Title
DISTRIBUTION IN ENERGY LOST BY CHARGED PARTICLES IN PASSING THROUGH TEEN ABSORBERS

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Mary Kraft, Nolan Mangelson and George Rogers

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ABSTRACT

A method for calculating the distribution in energy lost by charged particles in passing through thin absorbers is given. It is applicable to protons and heavier charged particles with kinetic energies from approximately 0.01 to 10 times their rest energies. The energy loss in the absorber may not exceed one-tenth of the kinetic energy of the particle for this method to be valid.

Curves giving the variation in full width at half maximum of the energy distribution as a function of absorber thickness for protons, deuterons, tritons, He³ particles and α-particles of various energies in silicon and other elements are included.
I. INTRODUCTION

The distribution in energy lost by charged particles in passing through thin absorbers is an important consideration in many aspects of nuclear physics and chemistry. For example, this distribution limits the energy resolution that can be obtained in nuclear spectroscopy using silicon detectors with inert windows. In particle identifiers using $\Delta E$ and $E$ semiconductor detectors, energy straggling in the $\Delta E$ detector can be a large source of error. Straggling in targets and absorber foils in an accelerator experiment can also limit the energy resolution obtained.

Symon has advanced a method of calculating the energy distribution resulting from charged particles in passing through thin absorbers.\footnote{1} This method is particularly suited to cases where the probability that a particle will lose a large fraction of its kinetic energy in a single collision is small, as in the case of collisions of protons or heavier particles with electrons. Only energy losses due to collisions with electrons are taken into account in this method.

II. CALCULATION OF ENERGY DISTRIBUTION

This method of calculating the energy distribution of particles after passing through matter is based on the fact that the energy loss of a particle in matter is a statistical phenomenon. The collisions that are responsible for this loss are independent events; therefore, particles of a given kind and energy do not all lose exactly the same amount of energy in traversing a given thickness of material. In the case of a proton or heavier particle interacting with electrons, the statistical fluctuations are comparatively small because the average transfer of energy in each individual collision is
small and the number of collisions necessary to cause any appreciable energy change is correspondingly large. If the thickness of matter traversed is sufficiently small so that the average energy loss is only a small fraction of the initial energy, it is called a thin absorber.

The theory and the derivations of the equations used in these calculations will not be discussed here. They can be found in Symon's original work. Only the equations and graphs necessary for the calculations will be given.

This method is applicable to protons or other charged particles with kinetic energies from approximately 0.01 to 10 times the rest energies of the particles. Two additional conditions must be fulfilled for the method to be valid.

a. \[ \xi \geq 5 \bar{Z} \]

where \( \xi \) is an energy proportional to the thickness of the absorbing material (the formula for \( \xi \) will be given below), and \( \bar{Z} \) is the average ionization potential of all the atomic electrons in the absorbing material and is approximately equal to 13.5 Z eV.

b. Either \( \bar{\Sigma} \leq 1/10 \frac{E_k^0}{E_k} \) or \( \lambda_w \geq 1 \)

where \( \bar{\Sigma} \) is the mean energy loss in thickness \( t \), \( E_k^0 \) is the kinetic energy of the incident particle (MeV) and \( \lambda_w \) is the weighted skewness of the differential distribution in energy loss, which will be found below.

The first step in the calculation of the energy distribution is to calculate the fractional total energy, \( W \).

\[ W = \frac{E_k^0 + \mu}{\mu} \]

where \( \mu \) is the rest energy of the incident particle (MeV). Using this value, \( \beta^2 \),
the square of the velocity, \( v \), of the incident particle in units of \( c \), the velocity of light, is calculated.

\[
\beta^2 = \left( \frac{v}{c} \right)^2 = 1 - \frac{1}{\beta^2}
\]

then \( \xi \) and \( 1/c \) are calculated using the following equations.

\[
\xi = \frac{2\mu_e}{\beta^2} (0.150 \frac{Z}{A} Z_1^2 \rho t)
\]

and

\[
1/c = \frac{1 + \frac{\mu e}{\mu W}}{\frac{\xi}{2\mu_e}}
\]

where \( Z, A, \rho \) and \( t \) are the atomic number, atomic weight, density \( (\text{g/cm}^2) \) and the thickness \( (\text{cm}) \) respectively of the absorbing material, \( \mu_e \) is the rest energy of an electron \( (\text{MeV}) \) and \( Z_1 \) is the atomic number of the incident particle.

Using the values of \( 1/c \) and \( \beta^2 \) found above, the values for the parameters \( \lambda_w \) and \( b \) are found using Figs. (1) and (2).

Then the value of \( \sigma_w \), a parameter with the dimensions of energy which is related to the width of the distribution function, is calculated.

\[
\sigma_w = b \xi
\]

Using Fig. (3), the two values of \( \left( \Sigma - \Sigma_p \right)/\sigma_w \) which correspond to the curve at half minimum are found. Here, \( \Sigma \) is the energy loss, \( \Sigma_p \) is the most probable energy loss, \( F(\Sigma) \) is the energy loss distribution and \( F \) is a normalization factor.

The full width at half maximum (FWHM) in MeV of the energy distribution resulting from the particles passing through the absorber is given by the formula.
FWHM = \left[ \frac{\sum E}{\sigma_w} \right]_{\text{high}} - \left[ \frac{\sum E}{\sigma_w} \right]_{\text{low}}

In a similar way, the entire distribution can be obtained using Fig. (3). The distribution curves of Fig. (3) are accurate to within about plus or minus one-fourth of the distance between them when used with the proper parameters.

A simplified equation for calculating the FWHM of the distribution in the limit of low energies has been suggested by Mollenauer, Wagner and Miller. A comparison of values obtained using their equation and the method described above has shown the simplified equation to give unsatisfactory results.

III. ENERGY STRAGGLING IN VARIOUS ABSORBERS

Plots have been made using the above method for calculation of the FWHM of the energy distribution as a function of thickness of absorber for protons, deuterons, tritons, He\(^3\) particles and \(\alpha\)-particles of various energies in silicon. Plots are also included for various particles and energies in germanium, carbon, vanadium and gold. (See Figs. 4-21.) Table I lists the densities and equivalent thicknesses for the absorbing materials.

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The contributions of Dr. Bernard Harvey, Dr. Howel Pugh, Dr. Joseph Cerny and Dr. Richard Pehl to this work are gratefully acknowledged.

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REFERENCES


Table I. Densities and equivalent thicknesses. 4

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<th>Densities</th>
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<td></td>
<td>$\rho$</td>
<td>1 micron</td>
<td>1 mil</td>
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<tr>
<td>Au$^{197}$</td>
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<td>49.0 mg/cm$^2$</td>
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<tr>
<td>V$^{51}$</td>
<td>5.69</td>
<td>0.569</td>
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FIGURE CAPTIONS

Figure 1. Symon's plot for the parameter $\lambda_w$ as a function of $\beta^2$ and $1/c$.

Figure 2. Symon's plot for the parameter $b$ as a function of $\beta^2$ and $1/c$.

Figure 3. Symon's plot for the determination of the energy distribution.

Variations of FWHM with absorber thicknesses

Figure 4. 25 MeV protons in Si and Ge.

Figure 5. 25 MeV protons in $^{12}C$, $^{51}V$, and Au$^{197}$.

Figure 6. 50 MeV protons in Si and Ge.

Figure 7. 50 MeV protons in $^{12}C$, $^{51}V$, and Au$^{197}$.

Figure 8. 25 MeV deuterons in Si, Ge, and Au$^{197}$.

Figure 9. 60 MeV deuterons in Si, Ge, and Au$^{197}$.

Figure 10. 22 MeV tritons in Si.

Figure 11. 20 MeV He$^3$ particles in Si and V$^{51}$.

Figure 12. 35 MeV He$^3$ particles in Si and V$^{51}$.

Figure 13. 25 MeV $\alpha$-particles in Si and Ge.

Figure 14. 25 MeV $\alpha$-particles in $^{12}C$, $^{51}V$, and Au$^{197}$.

Figure 15. 40 MeV $\alpha$-particles in Si.

Figure 16. 60 MeV $\alpha$-particles in Si and Ge.

Figure 17. 60 MeV $\alpha$-particles in $^{12}C$, $^{51}V$, and Au$^{197}$.

Figure 18. 85 MeV $\alpha$-particles in Si.

Figure 19. 100 MeV $\alpha$-particles in Si and Ge.

Figure 20. 100 MeV $\alpha$-particles in $^{12}C$, $^{51}V$, and Au$^{197}$.

Figure 21. 130 MeV $\alpha$-particles in Si.
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.
Fig. 7.
Absorber thickness (mg/cm$^2$)

Fig. 8.
Fig. 9.
Fig. 10.
Fig. 11.
Fig. 12.
Fig. 13.
Fig. 14.
Fig. 15.
Fig. 16.
Fig. 17.
Fig. 18.
Fig. 19.
Fig. 20.
Fig. 21.
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