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# CYCLOTRON TESTS TO DETERMINE THE RESPONSE OF SOLID-STATE DETECTORS TO PROTONS OF ENERGIES 50 TO 160 MEV FOR USE IN A PROTON SPECTROMETER


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Summary

Tests were conducted at the 160-Mev Harvard cyclotron on fully depleted solid-state detectors. This work was done in conjunction with a feasibility study of a proposed proton spectrometer consisting of two dE/dx detectors in a coincident telescope arrangement that can analyze protons over an energy range 0.5 Mev to greater than 200 Mev. The surface barrier sensors were exposed to protons of energies varying from 50 to 160 Mev to determine the response of these sensors to high-energy protons. The two major parameters to be determined were the most probable energy loss in the detector by protons of energy E and the resolution of the energy loss distribution. The results of the tests will be compared with the Symon treatment of the Landau effect. The proposed proton spectrometer will also be discussed briefly.

Introduction

The tests were conducted in conjunction with a feasibility study of a proposed proton spectrometer. The study itself is the result of the need for versatile radiation sensors that are reliable and lightweight to monitor the radiation hazards that exist in outer space. Local radiation fields in interplanetary space impose some restrictions on space travel to both spacecraft components and man. Thus, sensors that can aid in expanding our understanding of the existing radiation environment are in great demand. The study was directed upon a relatively new sensor, the semiconductor radiation detector, because it shows promise of meeting the above requirements.

Solid-State Detector

The basic detector for the proposed proton spectrometer, which will be discussed presently, is the solid-state detector. The particular sensors considered for the system were fully depleted surface barrier detectors with a depletion depth of 1 millimeter. The pulse amplitude from the solid-state sensor is directly proportional to the energy lost by the charged particle in the depletion region, that is, one electron-hole pair is produced for every 3.5 ev (electron volts) of energy deposited. For particles that are completely absorbed within the silicon wafer the pulse amplitude is linearly proportional to the incident particle energy. The amplitude is nonlinear for charged particles that pass completely through the sensor - the greater the energy of the particle the less the energy absorbed by the wafer. Figure 1 shows energy loss as a function of proton energy for a typical fully depleted detector. For normally incident protons the maximum pulse amplitude produced in the sensor would be from a proton whose energy is such that it enters the front surface and is just stopped within the back surface. As shown in figure 1, for a 0.1-cm depletion depth, a 13-Mev (million electron volt) proton would just penetrate the back surface. As is evident from the figure, for a particular pulse amplitude there are two possible values of the energy of the incident proton. For example, a 1.5-Mev proton produces approximately the same amplitude as an 85-Mev proton. This ambiguity can be dissolved by means of the proton spectrometer.

Proposed Spectrometer

The proton spectrometer consists of two solid-state detectors arranged in a coincidence telescope configuration. The telescope is bidirectional in the sense that it is open-ended with $0.3\pi$ steradian solid angles as shown in figure 2. A particle that passes through both detectors must be within this solid angle. At larger incident angles particles can pass through only one unit. The brass shield was designed to stop protons less than 100 Mev.

The ambiguity, stated above, is dissolved with this system. The majority of the protons that pass completely through one sensor and are within the acceptance solid angle will at least penetrate the second detector. Coincident pulses, thus, from the detectors will indicate the passage of a proton greater than 12 Mev. An anticoincident pulse indicates the presence of a proton whose energy is $\leq 12$ Mev in detector #1 or 12 to 18 Mev in detector #2.

As shown in figure 2, an aluminum absorber is placed in front of detector #2. The thickness of the absorber is such that it is equivalent to detector #1 as a stopping agent for protons. Thus, the energy loss $\Delta E$ of protons of energy $E_o$ passing through detector #2 from both ends of the telescope are the same. The latter detector is utilized for pulse height analysis and detector #1 is used for coincident gating. At the same time it is possible to obtain meaningful data by sampling the detectors separately.

The bidirectionality of the system serves two purposes. First, erroneous results would occur from protons entering from the back of a "unidirectional" telescope. Heavy or bulky shielding would be required to minimize this factor. (The criterion for evaluating the importance of this effect is dependent upon the steepness of the slope of the expected proton spectrum.) The proposed system would eliminate this effect completely. Second, pulses from each sensor can be analyzed separately and compared. Proper analysis can lead to the separation of meaningful data from "background" counts - counts resulting mainly from particles entering the detectors through the shield.

The instrument can be utilized as a simple proton counter or as a proton spectrum analyzer over a large energy range. When used as a counter, one energy threshold is set by a fixed discrimination level. As an analyzer, several discrimination levels can be commutated to give a number of energy windows that subdivide the spectrum over a possible range of 0.5 to 200 Mev or greater. Figure 3 is a



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block diagram of one of several possible electronics packages considered that utilizes commutated discriminator levels that feed a binary counter storage system.

## Theory

Two basic parameters need to be determined experimentally in order to evaluate the extent of the usefulness of the proton spectrometer, that is, in regard to energy window widths and the overall meaningful energy range of the spectrometer. The upper limit to the energy range of the telescope is dependent upon the slope beyond 12 Mev of the curve in figure 1 and upon the pulse amplitudes from the detector at high proton energies. The width of the commutated energy windows is dependent upon the resolution of the energy-loss distribution as a function of proton energy. Thus, the two parameters to be considered are the most probable energy loss and the resolution of the distribution curve.

When a monoenergetic stream of high-energy protons passes through the silicon wafer, the energy loss by each proton is not the same but varies about the most probable energy loss. A typical distribution is shown in figure 4. The predominant mechanism by which a proton loses energy to the silicon wafer is through inelastic collisions with bound electrons in the atom.

Landau[2] has given a rigorous treatment of the problem of determining the energy-loss distribution for charged particles. The problem was to derive the distribution function

$$f(E') = f(s, E_O, E') \tag{1}$$

defined as the probability that a particle of initial energy $E_O$ after passing through some material of thickness $x$ will have lost an amount of energy $E'$ - when given the probability function

$$w(\epsilon) = w(T, \epsilon) \tag{2}$$

that a particle of energy $T$ will suffer a collision resulting in an energy loss $\epsilon$. Landau derived the general differential-integral equation

$$\frac{\partial f(E')}{\partial x} = \int_0^\infty \left[w(E' - \epsilon)f(E' - \epsilon) - w(\epsilon)f(E')\right]d\epsilon \tag{3}$$

Landau simplified the problem considerably by assuming that

$$w(E' - \epsilon) = w(\epsilon) \tag{4}$$

since the ionization losses are small compared to $T_O$. As a result, we have

$$\frac{\partial f}{\partial x} = \int_0^\infty w(\epsilon)\left[f(E' - \epsilon) - f(E')\right]d\epsilon \tag{5}$$

By applying the Laplace transformation

$$g(p) = \int_0^\infty f(E')e^{-pE'}dE' \tag{6}$$

and

$$f(E') = \frac{1}{2\pi i}\int_{-i\infty+\sigma}^{+i\infty+\sigma} e^{pE'}g(p)dp \tag{7}$$

from the inversion theorem[3] to equation (5) Landau obtained for the distribution function the expression

$$f(E') = \frac{1}{2\pi i}\int_{-i\infty+\sigma}^{+i\infty+\sigma} e^{pE'-x\int_0^\infty w(\epsilon)\left(1-e^{-p\epsilon}\right)d\epsilon} dp \tag{8}$$

For the function $w(\epsilon)$ Landau selected from Rutherford scattering theory the classical expression

$$w(\epsilon) = \frac{\alpha}{\epsilon^2} \tag{9}$$

for which

$$\alpha = \frac{2\pi Ne^4\rho}{m_o V^2}\left(\frac{Z}{A}\right) \tag{10}$$

where

| | |
|---|---|
| N | Avogradro's number |
| e | charge of electron |
| $m_o$ | mass of electron |
| V | velocity of charged particle |
| $\rho$ | density of material |
| Z | atomic number of material |
| A | atomic weight of material |

Landau had the integral in equation (8) solved on a computer; his solution applies to cases such that

$$\frac{T_{max}}{\alpha x} \gg 1 \tag{11}$$

where $T_{max}$ is the largest possible energy transfer between the charged particle and an atomic electron. Since in the energy range 50 to 160 Mev for protons and for a 1-millimeter depletion depth the left side of equation (11) varies from 0.62 to 5.7, his solution is not applicable to our problem.

Through a more thorough treatment Symon[4,5] obtained for the probability distribution the more general expression

$$f(E') = \frac{1}{2\pi i}\int_{-i\infty+\sigma}^{+i\infty+\sigma} e^{pE'+\int_0^x\left[\tilde{w}(p,x)-\tilde{w}(0,x)-pX\right]dx} dp \tag{12}$$

where $\tilde{w}(p,x)$ and $\tilde{w}(0,x)$ are Laplace transforms of $w(\epsilon)$ and $X$ is a function of $x$. Landau's equation (eq. (8)) is a special case of equation (12).

For the function $w(\epsilon)$ Symon used the relations

$$w(\epsilon) = \left.\begin{aligned} &\frac{\alpha}{\epsilon^2}\left(1 - \beta^2 \frac{\epsilon}{E_{max}}\right) \qquad && \eta \lesssim \epsilon \lesssim E_{max} \\ &= 0 && \epsilon > E_{max} \end{aligned}\right\} \qquad (13)$$

where $\beta$ is the ratio of the velocity of the charged particle to the velocity of light and $\eta$ is large compared with the ionization potentials of the atomic electrons. The nonvanishing value of $w(\epsilon)$ comes from Bhabha's quantum mechanical expression.[6] Through a rather lengthy treatment of the integral in equation (12), Symon obtained a solution which is applicable to charged particles that satisfy the conditions:

$$\left.\begin{aligned} &M_p \gg M_e \\ &0.01E_p \lesssim T \lesssim 10E_p \end{aligned}\right\} \qquad (14)$$

where

$M_e$ rest mass of electron

$M_p$ rest mass of particle

$E_p$ rest energy of particle

$T$ kinetic energy of particle

Symon's solution will be used for comparison with the experimental data.

## Experiment

A surface barrier detector with a 0.98-millimeter depletion depth was exposed to the proton beam from the 160-Mev cyclotron at Harvard University. The sensor with a front surface diameter of 0.315 inch was centered behind a brass collimator with a 0.0625-inch aperture. The collimator (1.3 inches long with 2-inch sides) was alined parallel with the proton beam in order to minimize proton scattering within the collimator. With a reversed bias of 300 volts the detector was fully depleted. It was connected to a charge-sensitive preamplifier-amplifier system. The amplifier output was fed to a 512-channel pulse height analyzer. The readout instrumentation consisted of an oscilloscope, a typewriter, and an x-y recorder. The detector-analyzer system was calibrated utilizing a $Bi^{207}$ beta source. The average resolution (FWHM) of the 974-kev conversion electron peak was found to be 29 kev.

The 160-Mev cyclotron beam was degraded by means of absorbers to desired energy levels in seven steps down to the 50-Mev level. Based upon previous calibrations it was assumed that the energy spread at half the maximum peak energy of the degraded beam varied linearly from ±0.75 Mev at 160 Mev to ±5.0 Mev at 50 Mev. At each energy level spectra were obtained of energy losses by protons passing through the detector. At the 160-Mev level the detector bias voltage was varied in 50-volt steps down to zero voltage.

## Results

With the proton energy range 50 to 160 Mev three parameters were extracted from the experimental data - the most probable energy loss, the resolution of the distributions, and the energy loss as a function of detector bias voltage. Data points from the experiment of the most probable energy loss are plotted in figure 5. The data are compared with the following expression for the most probable energy loss $E_p$ from Landau's theory:

$$E_p = \alpha x\left[\ln \frac{2m_o V^2}{\left(1 - \beta^2\right)I^2} \alpha x - \beta^2 + j\right] \qquad (15)$$

For the value of $j$, Symon's function, which is dependent upon $\alpha$, $x$, and $E_{max}$, was used rather than 0.37 as given by Landau. The experimental points are accurate to within ±25 kev.

The percent resolution of the energy-loss distribution as a function of proton energy is plotted in figure 6. The resolution is defined as:

$$R = \frac{E_p - \Delta E}{E_p}\,(100\text{ percent}) \qquad (16)$$

where $\Delta E$ is the energy spread of the full width at half the maximum height of the peak. The probable cause of the divergence of the experimental data at high energies from data calculated from Symon's theory is the production of degraded protons resulting from proton scattering in the collimator. These lower energy protons deposit larger quantities of energy in the depletion region than do the unscattered protons (see fig. 1). As a result, the slope of the curve on the high-energy side of the energy-loss peak becomes less steep, as shown in figure 4. The theoretical curve was calculated from Symon's theory and the second curve in figure 4 is the result of curve fitting the experimental data with a 7070 computer program utilizing Chebychev polynomials.[7]

It is more profitable, therefore, to examine the half width at half maximum resolution on the low-energy side of the peak which is plotted in figure 7. In this case the results are in good agreement with theory. The error bars for each experimental point in the figures enclose the 95-percent confidence interval for the true mean value. The data are not corrected for the energy spread of the proton beam.

The energy loss in the detector as a function of bias voltage for 160-Mev protons is shown in figure 8. The depletion depth is a function of the applied voltage as seen in the equation:[1]

$$x^2 = \rho\mu eV\left(1.326 \times 10^{15}\right) \qquad (17)$$

where

$x$ depletion depth in microns

ρ resistivity in ohm-centimeters

μ mobility of majority carrier

e charge of electron

V applied voltage

In this case the mobility is equal to 1200 $cm^2$/volt-sec and the resistivity is equal to 14,100 ohm-cm. The values of $x$ in equation (17) were substituted into equation (15) to give the theoretical curve in figure 8. The experimental data are somewhat higher than theoretical data. The experimental points are estimated to be accurate to within ±25 kev.

## Conclusions

Proton energy-loss distributions from the experiment in the range from 50 to 160 Mev appear to be in agreement with Symon's theoretical treatment of the problem. Symon's distribution curves can, therefore, be applied in data reduction of information extracted from the spectrometer. Further investigation of these distributions is required to determine the practical limits of the energy ranges for the proposed spectrometer. It appears feasible to design a proton spectrometer that could have several energy windows extending up to and beyond 200 Mev.

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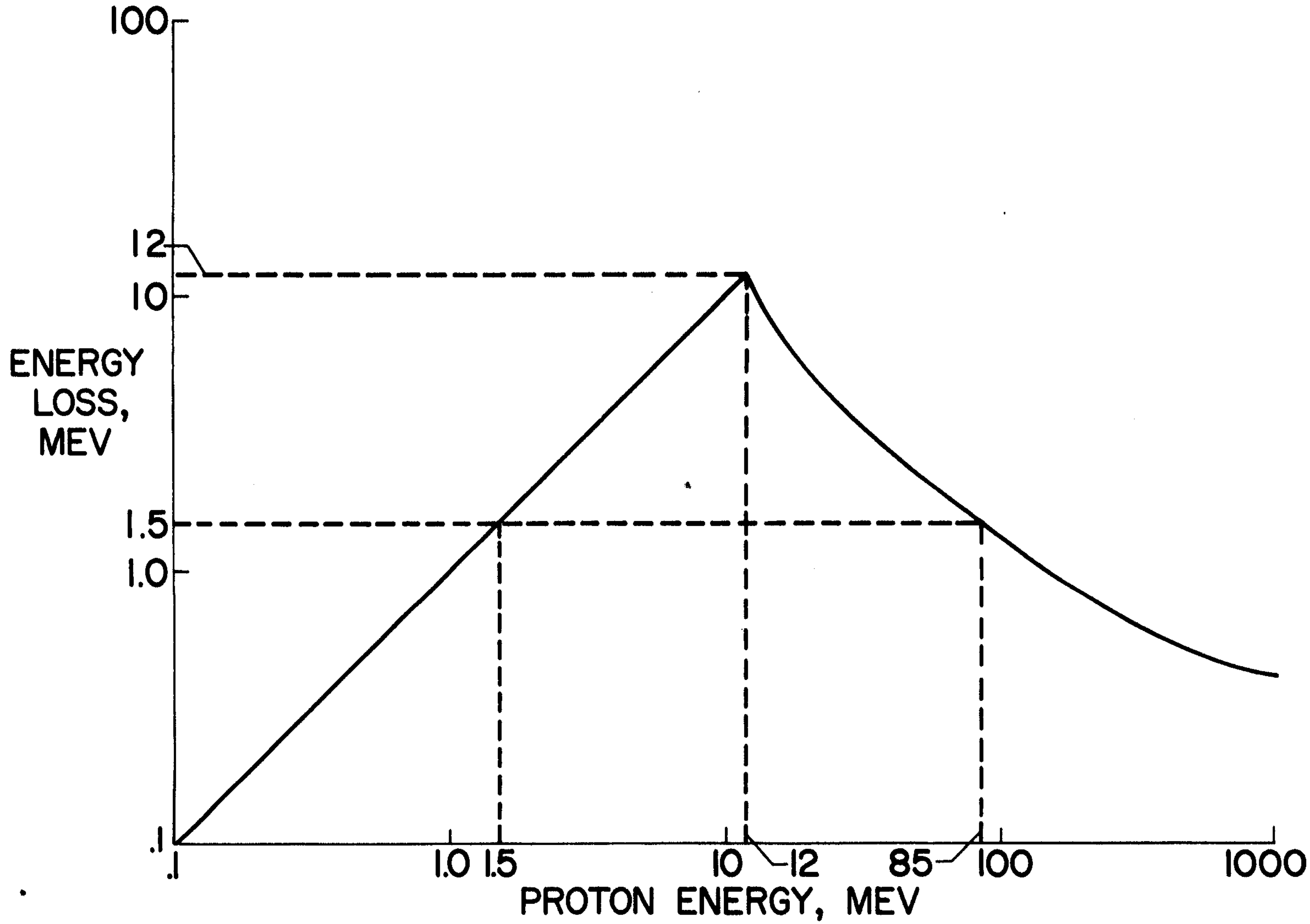


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Figure 1.- Energy loss in 0.1 cm depletion depth as a function of energy of normally incident protons.

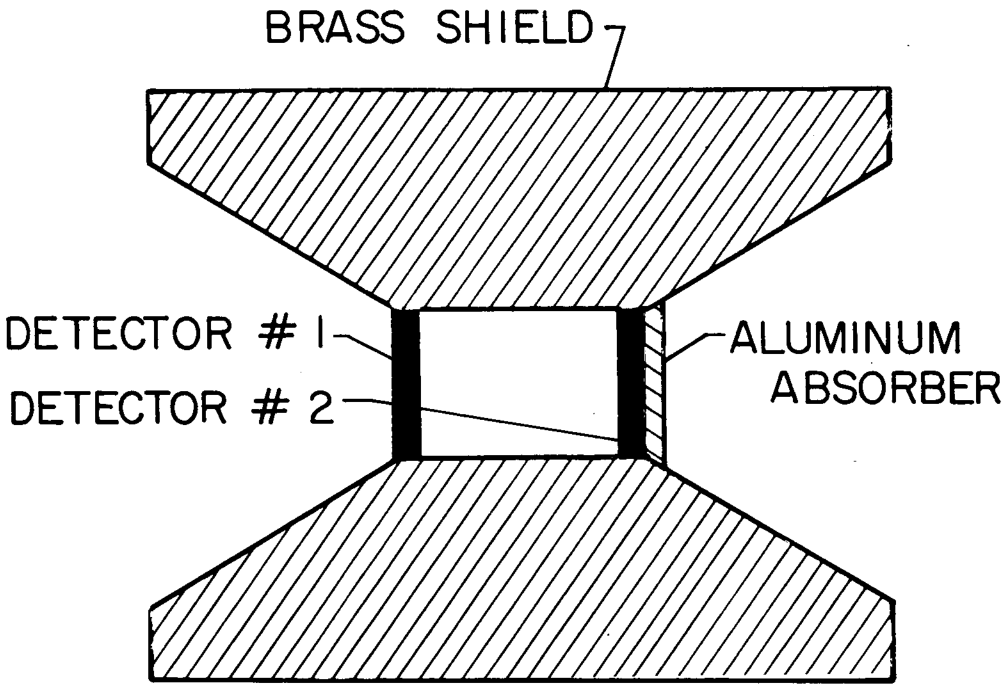


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Figure 2.- Cross-sectional view of proton telescope.

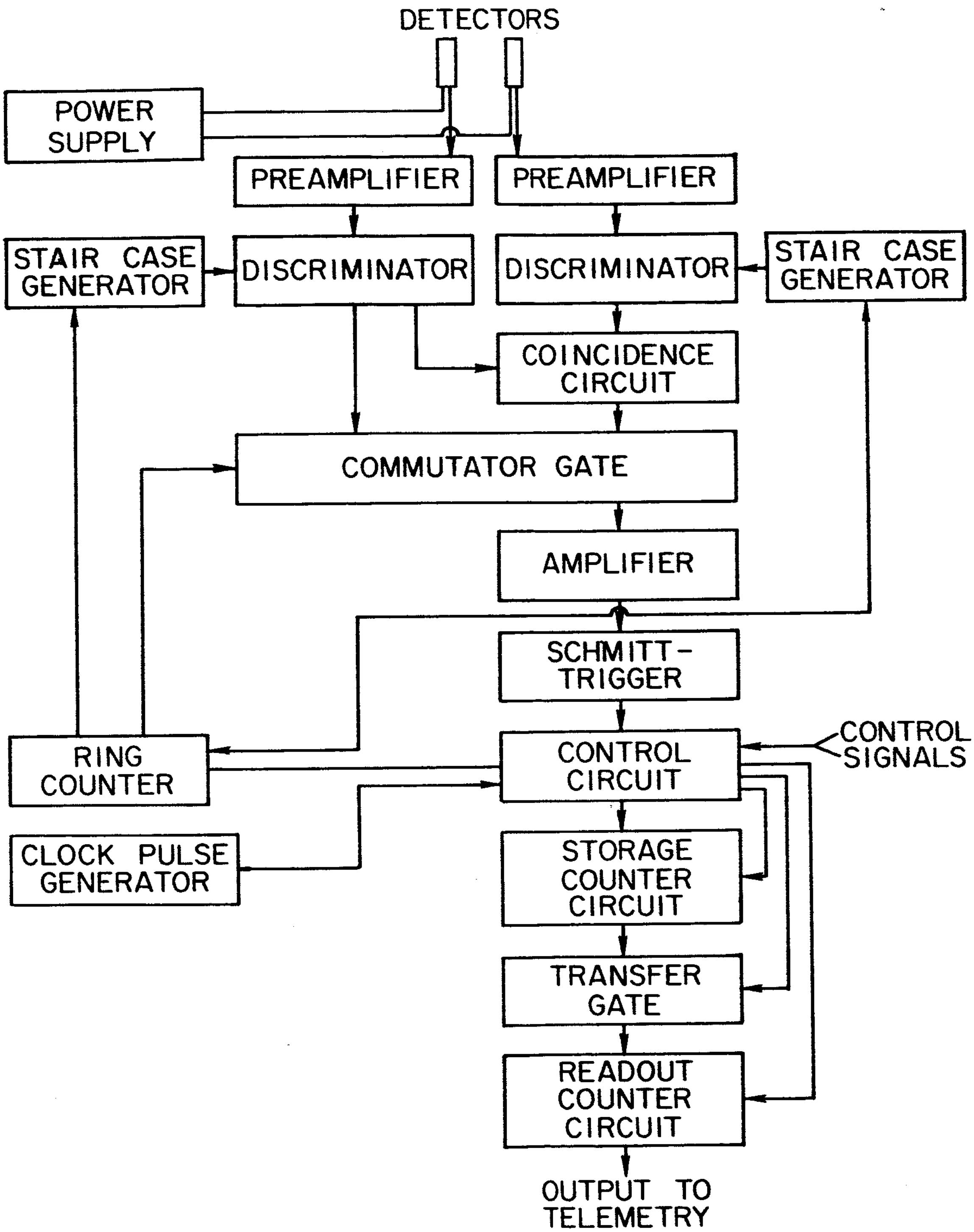


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Figure 3.- Block diagram of a possible electronics package for proton spectrometer.

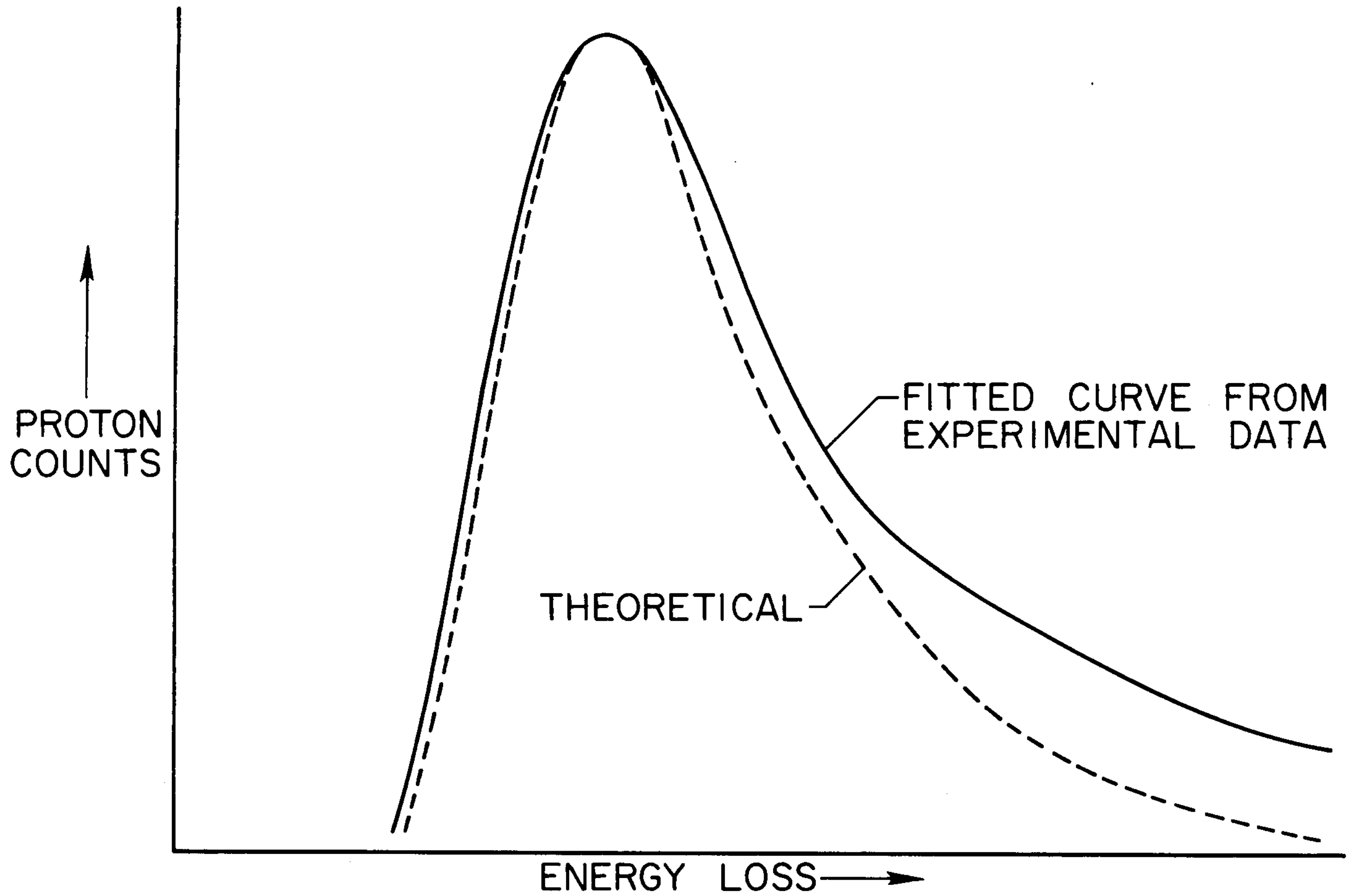


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Figure 4.- Energy loss distribution for 160 Mev protons normally incident upon 0.1 cm detector.

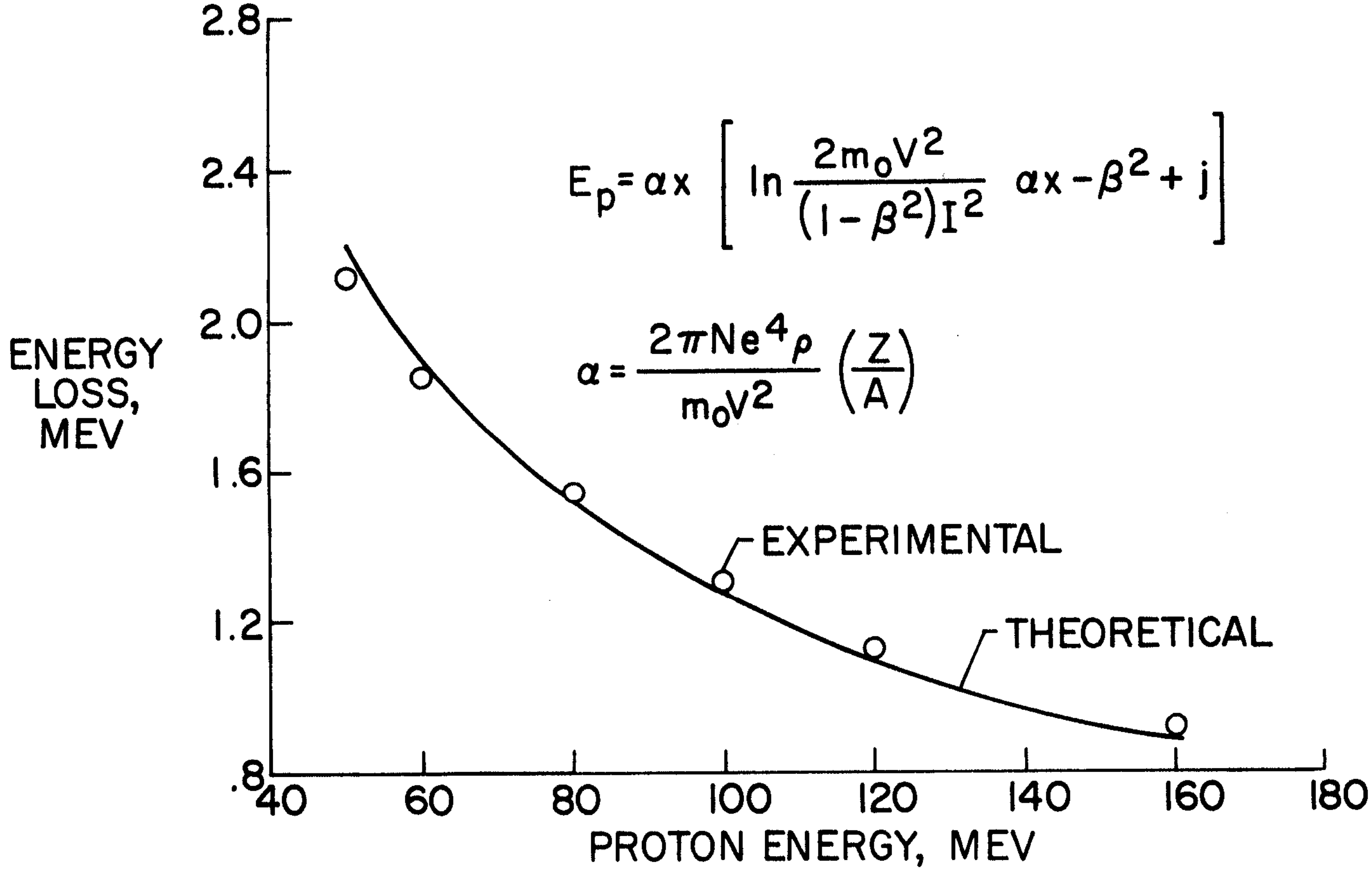


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Figure 5.- Most probable energy loss in the 0.1 cm silicon wafer by normally incident protons.

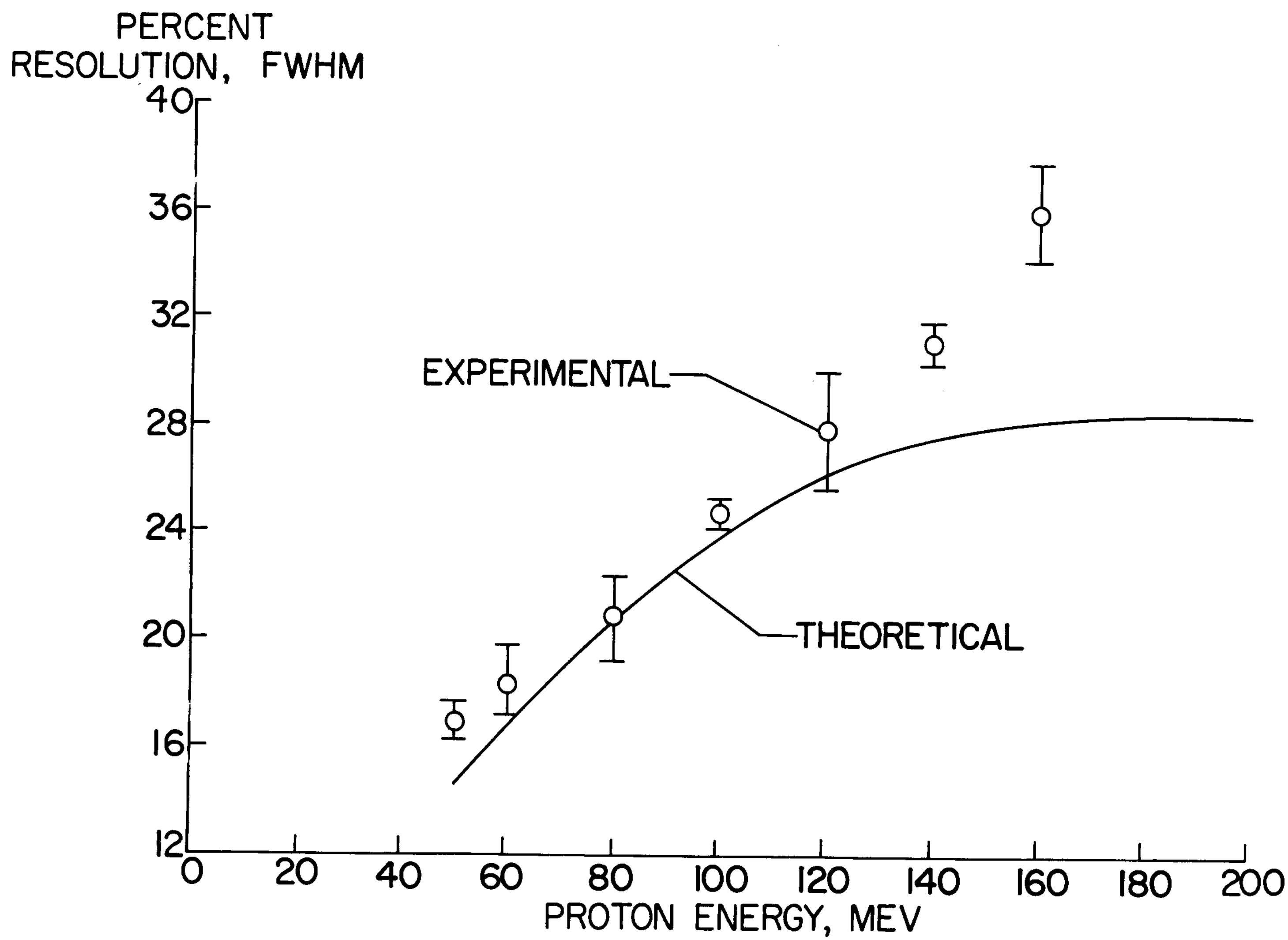


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Figure 6.- Full width at half maximum (FWHM) resolution of energy loss distributions for protons.

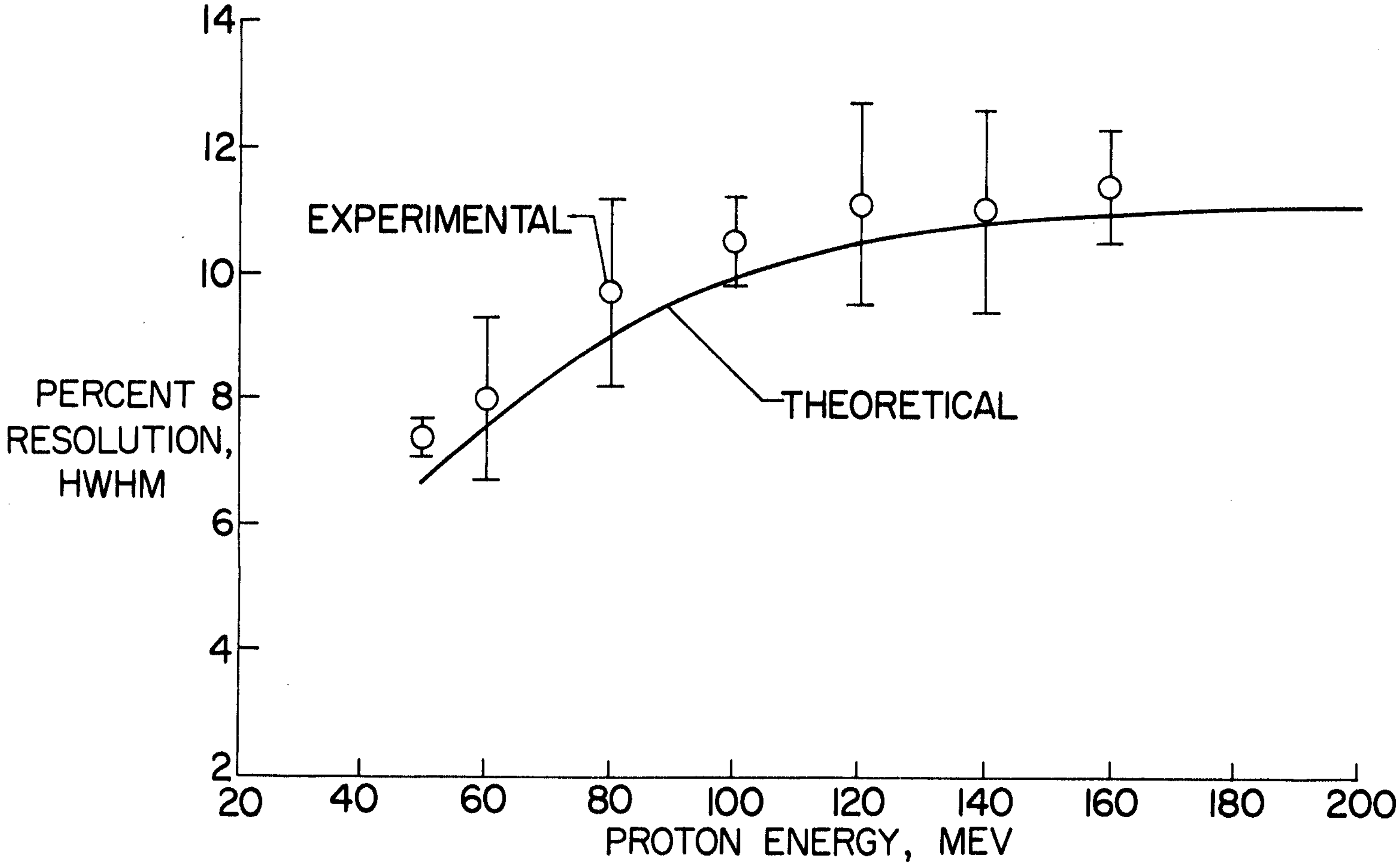


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Figure 7.- Half width at half maximum (HWHM) resolution of energy loss distributions for protons.

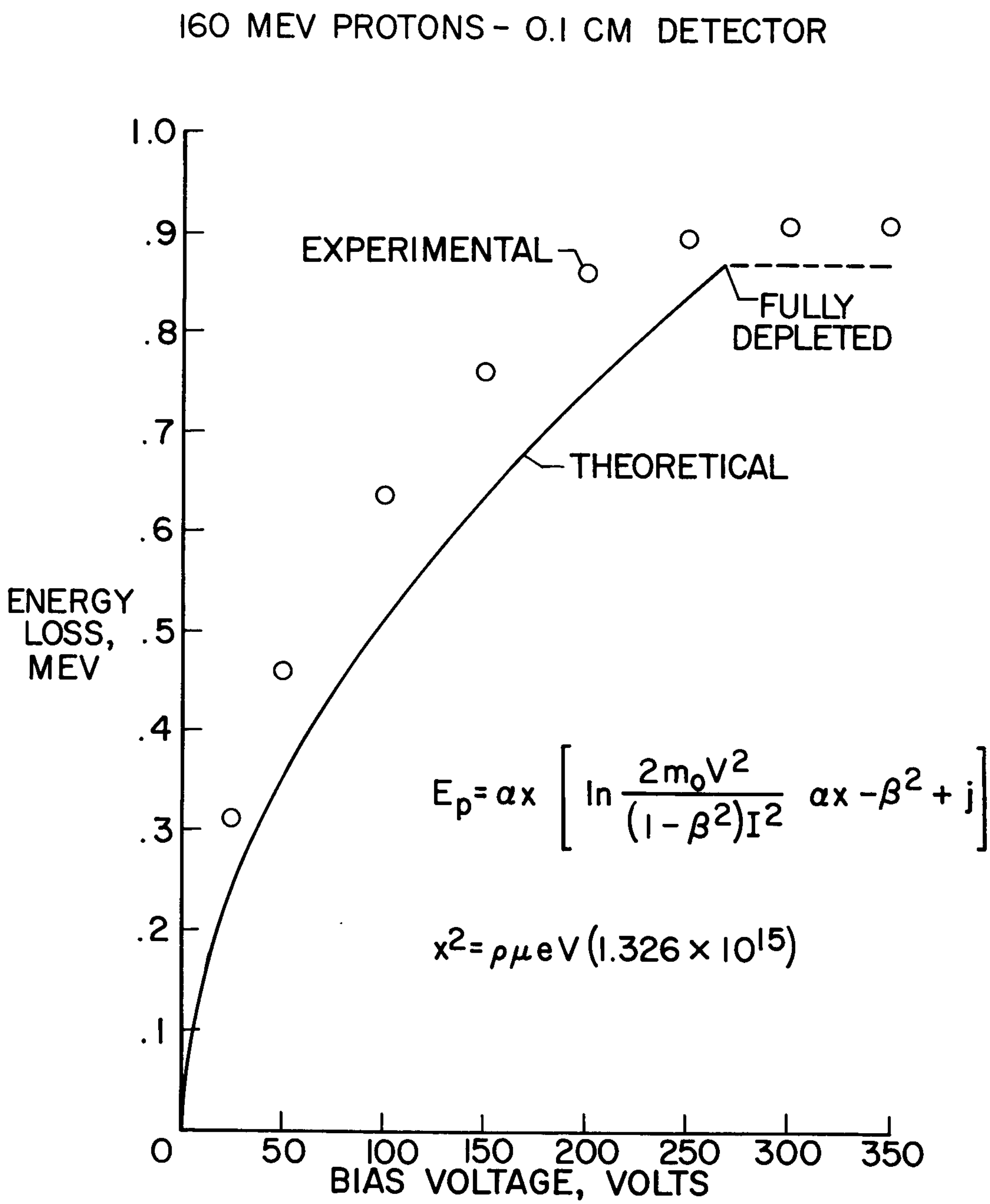


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Figure 8.- Energy loss for 160 Mev protons in 0.1 cm detector as a function of detector bias voltage.

NASA-Langley, 1964