Calculation of Stopping Power due to Ionization and Excitation for Heavy Charged Particles Moving in Nuclear Emulsion

Khin Than Tint

Abstract

In the present paper, the stopping power due to ionization and excitation for (8-MeV) p, d, t, α particles moving in nuclear emulsion is calculated. From the calculations, it is found that the quite difference in the value of stopping power for an alpha versus a proton, a deuteron and a triton of the same kinetic energy traversing the nuclear emulsion.

Introduction

The study of energy loss and penetration of radiation through matter is extremely important for radiation measurements because the detection of radiation is based on its interactions and the energy deposited in the material of which the detector is made. Therefore, to be able to build detectors and interpret the results of the measurement, we need to know how radiation interacts and what the consequences are of the various interactions.

A charged particle moving through a material interacts, primarily, through Coulomb forces, with the negative electrons and the positive nuclei that constitute the atoms of that material. As a result of these interactions, the charged particle loses energy continuously and finally stops after traversing a finite distance, called the range.

Since a bound atomic electron is in a quantized state, the result of the passage of the charged particle may be ionization or excitation. Ionization occurs when the electron obtains enough energy to leave the atom and become a free particle with kinetic energy equal to the difference between energy given by particle and ionization potential. Excitation takes place when the electron acquires enough energy to move to an empty state in another orbit of higher energy.

Assistant Lecturer, Department of Physics, Kalay University

Many different names have been used for the quantity dE/dx; names like energy loss, specific energy loss, differential energy loss, or stopping power. In this paper, the term stopping power will be used for dE/dx .[1]

Stopping Power and Nuclear Emulsion

2.1 Stopping Power due to Ionization and Excitation

A charged particle moving through a material exerts Coulomb forces on many atoms simultaneously. Every atom has many electrons with different ionization and excitation potentials. As a result of this, the moving charged particle interacts with a tremendous number of electrons-millions. Each interaction has its own probability for occurrence and for a certain energy loss. It is impossible to calculate the energy loss by studying individual collisions. Instead, an average energy loss is calculated per unit distance traveled. The calculation is slightly different for electron or positron than for heavier charged particles like p, d, and α, for the following reason.

It was mentioned earlier that most of the interactions of a charged particle involve the particle and atomic electrons. If the mass of the electron is taken as 1, then the masses of the other common heavy charged particles are in the following:

Electron mass=1

Proton mass≈ 1840

Deuteron mass≈ 2(1840)

Alpha mass ≈ 4(1840)

If the incoming charged particle is an electron or a positron, it may collide with an atomic electron and lose all of its energy in a single collision because the collision involves two particles of the same mass. Hence, incident electrons or positrons may lose a large fraction of their kinetic energy in one collision. They may also be easily scattered to large angles, as a result of which their trajectory is zig-zag. Heavy charged particles, behave differently. On the average, they lose smaller amounts of energy per collision. They are hardly deflected by atomic electrons, and their trajectory is almost a straight line.

Assuming that all of the atoms and their atomic electrons act independently, and considering only energy lost to excitation and ionization, the average energy loss per unit distance traveled by the particle is given by Equations 2.1, 2.2, and 2.3.

Stopping power due to ionization-excitation for p,d,t,α.

$$\frac{dE}{dx}(\mathrm{MeV/m}) = 4\pi r_0^2 z^2 \frac{mc^2}{\beta^2} NZ\left[\ln\left(\frac{2mc^2}{I}\beta^2\gamma^2\right) - \beta^2\right] \qquad (2.1)$$

Stopping power due to ionization-excitation for electrons

$$\frac{dE}{dx}(\mathrm{MeV/m}) = 4\pi r_0^2 \frac{mc^2}{\beta^2} NZ\left\{\ln\left(\frac{\beta\gamma\sqrt{\gamma-1}}{I}mc^2\right) + \frac{1}{2\gamma^2}\left[\frac{(\gamma-1)^2}{8} + 1 - \left(\gamma^2 + 2\gamma - 1\right)\ln 2\right]\right\} \qquad (2.2)$$

Stopping power due to ionization-excitation for positrons

$$\frac{dE}{dx}(\mathrm{MeV/m}) = 4\pi r_0^2 \frac{mc^2}{\beta^2} NZ\left\{\ln\left(\frac{\beta\gamma\sqrt{\gamma-1}}{I}mc^2\right) - \frac{\beta^2}{24}\left[23 + \frac{14}{\gamma+1} + \frac{10}{(\gamma+1)^2} + \frac{4}{(\gamma+1)^3}\right] + \frac{\ln 2}{2}\right\} \qquad (2.3)$$

The terms in equations 2.1, 2.2 and 2.3 are

$r_0 = e^2/mc^2 = 2.818\times10^{-15}\,\mathrm{m}$ = classical electron radius

$4\pi r_0^2 = 9.98\times10^{-29}\,\mathrm{m}^2 \approx 10^{-28}\,\mathrm{m}^2 = 10^{-24}\,\mathrm{cm}^2$

mc^2 = rest mass energy of electron= 0.511MeV

$\gamma = \left(T + Mc^2\right)/Mc^2 = 1/\sqrt{1-\beta^2}$

T= kinetic energy= $(\gamma-1)Mc^2$

M= rest mass of the particle

$\beta = v/c$

c = speed of light in vacuum= $2.997930\times10^8\,\mathrm{ms}^{-1} \approx 3\times10^8\,\mathrm{ms}^{-1}$

N= number of atoms/m^3 in the material through which the particle moves

N= $\rho(N_A/A)$ N_A= Avogadro's number= 6.022×10^{23} atoms/mol

A= atomic weight

Z= atomic number of the material

z = charge of the incident particle (z= 1 for e^-,e^+,p,d; z=2 for α)

I= mean excitation potential of the material

An approximate equation for I, which gives good results for Z>12 is

$$I(eV) = (9.76+58.8Z^{-1.19})\ Z \qquad (2.4)$$

Table (2.1) gives the values of I for the elements in emulsion. Value of I with * is from experimental results of Refs.2 and 3. Values of I with ** are calculated by using equation (2. 4). Others are from Refs.4 and 5.

Tables of dE/dx values are usually given units of MeV/(g/cm^2)[or in SI units of J/(kg/m^2)]. The advantage of giving the stopping power in these units is the elimination of the need to define the density of stopping medium that is necessary, particularly for gases. The following simple equation gives the relationship between the two types of units:

$$\frac{1}{\rho\left(g/cm^3\right)}\frac{dE}{dx}\left(MeV/cm\right) = \frac{dE}{dx}\left[MeV/(g/cm^2)\right] \qquad (2.5)$$

Table (2.1) Values of mean excitation potentials for the elements in nuclear emulsion

Elements	I(eV)
I	491.0
Ag	469.0*
Br	371.5**
S	190.9**
O	115.7
N	97.8
C	73.8
H	20.4

2.2 Stopping Power for a Compound or Mixture

Equations 2.1to 2.3 give the result of the stopping power calculation if the particle moves in a pure element. If the particle travels in a compound or a mixture of several elements, the stopping power is given by

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{compound} = \sum_i w_i \frac{1}{\rho_i}\left(\frac{dE}{dx}\right)_i \qquad (2.6)$$

where $\rho =$ density of compound or mixture

ρ_i= density of the i^{th} element

$1/\rho_i(dE/dx)_i$= stopping power in MeV/(kg/m^2) for the i^{th} element, as calculated using Equations 2.1, 2.2,2.3 and 2.5.

2.3 Nuclear Emulsion

It has been known for a long time that charged particles affect a photographic plate. A heavy charged particle traversing a photographic emulsion produces a latent image of its track. The track is revealed when the plate is developed. Ordinary optical photographic emulsions are not suitable for quantitative studies with nuclear radiations. The sensitivity of such emulsion is low. Further, the tracks due to charged particles have non-clear range because the developed crystal grains are large and widely spaced. The composition of the emulsion was changed so as to make it more suitable for the study of various ionizing particles, such as α-particles, protons, mesons and even electrons. The nuclear emulsions differ from the optical emulsions in that they have considerably higher silver halide content and smaller grain size. In nuclear emulsion, the thickness is greater than that of optical emulsion. The smaller the grain size, the more sensitive is the emulsion to ionizing particles. Thus different commercially available emulsions, differing chiefly in grain size, can be used to discriminate between different particles.[6]

2.3.1 Adventages of Nuclear Emulsion

The emulsion is relatively light and cheap. Emulsions were widely employed in cosmic ray studies and led to the discovery of the π and K mesons.

The high density of the emulsion gives it a stopping power about a thousand times that of standard air. Unstable high energy particles are brought to rest in the emulsions and their decay schemes can thus be studied. The emulsion is also the key detector to observe the production and the decay of the S= -2 nuclear system. The emulsion is continuously sensitive and is consequently always available to record an event. The photograph and composition list of the Fuji ET-7C and Fuji ET-7D emulsion are shown in Fig.(2.1) and Table (2.2) , respectively.[7]

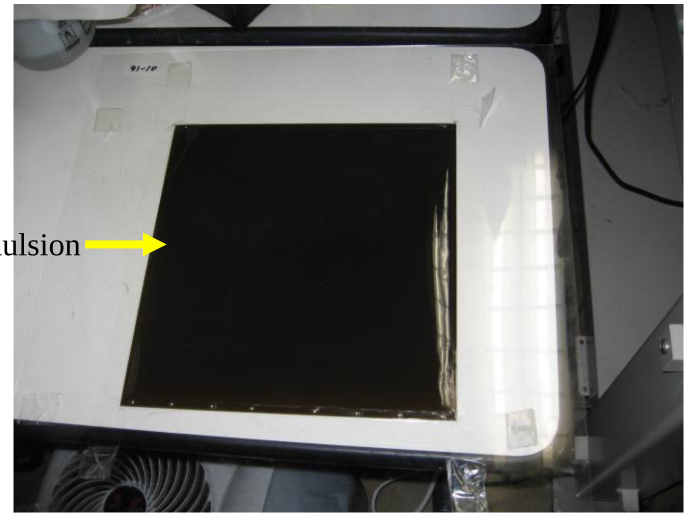

Fig. (2.1) A photograph of nuclear emulsion

Table (2.2). The composition of the Fuji ET-7C and Fuji ET-7D emulsion.

material	**weight ratio(%)**
I	0.3
Ag	45.4
Br	33.4
S	0.2
O	6.8
N	3.1
C	9.3
H	1.5

Calculation of Stopping Power for Heavy Charged Particles in Emulsion

3.1 Calculation of Stopping Power for 8-MeV proton (p) in Emulsion

In calculation, Eq. (2.6) would be used. At first dE/dx will have to be calculated for the eight pure elements which are composed in nuclear emulsion. Using Eq.2.1

For T= 8 MeV

$$\gamma = \frac{T + Mc^2}{Mc^2} = \frac{8 + 1\times 931.5}{1\times 931.5} = 1.0086$$

$$\gamma^2 = 1.017$$

$$\beta^2 = \frac{\gamma^2 - 1}{\gamma^2} = 0.017$$

For Iodine,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_I = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{127\times 10^{-3}}\times 53\times$$
$$\left(\ln(\frac{2\times 0.511}{491\times 10^{-6}}\times 0.017\times 1.017) - 0.017\right)$$

= 2.69 MeV/kg/m^2

For Silver,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{Ag} = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{107\times 10^{-3}}\times 47\times$$
$$\left(\ln(\frac{2\times 0.511}{469\times 10^{-6}}\times 0.017\times 1.017) - 0.017\right)$$

= 2.87 MeV/kg/m^2

For Bromine,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{Br} = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{80\times 10^{-3}}\times 35\times$$
$$\left(\ln(\frac{2\times 0.511}{371.5\times 10^{-6}}\times 0.017\times 1.017) - 0.017\right)$$

= 3.05 MeV/kg/m^2

For Sulfur,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_S = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{32\times 10^{-3}}\times 16\times$$
$$\left(\ln(\frac{2\times 0.511}{190.9\times 10^{-6}}\times 0.017\times 1.017) - 0.017\right)$$

= 4.08 MeV/kg/m^2

For Oxygen,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_O = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{16\times 10^{-3}}\times 8\times\left(\ln\left(\frac{2\times 0.511}{115.7\times 10^{-6}}\times 0.017\times 1.017\right)-0.017\right)$$

$= 4.54$ MeV/kg/m^2

For Nitrogen,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_N = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{14\times 10^{-3}}\times 7\times\left(\ln\left(\frac{2\times 0.511}{97.8\times 10^{-6}}\times 0.017\times 1.017\right)-0.017\right)$$

$= 4.69$ MeV/kg/m^2

For Carbon,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_C = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{12\times 10^{-3}}\times 6\times\left(\ln\left(\frac{2\times 0.511}{73.8\times 10^{-6}}\times 0.017\times 1.017\right)-0.017\right)$$

$= 4.94$ MeV/kg/m^2

For Hydrogen,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_H = 10^{-28}\times 1^2\,\frac{0.511}{0.017}\times\frac{6.022\times 10^{23}}{1\times 10^{-3}}\times 1\times\left(\ln\left(\frac{2\times 0.511}{20.4\times 10^{-6}}\times 0.017\times 1.017\right)-0.017\right)$$

$= 12.21$ MeV/kg/m^2

For Emulsion,

$$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{emulsion} = 0.3\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{I} + 45.4\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{Ag} + 33.4\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{Br} + 0.2\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{S} +$$

$$6.8\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{O} + 3.1\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{N} + 9.3\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{C} + 1.5\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{H}$$

$$= \begin{matrix} 0.3\times 2.69 + 45.4\times 2.87 + 33.4\times 3.05 + 0.2\times 4.08 + \\ 6.8\times 4.54 + 3.1\times 4.69 + 9.3\times 4.94 + 1.5\times 12.21 \end{matrix}$$

$$= 343.459 \text{ MeV/kg/m}^2$$

$$\left(\frac{dE}{dx}\right)_{emulsion} = 343.459\,\text{MeV}/(\text{kg}/\text{m}^2)\times 3.6\times 10^3\,\text{kg}/\text{m}^3$$

$$= 1.24\times 10^6\ \text{MeV}/\text{m}$$

$$= 1.24\times 10^4\,\text{MeV}/\text{cm}$$

Similarly, we calculated stopping power for 8-MeV deuteron (d), triton (t) and alpha (α) in Emulsion.

Results and Discussions

We have calculated stopping power dE/dx for heavy charged particles (p, d, t, α; $1 \le A \le 4$) with same kinetic energy (8-MeV) moving in emulsion as expressed in the previous chapter. The results are shown in Table (4.1). The values of stopping power with 8-MeV heavy charged particles are plotted in Fig.(4.1).

According to stopping power for ionization and excitation for p,d,t,α equation (2.1), we noticed that the stopping power is proportional to z^2 [$(\text{charge})^2$] of particle and density of the material (N). Since the value of

$\gamma = \dfrac{T + Mc^2}{Mc^2}$ is approximately equal to 1, the stopping power is independent of the mass of the particle and depends on the speed v of the particle.

In our calculation, we used the same kinetic energy 8MeV for every particle. We notice that the quite difference in the value of stopping power for an alpha versus a proton, a deuteron and a triton of the same kinetic energy traversing the nuclear emulsion.

Table (4.1) Calculated results of stopping power for 8-MeV heavy charged particles moving in emulsion

Heavy charged particle	**Kinetic energy**	**Stopping power (dE/dx) (MeV/cm)**
proton (p)	8-MeV	1.24×10^{4}
deuteron (d)	8-MeV	2.05×10^{4}
triton (t)	8-MeV	2.7×10^{4}
alpha (α)	8-MeV	13.1×10^{4}

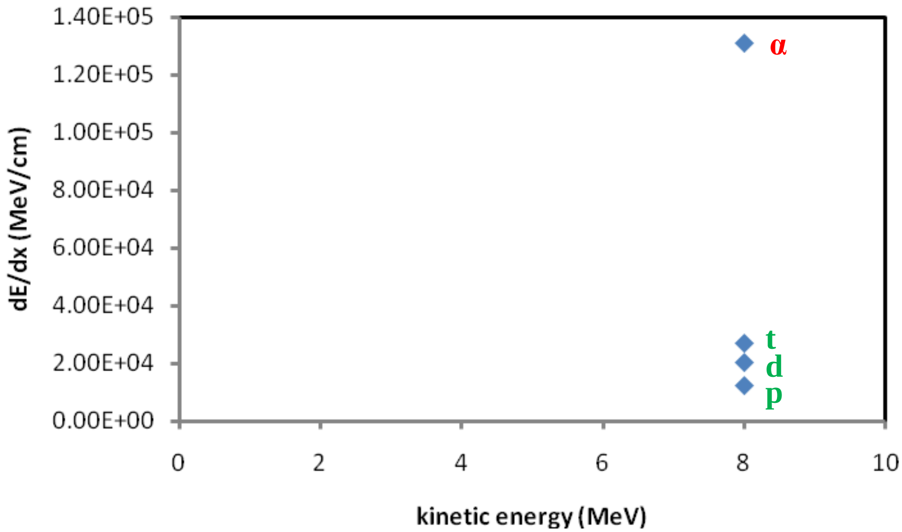

Fig.(4.1) The value of stopping power (dE/dx) with 8-MeV kinetic energy of heavy charged particles

Acknowledgement

I am sincerely grateful to Dr Khin Myint Htun, Head of Department, Department of Physics, Kalay University, for her encouragement on my research work.

References

[1] T. Nicholas, "Measurement and Detection of Radiation", Second Edition, (1995).

[2] Anderson, H.H., Sorensen, H., and Vadja, P., Phys. Rev. 180:383, (1969).

[3] Sorensen, H., and Anderson, H.H., Phys. Rev. 8B:1854, (1973).

[4] Janni, J. F., Proton range-energy tables, 1keV-10 GeV, Atomic Data Nucl. Data Tables 27: 147-339, (1982).

[5] Berger, M.J., and Seltzer, S. M., NBSIR 82-2550A, (1983).

[6] R.Murugeshan, "Modern Physics", (1998).

[7] H. Takahashi, Ph.D.Thesis, Univ. of Kyoto (2003).