Specific Ionization by High-Energy Electrons*

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The average specific ionization produced by electrons of energies ranging from 1 to 34 Mev was measured in H_2, He, and N_2 at atmospheric pressure. The measurements were made by sending a collimated beam of electrons through an ionization chamber into a Faraday cup. At minimum ionization the number of ion pairs per cm (probable specific ionization) was (7.56 ± 0.09), (6.15 ± 0.08), and (53.2 ± 0.7) at N.T.P. in the three gases, respectively. If these results are compared with the theory of energy loss, the values of W (the average number of electron volts to produce an ion pair) are calculated to be (37.8 ± 0.7), (44.5 ± 0.9), and ($34.8^{+0.9}_{-0.7}$) for the respective gases. The corresponding minimum values of the total specific ionization are calculated to be (9.19 ± 0.18), (7.55 ± 0.16), and ($61.6^{+1.2}_{-1.5}$) ion pairs per cm. The relativistic increase in ionization from minimum to 34 Mev agrees with the calculated increase in energy loss to within 1 percent for N_2, but in He and H_2 the increase in ionization is less than the predicted increase in energy loss. The effect is more certain in H_2 where an increase of about 3.3 ± 0.7 percent in W is observed. Calculations indicate that this effect may be due to the production of Čerenkov radiation which fails to produce ions in the gas.

INTRODUCTION

THE ionization of gases by moving charged particles serves as the basic mechanism of so many instruments that the phenomenon has been the subject of considerable investigation. With the increasing availability and use of high-energy electron beams, both the need for and the opportunity to make detailed checks on the predictions of the relativistic theory arise. The experimental work in the relativistic region has usually employed the cosmic radiation as a source of particles and cloud chambers, proportional counters, or Geiger-Müller counters as detectors. As a result of this work, the relativistic increase in both the primary and total ionization has been demonstrated, good evidence for the reality of the density effect has been accumulated, and the fluctuations in the ionization produced in proportional counters have been measured. The articles by Bethe and Ashkin[1] and West[2] discuss the basic features of the work done up to 1953. Related experiments have shown that the density effect modifies the relativistic increase in the light output of scintillators,[3] in the grain density of nuclear emulsions,[4] and in the energy loss itself.[5]

This paper is a report on measurements made with ionization chambers on electrons of energies from 1 to 34 Mev. (Similar experiments employing electrons of 10 to 20 Mev have been reported by Ovadia *et al.*[6]) The measurements were limited to the average ionization produced by a large number of electrons, a restriction which sacrifices any knowledge of fluctuations in ionization but permits high accuracy in the determination of the average result. A comparison of the measurements with theory is further restricted by the fact that the ion chamber is unable to distinguish between primary and secondary ionization and thus measures nearly the total ionization. Even though the theory of primary ionization is fairly well developed, it is practically impossible to apply to the multiple processes where energetic secondaries produce not only ions but further secondaries capable of producing ions. It has therefore been the usual practice to compare "total" ionization with the theory of energy loss and to define a quantity W, the average energy expended in making an ion pair.

The theory of energy loss of charged particles in traversing matter has been developed over a number of years beginning with Bohr and including important contributions by Bethe, Bloch, Fermi, and many others.[1] The most recent calculations including all known important effects have been made by Sternheimer[7,8] and Budini.[9] The result for the total energy loss of electrons can be written

$$-\frac{dE}{dx}=\frac{2\pi ne^4}{mv^2}\left[\ln\frac{mv^2T}{I^2(1-\beta^2)}+\frac{9}{8}-\beta^2-\delta\right]. \qquad (1)$$

An expression which is more useful than (1) for ionization-chamber measurements is the energy loss excluding the loss in collisions where an energy greater than T_0 is given to the secondary electron. This result, sometimes called the probable energy loss, is given by

$$-\left(\frac{dE}{dx}\right)_{\text{probable}}=\frac{2\pi ne^4}{mv^2}\left[\ln\frac{2mv^2T_0}{I^2(1-\beta^2)}-\beta^2-\delta\right]. \qquad (2)$$

The symbols used in (1) and (2) have their conventional meanings except for the following: n is the num-

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[1] H. A. Bethe and J. Ashkin, *Experimental Nuclear Physics.* I, edited by E. Segrè (John Wiley and Sons, New York, 1953).
[2] D. West, *Progress in Nuclear Physics*, III, edited by O. Frisch (Pergamon Press, London, 1953), Chap. 2.
[3] T. Bowen (to be published).
[4] J. R. Fleming and J. J. Lord, Phys. Rev. **92**, 511 (1953).
[5] Goldwasser, Mills, and Hanson, Phys. Rev. **88**, 1137 (1952).
[6] Ovadia, Laughlin, Beattie, and Henderson, Phys. Rev. **88**, 165 (1952); see also J. S. Laughlin, *Physical Aspects of Betatron Therapy* (Charles C. Thomas, Springfield, 1954), p. 81.
[7] R. M. Sternheimer, Phys. Rev. **88**, 851 (1952).
[8] R. M. Sternheimer, Phys. Rev. **91**, 256 (1953).
[9] P. Budini, Nuovo cimento **10**, 236 (1953).

ber of electrons per cm^3 of the medium; T is $\frac{1}{2}$ the energy of the incident electron; $T_0 \ll T$; I is the geometric mean excitation potential of the atoms of the material; and δ is the correction due to density effect.

At the gas pressures and beam energies used in the present experiments, the density effect is of almost negligible importance, and the value of δ is expected to be nearly zero. The experiments provide a check on the relativistic increase given by $1/(1-\beta^2)$ in the logarithm part of Eq. (2).

APPARATUS

A. Electron-Beam Formation and Measurement

The primary electrons were accelerated in the Stanford 35-Mev linear accelerator.[10] It was possible to produce electrons of any desired energy from 1 to 35 Mev by suitable adjustments of the rf power and frequency. The electrons were collimated and energy analyzed by a system of slits and a 12° magnetic deflection. The output beam was about $\frac{1}{8}$ in.$\times\frac{1}{2}$ in. in cross section with a spread in momentum of less than ± 1.5 percent. The *B-versus-I* curve for the magnet was measured to 0.2-percent accuracy with a rotating coil. An absolute energy calibration of the detecting system was made at 18.7 and 10.6 Mev by measuring the $Cu^{63}(\gamma,n)Cu^{62}$ and the $C^{12}(\gamma,n)C^{11}$ reaction thresholds. The error in the absolute energy measurement is estimated as ± 2 percent.

The collimated beam of electrons was passed through an ion chamber and into a Faraday cup. A drawing of the Faraday cup with the small ion chamber in position is shown in Fig. 1. The ion and electron currents were integrated simultaneously by accumulating the charges on condensers (polystyrene dielectric condensers manufactured by the John E. Fast Co., Chicago) having very high leakage resistance. The condensers were incorporated in slide-back circuits which used electrometer tubes as null detectors. One of the slide-back circuits was manual, the other was electronic. Either circuit could be used with either the ion chamber or the Faraday cup. The accumulated voltage on the condensers was read to high precision with a potentiometer. The relative values of the condensers were measured with an accuracy better than 0.3 percent by depositing

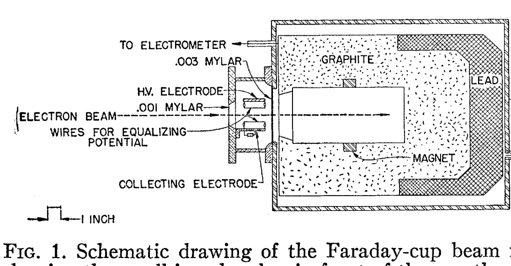

FIG. 1. Schematic drawing of the Faraday-cup beam integrator showing the small ion chamber in front of the mouth of the cup.

[10] Post, Shiren, and Brown, Stanford University High-Energy Physics Laboratory Report HEPL-11 (unpublished); also R. F. Post and N. S. Shiren, Rev. Sci. Instr. (to be published).

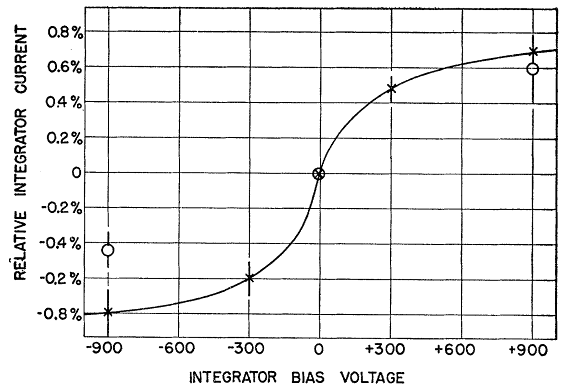

FIG. 2. Integrator response relative to monitor response as a function of the bias voltage applied to the Faraday cup.

the same fixed amount of charge onto them, then sliding back and measuring the voltage as usual.

The performance of the Faraday cup as a measuring instrument was tested in several ways: (1) Using the ion chamber operated under fixed conditions as a beam monitor, the radiation escaping out the back and sides of the cup was measured with thimble-type roentgen meters. At 35 Mev, the escaping radiation was easily measurable, but even under the most conservative assumptions that the ionization in the thimble was caused by minimum ionization particles of a single sign and all traveling in one direction, the number of escaping secondaries could amount to only 0.25 percent of the number of electrons in the primary beam. (2) The possibility of low-energy secondary particles entering or leaving the mouth or walls of the cup was checked by comparing the integrator-to-monitor response as a function of bias voltage applied to the cup. The crosses of Fig. 2 show a bias curve obtained with the configuration about as shown in Fig. 1. The bias curve does not tell the origin of the secondaries but the change from $-V$ to $+V$ is a measure of the total number of secondaries of energy less than V electron volts. Curves of this type were taken at primary energies ranging from 2 to 35 Mev, and no dependence of their shape on primary energy was observed. The magnitude of bias effect was influenced by the compositon and position of the foil which separated the ion-chamber gas from the integrator vacuum. However, not all the effect is due to this foil because even with very large distances between the foil and the integrator entrance an unexplained effect of about ± 0.4 percent for ± 900-v bias remained. The absolute measurements of specific ionization were taken with the configuration shown in Fig. 3, and the measured bias points are shown as circles in Fig. 2. With these conditions it is believed that the error due to secondaries of energy less than 900 v is less than ± 0.6 percent. Errors due to higher-energy secondaries which are knocked from the foils are not revealed by the bias curve. A calculation of the number of these for the configuration shown in Fig. 3 was made by using the Møller

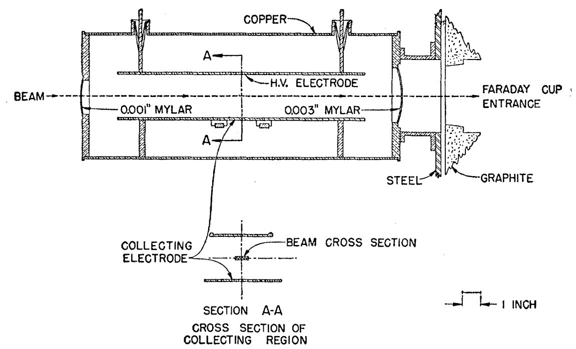

FIG. 3. Configuration of the large ion chamber showing the relative position of the Faraday cup.

formula for the cross section and empirical electron-range data to evaluate the probability of escape of the secondary. The calculated correction to the integrator current was (0.43±0.3) percent.

B. Ionization-Chamber Measurements

Reliable performance of the ion chamber depends on the effective length remaining constant and on the absence of recombination of ions. The chambers used in this experiment had a collecting field perpendicular to the beam, and the effective length of the chamber changed if the potential of the collector plate relative to the guard ring changed. In practice, this effect was either avoided by continuously sliding back to keep the collector at constant potential or by experimentally evaluating the effect and applying a correction. The resulting errors were less than 0.2 percent.

The effect of ion recombination was evaluated experimentally by measuring the ratio of ion charge to integrator charge as a function of the primary beam intensity and extrapolating the resulting curves (straight lines) to zero intensity. Any effects of space charge were also eliminated by this procedure. Curves of this sort were taken for each energy and each gas. Examples taken with the small chamber filled with N_2 are shown in Fig. 4. The reproducibility of these curves indicates the stability of the measurements. In most cases, the zero-intensity intercept was determined with an accuracy better than ±0.5 percent. The effect of secondaries, produced in the entrance and exit foils, on the operation of the ion chamber was evaluated theoretically and shown to be negligible. The reason is that the only secondaries of numerical importance are of too low an energy to reach the sensitive region of the chamber.

The ion chamber shown in Fig. 3 had long guard plates to insure a uniform field in the collecting region. The applied voltage was 7000 v, giving a collecting field of 1100 v/cm. The effective length of the chamber was taken to be the center-to-center distance between the gaps separating the collecting plate from the guard plate (2.499 in.). With this long chamber, the scattering of primary electrons out of the beam by the entrance foil or by the gas introduces possible errors. The effect is chiefly due to single scattering and is nearly proportional to $1/E^2$. Calculations and experimental tests indicate that the long chamber fitted with a 0.001-in. mylar entrance window and filled with H_2 scatters 0.2 percent of the primary beam beyond the integrator aperture at 13 Mev. The large chamber was used for primary energies of 13 Mev and higher, but for relative measurements which extended to the lower energies, the small chamber, mounted directly on the face of the integrator as shown in Fig. 1, was used. Using this chamber filled with N_2 gas, the error due to scattering is only about 0.5 percent at 1 Mev. Because the guard plates in this chamber were necessarily very short, wires carrying potentials intermediate between the high voltage and the collecting plate were mounted in the chamber to help make the collecting field uniform. The wires were located outside the main beam and were only 0.010 in. in diameter so that they intercepted only a negligible part of the scattered beam. The possibility of gas multiplication near the fine wires limited the voltage which could be applied to the small chamber so that the effects of space charge and ion recombination were considerably worse for the small chamber than for the large.

Some early measurements[11] were taken with a chamber of intermediate length. This chamber had a collecting region of the same nominal dimensions as the large chamber described above. However, the guard plates were inadequate and the effective length was not known with precision. The chamber was suitable for relative measurements in the energy range from 6 Mev upward.

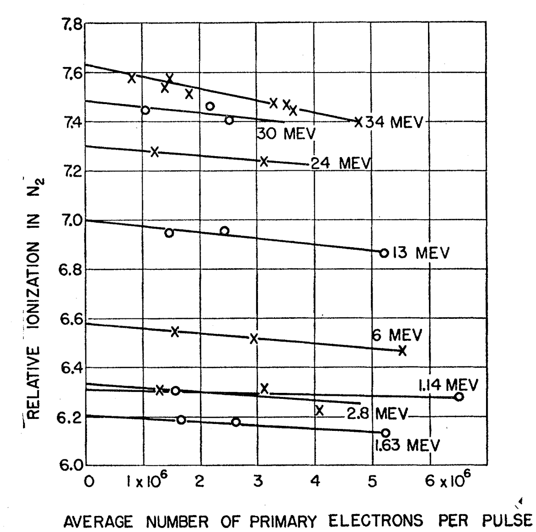

FIG. 4. Ratio of the collected ion charge to collected Faraday-cup charge (in arbitrary units) as a function of the average primary beam intensity.

[11] W. C. Barber, Phys. Rev. 93, 942 (1954).

C. Gases

All measurements were made with the gas flowing continually through the ion chamber, exiting through a tube which was under oil. The gas flow was such that the pressure in the chamber was 1 cm of oil above atmospheric. The chamber was water cooled so that its temperature did not change rapidly, and the temperature and pressure were measured periodically. With this system, it was found that results were reproducible to within about 0.25 percent with the large chamber and 0.5 percent with the small chamber over periods of several days.

Most of the measurements on H_2 were made using electrolytic H_2 (supplied by the Stuart Oxygen Co., San Francisco), which was passed through a catalyzing unit to form water from the oxygen impurity and then through a liquid-nitrogen trap. The measurements with this H_2 were compared with a series of measurements using mass-spectrometer-checked H_2 of purity greater than 99.99 percent (procured from the Linde Air Products Co., San Francisco), and it was found that the specific ionization of the purer hydrogen was only 0.24-percent lower.

The nitrogen gas used was Stuart "Hi-Pure" which was passed through a liquid-nitrogen trap at 2 psi over atmospheric pressure. According to the manufacturer, the purity of the gas so treated should be about 99.99 percent.

The helium gas was U. S. Grade-A, which was passed through a liquid-nitrogen trap. With He gas there was a long period after the chamber was filled and the gas flow started during which the observed specific ionization decreased with time. Also, a phenomenon of "clean-up" by the beam was observed. The measured ionization was lower if an electron beam had been traversing the chamber for several minutes prior to the measurement. It was found that reproducible results could be obtained if the He flow was set at a few cm^3 per second and the electron beam was allowed to traverse the chamber almost continuously. In view of the results of Jesse and Sadauskis[12] and Bortner and Hurst[13] that the ionization observed in He is greatly increased by traces of impurity, it is suggested that the observed decreases in ionization were caused by the removal of impurities, in the one case by the flowing gas, and in the other by the ionizing power of the beam. It is not certain that the results obtained are those for pure He. However, it is gratifying that the average energy required to produce an ion pair calculated from the present experiment is about the same as that obtained in experiments with very pure He.[12,13]

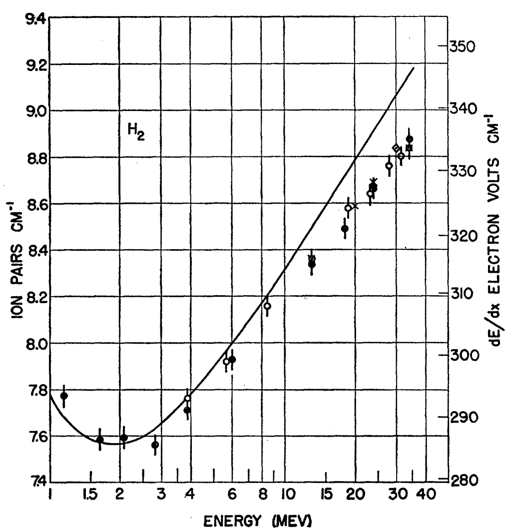

FIG. 5. Specific ionization and energy loss in H_2. The left ordinate scale refers to the experimental points. (The crosses show the absolute data obtained with the large chamber. The data taken with the small and intermediate-size chambers, shown as solid and open circles, respectively, were arbitrarily normalized to fit the crosses.) The right ordinate scale gives the probable energy loss per cm [Eq. (2)] when $T_0=17.4$ kev, which is the calculated value for the large chamber.

RESULTS

The camber shown in Fig. 3 was used with mass-spectrometer-checked H_2 to give an absolute value for the specific ionization. The results are shown in Table I. Column 2 of Table I gives the measured specific ionization reduced to N.T.P. and corrected for the hard secondaries knocked into the integrator (0.43 percent) and for recombination of ions (never more than 0.5 percent). The quoted error of 1 percent in the specific ionization is made up of the statistical combination of the following estimated errors: 0.3 percent uncertainty in the determination of the ratio of condensers; 0.3 percent uncertainty in gas temperature; 0.3 percent due to possible error in the calculation of the hard secondaries knocked into the integrator; 0.2 percent due to uncertainty in the evaluation of the loss due to recombination of ions; 0.6 percent due to uncertainty about low-energy secondaries (Fig. 2); 0.2 percent due to drifts in electrometer circuits or correction for finite leakage resistance; and 0.2 percent due to 2 percent error in energy calibration.

In order to compare the experimental results with the theoretical expression for the energy loss, it is necessary to have values for T_0 and I. If T_0 is chosen as the average energy of those secondary particles which just

TABLE I. The specific ionization observed in H_2 with the large ion chamber compared with the calculated probable energy loss.

1. Energy (Mev)	2. Observed ion pairs (cm^{-1})	3. Calculted dE/dx from Eq. (2) (ev)	4. Calculated ion pairs (cm^{-1}) due to secondaries beyond T_0	5. Net ion pairs (cm^{-1}): Col 2–Col 4	6. W (Mev)
13	8.467 ± 0.08	320.2 ± 3.6	0.11 ± 0.04	8.357 ± 0.09	38.32 ± 0.6
20	8.692 ± 0.09	331.5 ± 3.7	0.11 ± 0.04	8.582 ± 0.10	38.63 ± 0.6
24	8.799 ± 0.09	336.3 ± 3.8	0.11 ± 0.04	8.689 ± 0.10	38.70 ± 0.6
34	8.946 ± 0.09	345.6 ± 3.9	0.11 ± 0.04	8.836 ± 0.10	39.11 ± 0.6

[12] W. P. Jesse and J. Sadauskis, Phys. Rev. **90**, 1120 (1953).
[13] T. E. Bortner and G. S. Hurst, Phys. Rev. **90**, 160 (1953).

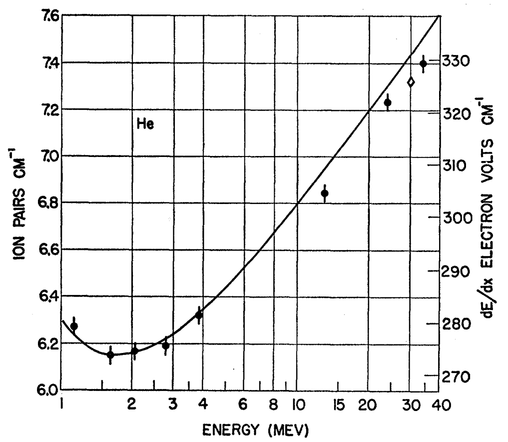

FIG. 6. Specific ionization and energy loss in He. The left scale refers to the experimental points taken with the small chamber, whose effective length was determined by the normalization indicated in Fig. 5. The right ordinate scale gives the probable energy loss per cm [Eq. (2)] when $T_0=16.4$ kev.

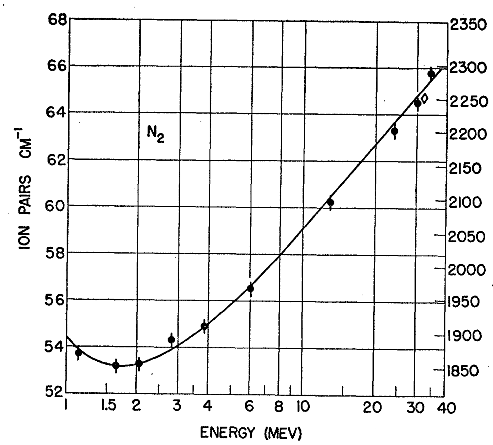

FIG. 7. Specific ionization and energy loss in N_2. The left scale refers to the experimental points taken with the small chamber. The right ordinate scale gives the probable energy loss when $T_0=70$ kev.

reach the boundary of the sensitive region of the chamber, Eq. (2) corresponds closely with the energy dissipated in the sensitive volume. A correction is required due to the fact that secondaries of energy greater than T_0 leave a portion of their energy in the ion chamber. This correction was evaluated by using the Møller formula for the cross section for producing secondaries, together with an empirical formula for the range of electrons. The correction is only about 1 percent and is nearly independent of primary energy. Values calculated assuming 38 ev is required to produce an ion pair are given in Column 4 of Table I. The calculation of T_0 involves the range and multiple scattering of low-energy electrons, and the transverse dimensions of the chamber. The length of the chamber is of little importance because the secondaries of interest are produced at angles nearly normal to the beam. For the chamber shown in Fig. 3, which has a cubical sensitive volume 2.5 in. on a side, T_0 was calculated as 17.4 kev for H_2 at 1 atmosphere and 20°C. The error in the calculation is about ± 2 kev, but since T_0 appears only in the logarithm term, the resulting error in dE/dx is about 0.7 percent.

The value of I is best taken from other experiments. In calculating Column 3 of Table I, a value of 18 ev was used. This value was obtained by Allison and Warshaw[14] from the measurements of Thompson on the stopping power of liquid H_2 for 340-Mev protons. An estimated error of 10 percent in I causes a 1 percent error in dE/dx.

Column 6 of Table I gives the value of W obtained from the ratio of Column 3 to Column 5. The errors listed are the absolute errors. Since all of the major errors are nearly independent of primary energy, the relative values indicating the trend of W with energy are accurate to about 0.5 percent.

The small chamber (Fig. 1) was used over the entire energy range with all three gases. The same integrating condensers were used with all three gases and hence the measurements give reliable relative results. Normalization of these relative results to the absolute results given in Table I yields values for the specific ionization of the three gases at all the energy points.

The results are plotted as a function of energy in Figs. 5, 6, and 7. In these figures, the left-hand ordinate scale refers to the experimental points which have been corrected as discussed in connection with Table I. The absolute points are plotted as crosses in Fig. 5. The points taken with the small chamber are solid circles. The right-hand scale refers to the solid curves and gives energy loss as calculated from Eq. (2). The values of I used in Eq. (2) are listed in Table II. The I values for H_2 and N_2 are taken from the calculations of Allison and Warshaw[14] based on Thompson's measurements of stopping power. The I value for He was taken from the paper of Sternheimer.[7] There are no arbitrary constants on either scale, and therefore comparison of an experimental point with the curve gives a value of W.

The transverse dimensions of the small chamber are only 80 percent of those of the large, and therefore T_0 is lower for the small chamber. However, this difference in T_0 causes only a 0.1 percent difference in the calculation of the energy loss at 35 Mev relative to the value at 2 Mev. This is smaller than other possible errors, and therefore in determining the relative shape of the energy-loss curves these small differences in T_0 can be ignored.

For making an absolute comparison, values of T_0 for the large chamber are used because the absolute ionization measurements were taken with the large chamber. The computed values of T_0 were (17.4 ± 2), (16.4 ± 2), (70^{+20}_{-10}) for the gases H_2, He, and N_2, respectively.

[14] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).

TABLE II. Comparison of the values of W as determined by this experiment with some other experimental values of W. The data used in evaluating W and values of the total specific ionization are also tabulated.

Gas	H_2	He	N_2
1. "Measured" ion pairs cm^{-1} at minimum	7.56 ± 0.09	6.15 ± 0.08	53.2 ± 0.7
2. T_0 (kev) calculated	17.4 ± 2	16.4 ± 2	70^{+20}_{-10}
3. I (ev) assumed	18 ± 1.8	27 ± 2.7	75.9 ± 7.6
4. $-dE/dx$ probable at minimum (ev cm^{-1})	285.5 ± 4	273.5 ± 4	1850^{+40}_{-25}
5. W at minimum	37.8 ± 0.7	44.5 ± 0.9	$34.8^{+0.9}_{-0.7}$
6. W from α-particle absorption[a]	36.3	42.7	36.6
7. W from α-particle absorption[b]	37.0	46.0	36.3
8. W, 340-Mev protons[c]	35.3	...	33.6
Computed total ion pairs (cm^{-1})			
9. at minimum	9.19 ± 0.18	7.55 ± 0.16	$61.6^{+1.2}_{-1.5}$
10. at 34 Mev	11.50 ± 0.22	9.67 ± 0.20	$82.0^{+1.7}_{-2.0}$

[a] See reference 12.
[b] See reference 13.
[c] C. J. Bakker and E. Segrè, Phys. Rev. **81**, 489 (1951).

The large uncertainty in T_0 for N_2 results from uncertainty in a large correction for multiple scattering of the secondaries in the gas.

Figure 5, for H_2, includes data (shown as open circles) which were taken using the intermediate-size chamber. These data were arbitrarily normalized to the four absolute points which are shown as crosses.

DISCUSSION

The comparison of experiment and theory is shown in Figs. 5, 6, and 7. In the case of N_2, the relativistic increase in the energy loss and the ionization are equal to within 1 percent, probably indicating that the theory of energy loss and the constancy of W can be trusted to this extent. In H_2 the rise in ionization is significantly less than the theoretically-predicted rise in the energy loss. A trend in this direction is also observed in the He measurements. Calculations on the density effect[15] indicate that at 35 Mev with 1 atmosphere of H_2, the reduction in energy loss due to the onset of the density effect is only 2.7 ev/cm. This is only about one-fourth of the discrepancy, the remainder of which must be due to an increase in the value of W with primary energy That W should change with energy is not surprising; indeed, the calculations of Bethe[16] on the primary ionization of atomic hydrogen by electrons show that the fraction of collisions producing excitation increases as the energy of the incident electron increases. Because of the difficulty in relating primary and total ionization, this effect is difficult to evaluate quantatively.

The recent calculations of Sternheimer[8] and Budini,[9] taking into account the collective behavior of the atoms in the gas, indicate that the production of Čerenkov radiation is an important part of the energy loss for highly-relativistic particles. If the Čerenkov radiation escapes from the chamber or is absorbed without producing ions, it could result in an increase of W. The intensity of the Čerenkov radiation is concentrated around the frequencies of electronic transitions in the gas atoms and therefore in pure H_2 or He not much of it could be absorbed to produce ions. Sternheimer's calculations give the energy escaping as radiation beyond a distance b from the particle tracks. The choice of b equal to the dimension of the chamber gives the result that the radiation escaping is negligible; however, because of the fact that in pure He or H_2 the radiation cannot produce ions when it is absorbed, this is not a wise choice of b for comparison with ionization experiments. If b is chosen as 0.1 cm, the Čerenkov loss begins at about 10–15 Mev and at 30 Mev it is about 6.1 ev/cm for H_2, 5.9 ev/cm for He, and 13 ev/cm for O_2. For H_2 and He this is 2 percent of the total energy loss, which is about equal to the observed change in the value of W. Sternheimer's result for O_2 should be a fair approximation for N_2, in which case the Čerenkov loss is only 0.6 percent of the total. This result is in agreement with the observed near-constancy of W in N_2.

The points marked as diamonds in Figs. 5, 6, and 7 give the theoretical energy loss after the Čerenkov loss has been subtracted, and the slight density-effect correction made. Because of the ambiguity in the choice of b, close quantitative agreement with the ionization measurements is not to be expected. It does appear significant, however, that experiment and theory agree in indicating an appreciable effect in H_2 and He and its near absence in N_2.

The absolute check between experiment and theory is revealed by the computed values of W. The results for the three gases in the region of minimum ionization are given in Row 5 of Table II. The assigned errors are derived from the combination of errors of measurement, the estimated error in calculating T_0, and an assumed 10 percent uncertainty in I. The latter introduces about 1 percent uncertainty in dE/dx which can be eliminated when better values of I become available.

Comparison of the W values of this experiment with those obtained from other experiments (Rows 6, 7, and 8 of Table II) indicates that for N_2 the electron value is nearly within experimental error equal to the 340-Mev proton value. The α-particle value for N_2 is probably higher because of K-shell binding effects. For He, the electron value is between values reported by different workers using α particles in very pure He. This result indicates a remarkable constancy of W in He over a wide range of particle velocities. In the case of H_2, the elec-

[15] R. M. Sternheimer (private communication).
[16] H. A. Bethe in *Handbuch der Physik* (Julius Springer, Berlin, 1933), Vol. 24, Part 1. 519 ff.

tron value of W is slightly higher than the other reported values. The increase in W for H_2 beyond the minimum has already been remarked, and it may be that the change from α-particle energies to minimum ionizing electrons is a part of this trend. The low value reported for 340-Mev protons is surprising in that the primary particle velocity is intermediate between the α particle and electron velocities.

Rows 9 and 10 of Table II give the expected total specific ionization for 1.7-Mev (minimum ionization) and 34-Mev electrons, respectively. These values were computed by dividing the difference in energy loss predicted by Eqs. (1) and (2) by the value of W at the minimum (Row 5 of Table II), and adding the result to the measured probable ionization.

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Polarization in Scattering by Complex Nuclei*

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Polarization effects in the elastic scattering of high-energy nucleons by complex nuclei are studied in terms of the impulse approximation. The principal aim is to reconcile the large polarizations produced by complex nuclei with the smaller effects found in nucleon-nucleon scattering. It is shown that these results are not inconsistent and can indeed be understood in terms of simple physical arguments. While, in general, our knowledge of nuclear structure is not adequate for explicit calculation of these effects even in the impulse approximation, it can be shown that for a particular class of nuclei (the deuteron and the alpha-particle nuclei) the polarization is independent of the nuclear wave function. Calculations for these nuclei have been carried out in detail, using existing nucleon-nucleon phase shifts. The resulting polarization effects are found to be large, in rough agreement with experiment, although their angular dependence is not satisfactory. It is proposed that a study of polarization in elastic scattering by deuterium and helium be used as a tool for investigation of the nucleon-nucleon interaction.

I. INTRODUCTION

EXTENSIVE experiments have been reported during the past few years concerning measurements of the azimuthal asymmetry in the double scattering of high-energy nucleons by various nuclei.[1–6] These measurements indicate the existence of quite large polarization effects in the energy region 130 to 400 Mev. The peak polarization produced in proton-proton scattering has been found to be about 40 percent in this energy region, while comparable effects are found in neutron-proton scattering. Protons of the same energy when scattered by complex nuclei seem to be polarized much more strongly, however, the major effect coming from elastic processes.[4,7] Experiments that discriminate against the inelastically scattered protons have detected polarizations as large as 80 percent.

Theoretical investigations of polarization effects in nucleon-nucleon collisions have been carried out by Goldfarb and Feldman[8] and by Swanson.[9] These calculations are based upon various assumed phenomenological potentials designed to fit existing scattering and bound-state data. A reasonably good estimate of the p-p polarization is provided by the singular tensor-force interaction, while the hard core and $\mathbf{L}\cdot\mathbf{S}$ models give, respectively, too small and too large an effect. The tensor-force model of Christian and Hart gives roughly comparable polarizations for the n-p case.

More recently, attention has been focused upon the scattering of nucleons by complex nuclei. Numerous calculations have been reported[10–15] in which the nucleon-nucleus interaction has been treated phenomenologically. The common feature of all these efforts has been the use of a complex central well con-

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