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FLUCTUATIONS OF ENERGY LOSS IN SEMICONDUCTOR DETECTORS

Howard D. Maccabee, Mudundi R. Raju, and Cornelius A. Tobias

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Summary

Significant fluctuations and broadening of the energy-loss spectrum are expected in certain cases of passage of charged particles through "thin" detectors. Experimental measurements of this phenomenon (by use of lithium-drifted silicon detectors) are in good agreement with the rigorous theory of Vavilov, as tabulated by Seltzer and Berger.

Introduction

When an energetic charged particle passes through a detector, it loses energy by a series of collisions with the electrons of the detector material. In first approximation, the probability of an energy loss $e$ in a single electronic collision is proportional to $e^{-2}$. Thus collisions resulting in a large energy transfer to an electron are relatively infrequent compared with small-energy-loss collisions. Although they are relatively infrequent, the large-energy-loss collisions account for a significant proportion of the total energy transfer. In a "thin" detector (one in which the total energy lost is small compared with the kinetic energy of the particle), the probable number of large-energy-loss collisions may be so small that the random statistical fluctuations in this number result in significant fluctuations in the energy lost in this mode, and thus fluctuations in the total energy transfer occur. This phenomenon has been theoretically investigated by Landau, 1 Symon, 2 Vavilov, 3 and others, and is often called the Landau effect. Experimental investigations have been carried out by Gooding and Eisberg, 4 Rosensweig and Rossi, 5 and Grew, 6 all of whom compared their data with the theory of Symon.

In Vavilov's exact treatment, the dimensionless parameter $\kappa$ is introduced, and it is shown that for $\kappa < 1$ the fluctuations are large, while for $\kappa > 1$, the fluctuations are negligible and the normal Gaussian shape of the total energy loss distribution is valid:

$$\kappa = 0.150 \frac{(SZ)^2}{(A)} \left(1 - \frac{\beta^2}{\beta^2}ight),$$

where

- $S$ = thickness of detector in g/cm$^2$,
- $Z$ = atomic number of detector material,
- $A$ = atomic weight of detector material,
- $\beta = speed$ of incident particle + speed of light in vacuum;

$\kappa$ may be thought of as a measure of the ratio of the total energy loss to the maximum possible energy loss in a single collision, i.e., an estimate of the number of large-energy-loss collisions suffered by the particle in passage.

The purpose of our investigation is to verify experimentally the Vavilov theory over the whole range of $\kappa$, and to determine its implications in semiconductor detector studies of energetic charged-particle beams. We will not treat other sources of energy loss fluctuations, such as channeling.

Method

In a previous paper 7 we have described the advantages of lithium-drifted silicon semiconductor detectors for this work, the general method used, and the results of several preliminary experiments. In the preliminary experiments we found significant deviations between the theoretical energy-loss distributions and those which we measured. We surmised that these discrepancies were due to edge effects in our detectors, i.e., the sensitive thickness is slightly less at the edges than at the center area, and some particles pass through at the edges without "seeing" the full detector thickness. In order to correct this geometrical problem in this series of experiments, we used another smaller detector as a coincidence gate to eliminate all pulses due to particles passing through the edges of the "analysing" detector. A block diagram of the experimental setup is shown in Fig. 1.

Results

We have performed a series of ten experiments at the 184-inch synchrocyclotron, using 730-MeV protons and 910-MeV alpha particles, covering the range of $\kappa$ from 0.0033 to 1.02. The results of three typical experiments are shown in Figs. 2, 3, and 4. Figure 2 is a plot of the data from 730-MeV protons passing through a silicon detector with depletion thickness 0.66 g/cm$^2$, yielding $\kappa = 0.0338$. The solid curve is a plot of the Vavilov theoretical distribution as computed from the program of Seltzer and Berger. 8 Figure 3 is a plot of the data from 910-MeV alpha particles passing through a detector of thickness 0.413 g/cm$^2$, yielding $\kappa = 0.638$. Figure 4 is a plot of the data from 730-MeV protons passing through a detector of thickness 0.0645 g/cm$^2$, yielding $\kappa = 0.0033$. 


Discussion

Agreement between measured energy-loss distributions and the theory is good in Figs. 2 and 3. Figure 2 is typical of what may be called the Landau spectrum, occurring at small \( \kappa \) values. The distribution is very asymmetrical, with a long high-energy-loss "tail" and a broad peak around the most probable energy loss, which is significantly less than the mean energy loss. Figure 3 is typical of intermediate values of \( \kappa \); i.e., \( \kappa = 1 \). The distribution is very similar to the "expected" Gaussian, but with slight asymmetry, and the most probable energy loss is slightly less than the mean.

In Fig. 4 there is considerable disagreement between experiment and theory; the measured distribution is much broader than the theoretical. Upon closer examination, however, we find that the full width of the theoretical distribution at half maximum (FWHM) is 29 keV, while the inherent FWHM resolution of the measuring system at room temperature is approximately 40 keV. Adding these two quantities in quadrature yields an expected value of 49.5 keV; this is in good agreement with the measured value. Thus physical resolution limitations on our present measuring system prevent direct verification of the theory in this region of very small \( \kappa \). Experiments are now in progress, using a system with improved resolution gained by cooling the detectors and using special low-noise electronics as developed by Goulding et al. 9

Work is continuing on several other aspects of this problem. We are working on the tabulation of our findings into a form which will be convenient and useful to future experimenters.

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References

Figure Captions

Fig. 1. Block diagram of experimental setup.

Fig. 2. Energy-loss probability,
730-MeV protons in 0.66-g/cm$^2$ silicon;
$\kappa = 0.0338$.

Fig. 3. Energy-loss probability,
910-MeV $\alpha$ particles in 0.413-g/cm$^2$
silicon; $\kappa = 0.638$.

Fig. 4. Energy-loss probability,
730-MeV protons in 0.0645-g/cm$^2$ silicon;
$\kappa = 0.0033$. 
BLOCK DIAGRAM OF EXPERIMENTAL SYSTEM
Fig. 2
Vavilov theory

Experiment for $\kappa = 0.638$

Most probable energy loss

Average energy loss

Fig. 3
Vovilov theory for $\kappa = 0.0033$

Most probable energy loss

Average energy loss

Fig. 4
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