the information is an assurance of its suitability for expanded investigations with different materials or energy levels. Besides, the present research carries great work in the above-mentioned fields of radiation shield, particle detector development, and accelerator physics, which demand the designed modeling of proton-matter interactions. Thus, we can conclude that the range of protons predicted by different combinations of materials of selected target elements will provide important information that can play an important role in analyzing the composition of materials and their various applications, which are very important to the scientific community.

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