Energy Loss of Heavy Charged Particles through Matter

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October 1, 2014

Abstract: Plasma, one of the states of matter, is a hot, ionized gas that is composed of positively and negatively charged particles. Under specific conditions, a plasma consisting of deuterium (^{2}H) gas can be made to undergo fusion reactions. These reactions emit both neutral and heavy charged particles, specifically protons, tritons, and helium-3 particles. The FIU Experimental Plasma Physics (FEPP) group developed the Proton Detector, a charged fusion product diagnostic that is intended to detect the charged products from deuterium-deuterium fusion reactions. A foil was installed in front of the detectors to filter particles of a certain energy in order to better detect desired particle emissions. It was necessary to calculate a foil thickness that resulted in no more than a 10% energy loss of the particle in the following materials: Aluminum, Iron, Gold, Molybdenum, Beryllium, and Tungsten. The interaction between the heavy charged particle and a medium results in some energy loss of the heavy particle in a process called stopping power. To calculate the energy loss of the particle, the stopping energies of the materials, provided by the National Institute of Standards and Technology (NIST), were graphed. Utilizing python programming, the thickness of the material resulting in a maximum 10% energy loss was extracted from the graphs. Commercially-sold foil thicknesses of Gold, Beryllium, Molybdenum and Tungsten would not allow for the detection of (^{3}H$^+$) particles and were therefore no longer under consideration Due to convenience and pricing, Aluminum was chosen over Iron. The thicknesses resulting in a 10% energy loss for Aluminum are 12.61 microns for the proton, 2.28 microns for the triton, and 0.23 microns for the helium-3 particle. A 0.8 micron foil was chosen for the experimental setup; the energy loss for the proton, triton, and helium-3 particles are 0.63%, 3.46% and 35.3% respectively.

Contents

1 Introduction

In studying how nuclear particles lose energy in various materials, the types of radiation can be separated into four categories according to how they interact with the material: fast electrons, heavy charged particles, massive nuclei, and neutrons.

The nuclear particles relevant to this experiment are heavy charged particles which include the nuclei from various isotopes of hydrogen and helium [2]. Hydrogen isotopes are known as protons ($^1H^+$) , deuterons ($^2H^+$), and tritons ($^3H^+$). Helium ions include $^3He^{++}$ and $^4He^{++}$.

Heavy charged particles interact primarily through the coulomb force between their positive charge and the negative charge of the orbital electrons within the absorbing medium's atom. During the encounter between the positively charged particle and the electron, the electron feels an impulse from the attractive coulomb force as the particle passes through its vicinity. [3] Depending on the proximity, the impulse may either excite the electron to a higher shell within the absorber atom, or completely ionize the electron from the atom. During this reaction, energy is transferred from the proton to the electron which therefore reduces the velocity of the proton as well. The maximum energy the charged particle of mass m with kinetic energy E loses to an electron of mass m_0 from a single collision is $4Em_0/m$ or about 1/500 of the particle energy per nucleon [2]. The particle interacts with many electrons during its passage through an absorber so the net effect continuously decreases the proton's velocity until the particle is stopped [3].

Since the encounters do not affect the track of the particle as interactions occur in all directions simultaneously, the charged particles are characterized by a definite *range* in a given absorber material. Range, expressed in terms of weight per unit area, instead of distance, allows the curves for different absorber materials to be plotted on a more compressed vertical scale [1]. The linear stopping power S for charged particles in a given absorber is defined as the differential energy loss for the particle within the material divided by its differential path l, x:

$$S = -\frac{dE}{dx}$$

where $-dE/dx$ is called its specific energy loss, or the rate of energy loss. For charged particles, S increases as the particle velocity decreases. The Bethe formula is the classical expression that describes the specific energy loss and is written as:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi e^4 z^2}{m_0 v^2} NB$$

where

$$B \equiv z\left[ln\frac{2m_0 v^2}{I} - ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

in both expressions [1]:

v = velocity
z = the atomic number of the incident particle
e = electronic charge
N = number density
c = velocity of light
m_0 = electron rest mass
I = mean ionization potential of the target
E = energy of the incident particle

However, for nonrelativistic particles, only the first term in B is significant meaning dE/dx varies as $1/v^2$. This is due to the fact that the charged particle spends a greater time in the vicinity of any given electron when its velocity is low, so the impulse felt by the electron and its energy loss is the largest. Therefore, particles with the greatest charge will have the largest specific energy loss. For example, alpha particles will lose more energy than a proton of the same velocity. Consequently, high atomic number and high-density materials result in the greatest linear stopping power [2].

2 Calculating Energy Loss of Heavy Charged Particles through Matter

The listing of the Range and Energy Curve for Protons and Alpha particles for a given element is given by the PSTAR and ASTAR databases respectively [4]. The range is expressed in weight per unit area instead of distance so that it may allow the curves for different absorber materials to be plotted in a more compressed vertical scale.

The theoretical range-energy curve is plotted and a polynomial is fit to the data. The energy loss ΔE, for a given foil thickness, Δx, is predicted for an initial energy E_0 from the following:

The original energy of the particle, E_0, is used to determine the value of R_0, from the Range Versus Energy Curve. The thickness of the foil, Δx in units of weight per unit area, is then subtracted from R_0 to find R_f. The point on the curve determined by R_f is used to find the corresponding value, E_f, the energy with which the particle exits the foil. The predicted energy loss of the particle as it travels through a foil of thickness Δx, is the difference between E_0 andE_f [1].

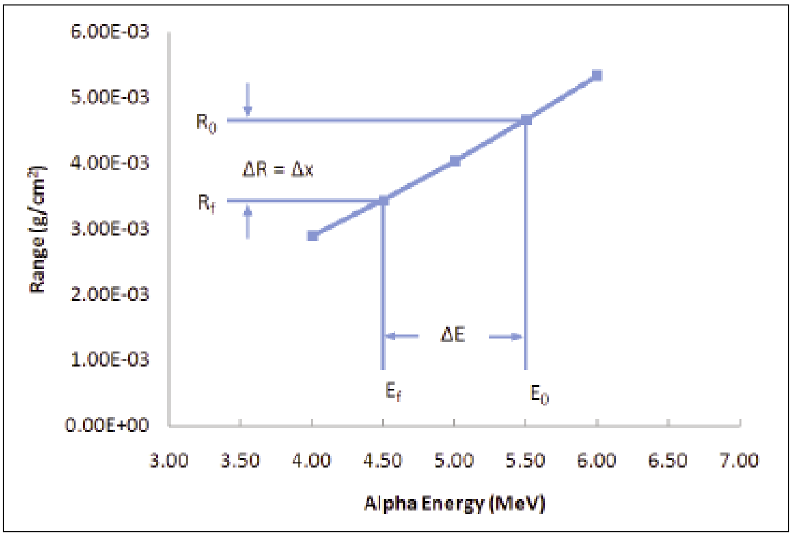

Figure 1: Deriving the Energy Loss, ΔE, from the Material Thickness, Δx, using a Range-Energy Graph [1]

However, the purpose of calculating the energy loss with heavy charged particles was to find an element with a thickness that would yield no more than 10% energy loss. To do so, a second plot of the energy difference as a function of the thickness of the foil was necessary. From the fit, the energy difference of ten percent of the initial energy value is used to find the corresponding difference.

3 Creating the foil/washer sandwich

3.1 Creating the washer

Materials Used

- shimstock - Type 316 Stainless Steel Rolls—Soft (Annealed) Temper
- Arch Punch Carbon Steel 3/8”
- Arch Punch Carbon Steel 13/16”
- stencil of arch punches
- A large block of metal

To create a stencil of the arch punches, draw an inner circle of 3/8 inches centered within a circle of 13/16 inches. This is to ensure that the washer created is as symmetrical as possible

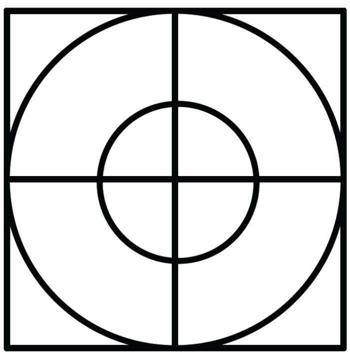

Figure 2: Punch Stencil created for precision

Tape the stencils on top of the uncut shimstock so that it does not move throughout the procedure.

Place the shimstock on a hard yet pliable surface. A block of metal provided the sharpest cut hole, however it deteriorated the arch punch quickly. A self healing cutting board worked as well, however, the arch punch pushed the shimstock into the board and warped the shimstock.

Align the smaller arch punch with the inner circle. Using a rubber mallet, with a heavy swing, pound the arch punch until the smaller hole is punched out.

Align the larger arch punch with the remaining circle (the larger one), swiftly and sturdily punch the hole out too. Although the order of the hole punch does not matter, it is recommended that the smaller hole is cut out first so that the shimstock continues to keep the larger stencil in place.

The washer punched out will most likely have a curve. To flatten the washer, place it under a block of metal larger than the diameter of the washer and on a flat, sturdy surface. Hammer the top of the block. Be sure to keep the washer away from the edge of the block so it won't stick out, or it will crease the washer. File away any sharp edges to prevent accidental foil tearing.

3.2 Punching the foil

The foil was shipped in a packet containing plastic covers and a thin sheet of paper. Only the large arch punch is necessary for cutting the foil.

Make sure the arch punch is sharp. We purchased a new arch punch for the foils. Punch out the foil with both the plastic and the paper holding the foil in place. Do the punching on top of the self healing cutting board. Carefully remove the foil from the punch and store the foils until they are ready to be spot welded. The foils proved to be extremely delicate when one of them tore solely from wind resistance; be sure to transfer them slowly.

3.3 Spot-welding the sandwich

Materials Used

- Type 316 Stainless STeel shims ordered from McMaster-Carr
- handmade washers from section 3.1
- tweezers with a softened edge
- Spot welding machine
- Safe Container for the sandwhich

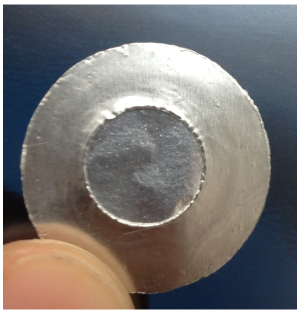

Figure 3: Completed Washer Foil Sandwich

Prior to spot welding , the handmade washers and the pre-made washers need to be cleaned in a sonicating bath since the foil cannot be put into the bath and they are to be installed in ultra high vacuum. Make a sandwich of the handmade washer, the cut foil and a pre-made SS316 washer. Make sure that they are lined up and that there is a way to pick up the foil with the tweezers by the base and top of the foil. To make 'blunted' tweezers, cut and tape two tiny sheets of paper onto the tip of the tweezers. Set the spot welding machine to between 400 and 500 Volts. Keeping the sandwich in place with the tweezers, spot weld the visible part of the washer, avoiding the foil. When the visible part is sufficiently spot welded, use the spot welder to keep it in place, without applying the extra pressure to actually spot weld, and grab a different part of the washer with the tweezers. Spot weld the remaining area. The completed foil sandwiches were stored securely in the foil packaging and left unopened until installation.

4 Results and Measurements used for the experiment

Table 1: Thickness of foil compositions resulting in a 10% energy loss of various particles

Foil Composition	3 MeV particle	1 MeV particle	0.8 MeV particle
Aluminum	12.61 μm	2.29 μm	2.37 $\times 10^{-2} \mu$m
Gold	———	———	———
Beryllium	———	———	———
Iron	5.35 μm	1.03 μm	1.02 μm
Molybdenum	5.15 μm	1.03 μm	———
Tungsten	3.91 μm	0.86 μm	———

Table 2: Energy loss (MeV) of various energies through various thicknesses of Aluminum

Thickness (μm)	3 MeV	1 MeV	0.8 MeV
0.4	9.20×10^{-3}	1.72×10^{-2}	1.39×10^{-1}
0.8	1.84×10^{-2}	3.46×10^{-2}	2.84×10^{-1}
1.5	2.77×10^{-2}	5.21×10^{-2}	5.52×10^{-1}
2.0	3.46×10^{-2}	6.54×10^{-2}	7.57×10^{-1}
3.0	3.69×10^{-2}	6.98×10^{-2}	———
6.0	4.39×10^{-2}	8.31×10^{-2}	———

Table 3: Energy loss of 3, 1, and 0.8 MeV particles through 1.5 μm Aluminum foil

Initial Energy (MeV)	Energy Loss (MeV)
3.0	3.46×10^{-2}
1.0	6.53×10^{-2}
0.8	5.52×10^{-1}

Table 4: Energy loss of 3, 1, and 0.8 MeV particles through 0.8 μm Aluminum foil

Initial Energy(MeV)	Energy Loss (MeV)
3.0	1.84 $\times 10^{-2}$
1.0	3.46 $\times 10^{-2}$
0.8	2.82 $\times 10^{-1}$

5 Conclusion

A 0.8 μm thick Aluminum foil was chosen for the experimental setup utilized at MAST. Commercially- sold foil thicknesses of Gold, Beryllium, Molybdenum and Tungsten would not allow for the detection of ($^3H^+$) particles and were therefore no longer under consideration. Due to convenience and pricing, Aluminum was chosen over Iron. The thicknesses resulting in a 10% energy loss for Aluminum are 12.61 μm for the proton, 2.28 μm for the triton, and 0.23 μm for the helium-3 particle. The energy loss for the proton, triton, and helium-3 particles are 0.63%, 3.46% and 35.3% respectively for the 0.8 μm thick Aluminum foil.

There are several improvements that can be made upon the creation of the foils. The particular method used to create the washers blunted several arch punches. This is largely due to the hardness of the material used to serve as a punching mat. However, if the material was too soft, the washer deformed greatly. To improve upon this, wood is highly suggested to serve as a punching mat as it is soft enough to not dull the arch punch, yet firm enough to avoid deforming the washers. If it is necessary to punch a great amount of washers, it might be wise to invest in a mechanical arch punch machine. Additionally, while the makeshift tweezers used to hold the washer/foil sandwich in place worked well, in the future, it is suggested to research how companies handle thin materials and invest in those tools as well.

6 References

1. Energy Loss with Heavy Charged Particles (Alphas). Publication. ORTEC, n.d. Web.

2. Knoll, Glenn F. Radiation Detection and Measurement. New York: Wiley, 1979. Print.

3. Leo, William R. Techniques for Nuclear and Particle Physics Experiments. N.p.: Spring-Verlag, 1987. Print.

4. M.J. Berger, J.S. Coursey, M.A. Zucker and J. Chang, Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions, NISTIR 4999, ASTAR Program, NIST Physics Laboratory, http://www.nist.gov/physlab/data/star/index.cfm.

5. Nucleonica. European Atomic Energy Community, n.d. Web.