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Stopping Power of (1.895-7.4 MeV) ^{4}He Ions in Composite Foils and Pure Elements

Nadwa I. Mahmood
Department of Physics
College of Science
Mosul University

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ABSTRACT

This paper deals with the calculation of stopping power for solid media. A semi-empirical formula for stopping power used by other author for liquid media, was adjusted via the values of the parameter K in order to suit the solid media. This modification proved to give better agreement of the calculated stopping power with the experimental value.

قدرة الايقاف لايونات الهليوم للطاقات (1.895-7.4 MeV) للمركبات والمعادن النقية

الملخص

في هذا البحث تم حساب قدرة الإيقاف للأهداف الصلبة باعتمادنا على معادلة شبة تجريبية لباحث سابق ومختارة للأهداف السائلة وقد تم تعديل قيم المعامل K الموجود في هذه المعادلة لكي تناسب الأهداف الصلبة. هذا التعديل في قيم K برهن على أن نتائج قدرة الإيقاف المحسوبة من هذه المعادلة تتطابق مع النتائج العملية المنشورة.

INTRODUCTION

The interaction of heavy ions with matter has always been a subject of vital interest for more than fifty years, and the penetration of charged particles in matter has played a very important role in the development of modern physics particularly in radiation dosimetry field (Sharma et al., 1995). Stopping power is the most important parameter of the energy loss process of energetic ions passing through matter. The most famous application of such parameter is ion implant technique which is used in semiconductor device fabrication. The slowing down and scattering of energetic ions in materials have to be determined in order to implant the ions to the certain depth inside the target. The energy loss of heavy ions is complicated because of the charge-exchange effect which leads to charge-state fluctuations. (Yang, 1994). Due to the complexity of atomic structures, a straight forward formula which allows one to calculate the stopping power of any projectile within any target over a wide energy range, is difficult to achieve. Therefore, one is forced either to adopt certain approximations in order to simplify the calculation, or one must depend on a semi-phenomenological treatment. In the high velocity regime the incident ion is stripped of all its electrons upon entering the target, and the Beth-Bloch theory with corrections is applicable. In the low velocity regime the incident ion is assumed to retain all its electrons and approaches such as those of Lindhard, Scharff and Firsov (Roy and Apfel, 1984) have been found to be reasonably successful. In the intermediate velocity region the calculations are considerably more complicated. The ions are partially stripped and their slow-down in matter which is completely dominated by the so-called electronic stopping effects, is not very reliably predicted by theories. (Hubert et al., 1989). Accurate stopping power data of α-particles in matter are needed in many applications. Of special interest is the stopping in composite foils such as Havar, Kapton and Mylar, of which less data may be found than for the pure elements. For Havar, Kapton, Mylar and Nickel, the stopping power measurements were done by (Kiss et al., 1989) for (1.5-7.2MeV) ^{4}He ions. (Santry et al., 1984), have determined the stopping power of (2.6-7.4MeV) alpha particles for Mylar and of (4.784-7.687MeV) alpha particles for C and Ni.

(Roy and Apfel, 1984) used a semi-empirical equation for calculating the stopping power for liquid targets in the energy region of $u/v_0 \leq 5$. This equation contains the parameter K, and its value equals 0.3818 for any ion except for carbon. It was found that when this is applied for solid targets, a big discrepancy was obtained between the theoretical and experimental results. Therefore, it was decided in this work to determine a new value for the parameter K which will give a better agreement of the calculated stopping power with experimental values.

THEORY

The stopping power equation, which is valid in the low velocity region $u/v_o<1$, can be written in *the* form (Roy and Apfel, 1984).

$S_{e(firsov)} = 5.15\text{x}10^{-21}\,(Z_1 + Z_2)\,u/v_0$ ……………… (1)

Z_1, Z_2 are *the* atomic numbers of the projectile and target respectively.

u is the *projectile* velocity,

v_0 is *the* Bohr velocity = $2.188\text{x}10^8$ cm/sec.

A semi-empirical formula to estimate the stopping power S_e for any projectile-target *combination* in the energy region $u/v_0 < 5$, can be expressed as follows (Roy and Apfel, 1984).

$$S_e = (1.1)(S_{e(Firsov)})\left(1+\frac{10\varepsilon+1}{9\varepsilon^{1/2}}\arctan\varepsilon^{1/2}\right)\exp(-Ku/v_0) \;\ldots\ldots\ldots\ (2)$$

The parameter K is found to be 0.3818 for all ions except Carbon. This parameter can be adjusted to give the best fit with the experimental stopping power.

$\varepsilon = (u/2v_0 Z^*)^2$, Z^* is the effective charge of the incident ion.

At $u/v_0 >2$ the projectile charge Z must be replaced by the velocity dependent reduced *charge*, $Z^* < Z$ and their values can be calculated from the following equation (Forster et al., 1976*)*.

$Z^* = 1 - A(Z_1)\exp(-0.879\,(u/v_0)\,Z_1^{0.65}$

$A(Z_1) = 1.035 - 0.4\exp(-0.16Z_1)$ ………………(3)

To *estimate* the value of the parameter K, equation (2) can be rewritten as follows:

$$K = -\frac{v_0}{u}\ln\left[\frac{S_e}{S_{e(firsov)}\ 1.1\ \left(1+\frac{10\ \varepsilon + 1}{9\ \varepsilon^{1/2}}\ \arctan\ \varepsilon^{1/2}\right)}\right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

The stopping power of a given projectile in a composite foil target of molecular weight M, containing N_i atoms of atomic weight A_i in the molecule can be calculated according to Bragg additivity rule.

$(dE/dx)_{compound} = \sum N_i\ A_i\ (dE/dx)_i\ /M$ …………………..(5)

$(dE/dx)_i$ is the stopping power of the pure element.

CALCULATIONS

(Roy and Apfel,1984) used an equation to calculate the stopping power for liquid targets. This equation contains the parameter K, and its value equals 0.3818 for any ions except for carbon.

When this value is used in equation (2) to estimate the stopping power of composite foils and pure elements (Mylar, Kapton polymethyl methacrylate, Carbon, Nickel and Uranium), it was found that the percentage difference between the calculated and the experimental values are very high. Therefore, the parameter K was calculated from equation (4) by substituting the experimental data obtained from (Kiss et al., 1989) for S_e.

From equation (1) the value of $S_{e(firsov)}$ was calculated.

The results of these calculation are listed in Tables (1-5).

The calculated values of the parameter K from the previous tables as a function of energy E are fitted to the fourth order polynomial equation of the form:

$K = a_0 + a_1E + a_2E^2 + a_3E^3 + a_4E^4$ …………….(6)

where

E is in MeV.

The values of a_0, a_1, a_2, a_3 and a_4 are listed in Table (6).

Equations (1, 2, 3, 5 and 6) were used to calculate stopping power S_e for (1.895 – 4.995 MeV) ^{4}He ion in Ni and for (2.6 – 7.4MeV) ^{4}He ion in Mylar. The results are shown in Tables (7 and 8). These tables show also a comparison of the calculated stopping power with experimental ones. A percentage difference of not more than ±5.1 is noticed for Nickel and ±4.1 for Mylar. The detailed comparison of the calculated and experimental results for Ni and Mylar, is the only way that one can judge the accuracy of the above equations used.A graph of stopping power against energy is shown in figs(1,2).

Table 1: ^{4}He ions in Mylar.

E(MeV)	**U/Vo**	**K calculated**
1.51	3.901	1.724
1.935	4.415	1.609
2.335	4.8506	1.530
2.67	5.187	1.470
2.975	5.475	1.430
3.765	6.159	1.340
4.83	6.976	1.245
5.945	7.739	1.173
6.975	8.383	1.124

Table 2: ^{4}He ions in Kapton.

E(MeV)	**U/Vo**	**K calculated**
2.1	4.596	1.577
2.365	4.87	1.5249
2.81	5.316	1.455
2.985	5.479	1.432
3.995	6.339	1.316
5.04	7.12	1.2305
6.16	7.87	1.159
7.11	8.457	1.1116

Table 3: ^{4}He ions in Polymethyl methacrylate.

E(MeV)	**U/Vo**	**K calculated**
2.1	4.596	1.61
2.365	4.87	1.55
2.8	5.316	1.477
2.985	5.479	1.452
3.995	6.339	1.335
5.04	7.12	1.245
6.16	7.87	1.171
7.11	8.457	1.109

Table 4: ^{4}He ions in Cabon.

E(MeV)	**U/Vo**	**K calculated**
1.895	4.366	1.61
2.275	4.784	1.54639
2.715	5.2262	1.4659
2.99	5.484	1.427
3.97	6.319	1.3175
4.784	6.937	1.247
4.995	7.088	1.231
5.486	7.429	1.1968
5.805	7.642	1.176
6.003	7.771	1.164
7.687	8.794	1.078

Table 5: ^{4}He ions in Uranium.

E(MeV)	**U/Vo**	**K calculated**
1.895	4.366	1.803
2.275	4.784	1.7
2.715	5.2262	1.616
2.99	5.484	1.568
3.97	6.319	1.4336
4.995	7.088	1.3301

Table 6: The values of a_0,a_1,a_2,a_3,a_4

	Compound	**Element**
a_0	2.28499	2.508862
a_1	-0.5026682	-0.6661196
a_2	0.1014671	0.1665688
a_3	-1.08358×10^{-2}	-2.246517×10^{-2}
a_4	4.565931×10^{-4}	1.160311×10^{-3}

The standard error of compound = 1.122129×10^{-2}
The standard error of element = 7.392728×10^{-2}

Table 7: The stopping power values of ^{4}He ions for Nickel.

E(MeV)	**U/Vo**	**Se (firsov) MeV-cm^2/mg**	**K Calc.**	**◊ Se Calc. MeV-cm^2/mg**	**Δ Se Exp. MeV-cm^2/mg**	**□ Se Calc. MeV-cm^2/mg**	**D%**
1.895	4.366	6.924	1.71	0.7083	0.7	0.711	-1.185
2.275	4.784	7.589	1.62	0.6571	0.67	0.66	+1.925
2.45	4.9137	7.878	1.592	0.6509	0.64	0.646	-1.703
2.715	5.2262	8.2885	1.54	0.595	0.62	0.6185	+4.03
2.86	5.363	8.508	1.51	0.6005	0.61	0.6006	+0.155
2.99	5.484	8.6987	1.49	0.5866	0.59	0.5921	+0.576
3.97	6.319	10.02122	1.37	0.4942	0.52	0.5150	+4.96
4.995	7.088	11.244	1.26	0.4835	0.46	0.452	-5.108

◊ Calculated values obtained in the present work.
Δ Experimental values taken from, Kiss, A. Z.
□ Calculated values by using Ziegler formula.

Table 8: The stopping power values of ^{4}He ions for Mylar.

E(MeV)	**U/Vo**	**Se (firsov) MeV-cm^2/mg**	**K Calc.**	**◊ Se Calc. MeV-cm^2/mg**	**Δ Se Exp. MeV-cm^2/mg**	**□ Se Calc. MeV-cm^2/mg**	**D%**
2.6	5.1143	11.9047	1.4944	1.248	1.2	1.2114	-4.045
3.89	6.2787	14.5615	1.332	0.9559	0.947	0.9549	-0.944
4.34	6.6076	15.3807	1.2908	0.909	0.881	0.8824	-3.17
4.7	6.8762	16.0059	1.2617	0.857	0.833	0.8385	-2.88
4.92	7.0353	16.3762	1.2451	0.828	0.801	0.8141	-3.7
5.05	7.1277	16.59116	1.2356	0.813	0.794	0.8005	-2.39
5.12	7.1769	16.7058	1.231	0.8027	0.791	0.7934	-1.479
5.28	7.3149	16.9648	1.2195	0.765	0.768	0.7777	+0.37
5.65	7.5325	17.5492	1.1949	0.753	0.739	0.7439	-2.01
7.11	8.457	19.672	1.1126	0.642	0.621	0.6233	-3.38
7.4	8.6282	20.0839	1.0998	0.621	0.612	0.6216	-1.47

◊ Calculated values obtained in the present work.
Δ Experimental values taken from, Santry and Werner, 1984.
□ Calculated values by using Ziegler formula.

F 1

F 2

DISCUSSION

A new values for the parameter K was calculated which will give a better agreement of the calculated stopping power with experimental. The experimental stopping power in Mylar and Nickel shows a good agreement when compared to calculated values.

As can be seen from Fig.(1), the agreement between the calculated and experimental stopping power for Ni is good with a difference of not more than 5.1%.

A similar agreement is obtained for Mylar as shown in Fig. (2) when a difference of up to 4.1% is noticed.

The exponential term in equation (2) which contains the parameter K works well, after modification in the energy namely $u/v_0 < 10$. The parameter K was found in this study to be dependent on energy.

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