TABLE I. Comparison of measurements on germanium.

Experimenters	Benedict, Shockley	Lax, Zeiger, Dexter	Crawford, Stevens	Present
Temperature	160–300°K	4°K	65–300°K	200°–300°K
Electron mass	$0.6\,m_0$	$0.12\,m_0$	$0.15\,m_0 \pm 0.02\,m_0$	$0.10\,m_0 \pm 0.05\,m_0$ $0.08\,m_0 \pm 0.04\,m_0$
Hole mass	$\approx 0.45\,m_0$	$0.27\,m_0$	$0.23\,m_0 \pm 0.03\,m_0$	$0.29\,m_0 \pm 0.05\,m_0$ $0.32\,m_0 \pm 0.05\,m_0$

work by Abeles and Meiboom[13] on magnetoresistance in germanium. They find agreement between their theory and the experimental results obtained by Pearson and Suhl[14] at 77°K and 300°K on n-type germanium if they assume the eight ellipsoidal model and a mass ratio of 20. The mass ratio obtained in the resonance experiments was 17.

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Direct Measurement of the Effect of Polarization on Energy Loss*

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The energy losses suffered by 15.7-Mev electrons in traversing samples of about one gram per cm² of absorber in gas and solid form have been measured. Two pairs of absorbers have been used; perfluorocyclobutane gas and its polymer, tetrafluoroethylene resin, "Teflon," and chlorotrifluoroethylene gas and its polymer, "Kel-F" plastic. The losses measured were of the order of one Mev and the resolution of the apparatus made possible an accuracy of 20 kev. The measured losses compared with theoretical predictions are as follows: Teflon—gas 1.33 Mev by experiment and 1.33 Mev by theory, solid 1.27 Mev by experiment and 1.24 Mev by theory; Kel-F—gas 1.29 Mev by experiment and 1.33 Mev by theory, solid 1.09 Mev by experiment and 1.11 Mev by theory.

INTRODUCTION

THERE has been a long series of discussions and experiments presented and performed in the study of ionization losses of charged particles in passing through material media.[1–12] Many of these have pursued, in particular, the effect of the density of the medium upon the ionization loss suffered by a charged particle in traversing that medium. In most cases this change in ionization loss (density or polarization effect) has been observed indirectly. It was the purpose of the present work to observe the difference directly by passing 15.7-Mev electrons through equal numbers of grams/cm² of gases and solids of the same chemical composition.

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The experimental arrangement and procedure followed were almost identical with those employed in the measurement of ionization loss and straggling of fast electrons.[12] For future reference the paper describing that work will be referred to as G.M.H. The experimental arrangement is shown in Fig. 1. The absorbers, both solid and gaseous, were contained in a brass cylinder 16 in. long and 2 in. in diameter. The ends of the cylinder were sealed with 5-mil foils of "Mylar" film. The entrance end was stopped down to a 1-in. diameter circular hole. The exit end was at the center of the scattering chamber and contained a horizontal

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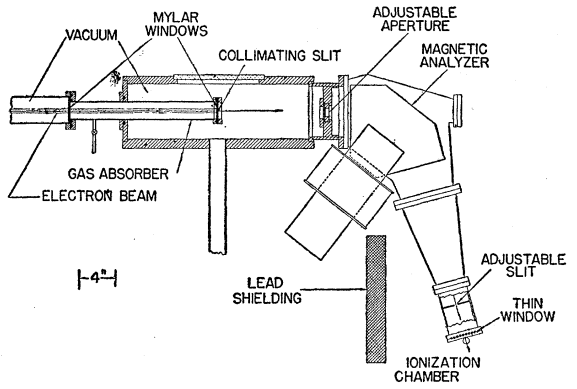

FIG. 1. Side view of absorber and analyzer.

gold slit $\frac{1}{16}$ in. high and $\frac{1}{2}$ in. long. The gaseous samples occupied the entire volume of this cylinder, while the solids were distributed evenly along its length in sections approximately $\frac{1}{32}$ in. thick. From the exit slit through the magnetic analyzer to the ionization chamber and vibrating reed detector, the experimental arrangement was identical with that described in G.M.H. The calibration and resolution of the equipment was also the same as in G.M.H.

ABSORBERS

In order to have an error of the order of 2 percent in the measured energy losses, it was necessary to use samples with a thickness of about 1 g/cm^2. Gases of high molecular weights had to be found to give thicknesses of this order in the available space at a convenient temperature and at a pressure which could be contained by relatively thin windows. Two different gas-solid pairs of absorbers were found which satisfy this criterion: perfluorocyclobutane gas (molecular weight $=200$) and its polymer, tetrafluoroethylene resin (Teflon); and chlorotrifluoroethylene gas (molecular weight$=116.5$) and its polymer, Kel-F plastic. These gases have a behavior which departs significantly from the ideal gas law in the region investigated. Thus in order to measure their thicknesses in g/cm^2, the length of the container and the density of the gas under the conditions of the experiment were accurately measured.

Perfluorocyclobutane is composed of fluorine and carbon in the ratio 2:1; chlorotrifluoroethylene is composed of fluorine, carbon, and chlorine in the ratio 3:2:1. A study made of the effect of chemical structure on stopping power[13] indicates that the effect of the chemical bonding involved in polymerization is negligible in the results of this experiment.

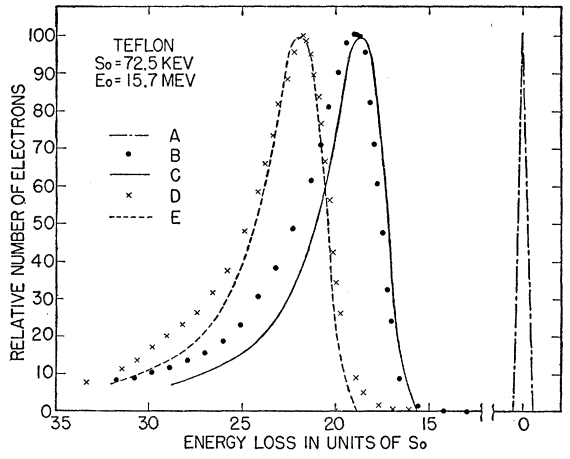

FIG. 2. Energy distributions of: (A) unobstructed electron beam; (B) experimental points for solid Teflon; (C) theoretical prediction for solid; (D) experimental points for Teflon's gaseous monomer; (E) theoretical prediction for gas.

THEORY

Theoretical work done by Landau[2] and others and described in G.M.H. gives for the most probable energy loss:

$$\Delta_p = S_0\left[\ln\frac{2mc^2\beta^2 S_0}{(1-\beta^2)I^2} - \beta^2 + 0.37\right], \qquad (1)$$

where $S_0 = 2\pi e^4 nt/m\beta^2c^2$; m, e are the electron charge and mass, β is velocity of particle in units of the velocity of light, c; n=number of electrons/cc; and I is the mean ionization potential for the absorbing medium.

In this paper the I values used are calculated in accordance with the method described by Sternheimer.[6] This gives for Teflon $I_T=120$ ev and for Kel-F, $I_K=140$ ev. The energy loss in chemical compounds has been treated as if they were mixtures of the proper proportions of disassociated atoms. The mean ionization potential has been found to be, quite closely, directly

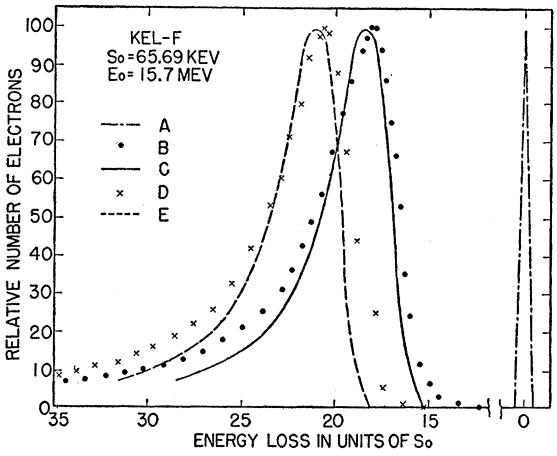

FIG. 3. Energy distributions of: (A) unobstructed electron beam; (B) experimental points for solid Kel-F; (C) theoretical prediction for solid; (D) experimental points for Kel-F's gaseous monomer; (E) theoretical prediction for gas.

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proportional to the atomic number, Z, and is commonly expressed in the form $I=KZ$. For the chemical compounds of this experiment, it may be written

$$I=KZ_{\text{eff}}, \tag{2}$$

where the effective Z of the compound is given by:

$$\ln\frac{1}{Z_{\text{eff}}^2}=\sum_i \frac{n_i}{n}\ln\frac{1}{Z_i^2}. \tag{3}$$

Here n_i and Z_i are the electron density and atomic number of the ith component of the compound. The values of I calculated above then correspond to $K=14.6$ for Teflon and $K=14.0$ for Kel-F. These numbers are somewhat higher than would be expected from the work of Bakker, Mather, and Segrè[14,15] as corrected by Sternheimer.[16]

Equation (1) does not take into account the shielding effects occurring in condensed media as a result of the polarization of the medium in the region of the path of the charged particle. This phenomenon has been treated theoretically by many authors.[3–6] All agree in one essential; that as the energy of the particle increases, its rate of energy loss asymptotically approaches a limiting value. As shown in G.M.H. this value is independent of the constant, I. The asymptotic value of the most probable energy loss is:

$$\Delta_{pc}=S_0[19.43+\ln(D/\rho)], \tag{4}$$

where ρ=volume density of the absorber in g/cm³ and D=surface density of the absorber in g/cm².

In between the region of no density effect and that of the asymptotic value of energy loss, the energy loss can be calculated by methods given by Sternheimer.[6] The solid and gas samples used in this work have density ratios of about 100. For the electron energy used, the gases both lay in the region of very small density effect, the solids in the region of asymptotic energy loss.

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TABLE I. Theoretical and observed values of energy losses and straggling distribution widths in gaseous and solid samples.

					Expt.		Theory	
		D g/cm²	ρ g/cm³	S_0 Mev	$\Delta_{\frac{1}{2}}$ Mev	Γ/S_0	$\Delta_{\frac{1}{2}}$ Mev	Γ/S_0
F_2C	Solid	0.9832	2.09	0.0725	1.27	4.7	1.24	3.98
	gas	0.9003	0.0218	0.0664	1.33	4.4	1.33	3.98
F_3C_2Cl	Solid	0.8889	2.13	0.0657	1.09	4.7	1.11	3.98
	gas	0.9135	0.0221	0.0675	1.29	4.6	1.33	3.98

DISCUSSION OF RESULTS

As described in G.M.H., the experimental data are more sensitive to the position of the "upper-half point" than to that of the peak of the straggling distribution. The "upper-half point" is the point having one-half of the peak intensity value and lying on the high-energy (steep) side of the peak. The shape of the Landau distribution is such that this point is related to the most probable value by the equation, $\Delta_{\frac{1}{2}}=\Delta_p-1.58S_0$. In Table I are given the unnormalized experimental results and corresponding theoretical values. The full width of the straggling distribution at $\frac{1}{2}$ intensity, Γ, is a parameter useful in considerations of the shape of the distribution and is also presented below. It was impossible to obtain identical gas and solid sample thicknesses. Therefore, for convenience, in plotting the results the parameter used is $\Delta_{\frac{1}{2}}/S_0$, since this has only a very small dependence on sample thickness. A small correction, $+\ln(D_{\text{solid}}/D_{\text{gas}})$, has been applied to normalize the thickness of each gas sample to that of its solid. The experimental results and corresponding theoretical curves, normalized in this way, are presented in Figs. 2 and 3.

TABLE II. Theoretical and observed values of the reduction in ionization loss by the density effect, for the two pairs of absorbers used.

	$\delta(\Delta_{\frac{1}{2}}/S_0)$	
	Observed	Theory
F_2C	2.8±0.4	3.0
F_3C_2Cl	2.6±0.4	2.6

The agreement of theoretical and experimental energy losses is well within the accuracy of the data. A systematic broadening of the experimental straggling distributions is observed. This was not true of the work described in G.M.H. and is thought to arise from electrons scattered from the walls of the brass sample container.

A comparison of the observed and calculated density effect, $\delta(\Delta_{\frac{1}{2}}/S_0)$, is made in Table II. The indicated errors are based on a 20-kev uncertainty in the absolute measurement of each energy.

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