TABLE VII. The pressure shifts for hydrogen, deuterium, and tritium in the various buffer gases. The shift is expressed in terms of the pressure at 0°C so that the density in the bulb is given by $N/V=p/T_0k$, where T_0 is 273°K. The measurements were made at a temperature of 45±5°C.

Buffer gas	Hydrogen isotope	Pressure shift [(cps)/mm Hg]	(Pressure shift/$\Delta\nu$)×10^9 [(mm Hg)$^{-1}$]
He	H	6.81±0.13	4.80±0.09
Ne	H	4.09±0.07	2.88±0.05
	D	1.06±0.15	3.24±0.45
	T	4.90±0.13	3.24±0.09
H_2	H	−0.80±0.15	−0.56±0.10
Ar	H	−6.76±0.15	−4.77±0.12
	D	−1.48±0.13	−4.52±0.40
	T	−7.66±0.23	−5.05±0.15

determination of the density of the oil used in the manometer. The total errors in the bulb pressures are estimated to be less than 1% and they are probably mostly of a systematic nature. The pressure shifts have been expressed in terms of the pressure in the bulb at 0°C so that the density in the bulb is given by

$$N/V=p/kT_0, \qquad (2)$$

where $T_0=273$°K. All the measurements were made at a temperature of 45±5°C. The quoted bulb pressures are mm of Hg at 0°C. The quoted errors are one standard deviation. These measurements suggest that the fractional pressure shifts are slightly greater for tritium than for hydrogen.

ACKNOWLEDGMENTS

We are particularly indebted to Professor George Bradley of Western Michigan University for his aid in helping to understand and eliminate the sources of magnetic broadening. Fong-Ching Chen helped to construct some of the circuits and reduce the data. Once more we wish to thank Larry Donaldson for his work as glass blower.

PHYSICAL REVIEW VOLUME 127, NUMBER 3 AUGUST 1, 1962

Partial Atomic Stopping Power of Gaseous Hydrogen for Hydrogen Beams. I*

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(Received March 20, 1962)

The stopping power of H_2 gas for the atomic component of a hydrogen beam in charge equilibrium has been measured by placing the stopping cell in an intense transverse magnetic field. This allows only those particles to reach the exit which have entered as neutrals and have not experienced any collision, as a result of which they became electrically charged. These neutrals are partially converted to protons in a subsequent gas stripper cell, and their energy measured in an electrostatic deflector. As H_2 gas is admitted to the stripping cell, there is a rapid decay in beam intensity, since at each charge-changing collision the particle is extracted from the beam by the magnetic field. By counting individual exit particles, however, a beam diminution factor of 10^{-7} is acceptable and a well-defined energy group is detected which has experienced a loss of approximately 1% of its energy, and for which the stopping power ϵ_0 of H_2 gas, for instance at 50 keV, is only 0.42 of the conventional ϵ, measured with the field off. The values of ϵ reported agree with those of Reynolds, Dunbar, Wenzel, and Whaling. The results for ϵ_0 and ϵ_0/ϵ are:

Kinetic energy (keV)	ϵ_0 in eV cm^2/atom	ϵ_0/ϵ
20	$(3.3\pm0.5)\times10^{-15}$	0.64±0.10
50	2.8×10^{-15}	0.42
100	1.8×10^{-15}	0.31
150	$(1.4\pm0.35)\times10^{-15}$	0.30±0.08

Above 50 keV the experimental ϵ_0 values agree well with those theoretically calculated by Dalgarno and Griffing for atomic hydrogen gas; at lower energies the experimental values are somewhat higher.

INTRODUCTION

THE term "proton beam" is well known to be inadequate to describe the composition of a pencil of hydrogen projectiles of velocities comparable to $c/137$ (2.19×10^8 cm/sec) moving through matter. The processes of electron capture and loss take place with the result that the components H^0 and H^-, in addition to H^+, appear in the beam in certain characteristic fractions, F_0 and $F_{\bar{1}}$, dependent on the beam velocity, the atoms per cm of material traversed, and the target material itself. This assemblage of particles in essentially unidirectional motion we call a hydrogen beam. In the experiments to be described here, the beam contains no H^- before it begins to interact with the gaseous hydrogen target, and it is known[1] that after sufficient material has been traversed to establish the equilibrium fraction $F_{\bar{1}\infty}$, the maximum $F_{\bar{1}\infty}$ attainable in H_2 gas is 0.020, at about 15-keV kinetic energy. H^- plays no detectable role in the effects to be described and we will treat the hydrogen beam as a two-component system, containing H^0 and H^+. Our experimental definition

* This work was supported in part by the U. S. Atomic Energy Commission.

[1] P. M. Stier and C. F. Barnett, Phys. Rev. **103**, 896 (1956).

of H^0 is that it is the beam component which cannot be deviated in a magnetic field; hence, it may include atomic metastable states in unknown amounts.

The capture of electrons from the target gas, and their subsequent loss by being stripped off, are charge changing events among the various inelastic collisions which make up the stopping process. The cross sections σ_{10} and σ_{01} for the capture and loss of electrons by hydrogen projectiles have been measured by many investigators (see Fig. 1), and the equilibrium fractions $F_{0\infty}$ and $F_{1\infty}$ of the atomic and protonic beam components have either been directly measured, or computed from the cross sections. We shall use the values of σ_{01}, σ_{10}, $F_{0\infty}$, $F_{1\infty}$ tabulated by Allison,[2] which are based, in the energy region under consideration, on the work of Montague,[3] Ribe, Stier and Barnett,[1] and Barnett and Reynolds.[5] We shall follow the convention of stating the cross section per target atom, even in molecular hydrogen gas.

One of the phenomena which make the experiment described in the report feasible is that a pure proton beam leaving a highly evacuated compartment and entering a cell containing hydrogen gas develops a neutral component which attains the fraction $[1-\exp(-1)]$ of its equilibrium value before more than a negligible decrement in the beam's kinetic energy has taken place.

This can be elaborated as follows. The growth of the neutral fraction F_0 in an originally pure proton beam is described by

$$F_0=F_{0\infty}\{1-\exp[-\pi(\sigma_{01}+\sigma_{10})]\}, \quad (1)$$

where π is the number of atoms per cm² which have been traversed by the beam. If $\bar{\pi}$ is the value of π at which $F_0=0.632\, F_{0\infty}$, then

$$\bar{\pi}=(\sigma_{01}+\sigma_{10})^{-1}. \quad (2)$$

Let ϵ represent the stopping power in eV per atom per cm² (hereafter referred to as the total stopping power). Then the energy loss (E_p-E_p') during the traversal, from a beam originally of energy E_p, is $\bar{\pi}\epsilon$, and the fractional loss is

$$E_p-E_p'/E_p=\epsilon/E_p(\sigma_{01}+\sigma_{10}), \quad (3)$$

E_p and E_p' are in electron volts. The range of E_p in our experiments is from 15 to 150 keV. In this range ϵ varies from 4.6×10^{-15} through a maximum of 6.4×10^{-15} to 4.6×10^{-15} eV cm²/atom, while $(\sigma_{01}+\sigma_{10})$ decreases from 41 to 4.6×10^{-17} cm². Thus, the loss in energy is less than 0.1% of the original energy for this approach to equilibration.

Having thus rapidly attained charge equilibration, the beam proceeds with the effective charge $|e|F_{1\infty}$. In general, the fraction of the equilibrated beam which

[2] S. K. Allison, Revs. Modern Phys. **30**, 1137 (1958).
[3] J. H. Montague, Phys. Rev. **81**, 1026 (1951).
[4] F. Ribe, Phys. Rev. **83**, 1217 (1951).
[5] C. F. Barnett and H. K. Reynolds, Phys. Rev. **109**, 355 (1958).

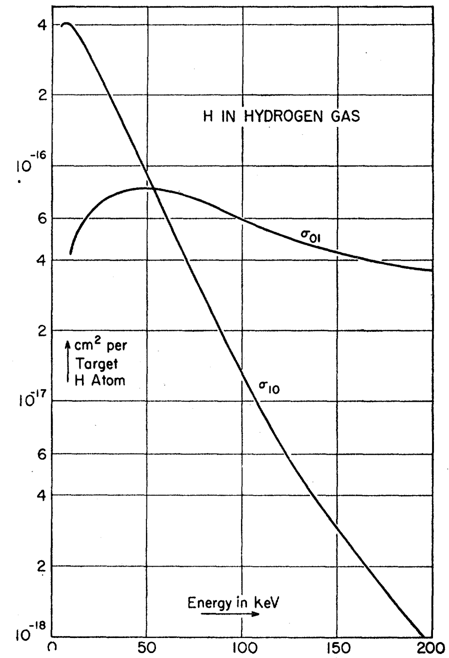

FIG. 1. Cross section for electron capture by protons σ_{10}, and for electron loss by atoms σ_{01}, in a hydrogen beam in molecular hydrogen gas.

is neutral, or the fraction of the time during which a given beam particle is neutral, is

$$F_{0\infty}=\sigma_{10}/(\sigma_{01}+\sigma_{10}) \quad (4)$$

and $F_{0\infty}$ attains the value 0.5 at about 50 keV for a hydrogen beam in hydrogen gas. This may be seen from Fig. 1, in which $\sigma_{01}=\sigma_{10}$ at $\sim$50 keV. Since we are neglecting H^-, $F_{1\infty}=(1-F_{0\infty})$.

Under conditions in which there is an appreciable neutral component the total stopping power can be considered as a weighted sum of the partial stopping power ϵ_1 for the particle as a proton, the partial stopping power ϵ_0 for the neutral atoms, and a term giving the kinetic energy losses accompanying the events in which the charge is changed. This particular breakdown of the total stopping power, suited to the experiment described here, is somewhat different from that resulting directly from the theoretical calculations, as we shall see later.

The object of the experiment reported here is to measure ϵ_0, the partial atomic stopping power. The basic idea is to place the gas chamber in which the stopping power is being measured in a strong magnetic field, which removes the protonic component, and also any regenerated protons from the loss of an electron from a moving neutral atom.

FEASIBILITY OF THE EXPERIMENT

The essential features of the experiment are shown in Fig. 2. The proton beam, entering from the right, is first charge equilibrated in cell No. 1, the equilibrator

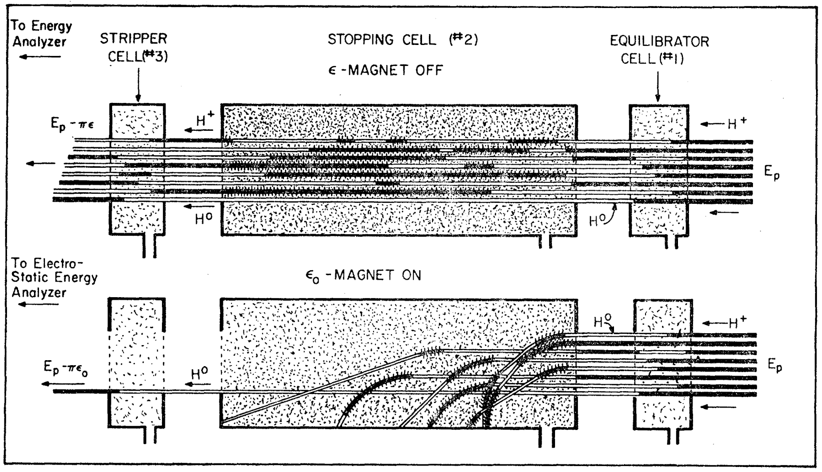

FIG. 2. Schematic diagram of the experimental method. The apertures in the cells are actually 0.091 cm in diam, π is the number of atoms per cm^2, ϵ the conventional, or total stopping power, and ϵ_0 the partial atomic stopping power. The attenuation of the beam from the ϵ to the ϵ_0 measurement is actually by a factor of 10^{-7}.

cell. It then passes into the stopping chamber, cell No. 2, on which a transverse magnetic field may be applied. When ϵ_0 is being measured, only neutrals can emerge from the stopping cell. In order to measure their kinetic energy some of them must be stripped to protons again (cell No. 3) before electrostatic analysis. As has been shown, the losses in energy in cells No. 1 and 3 need be less than 0.1%; but in the experiment the pressure in these cells (a few microns) is not changed and the loss in them does not appear in the result.

The most striking feature of the experiment is the very large attenuation of the beam when enough gas is admitted to the stopping cell, in the presence of the magnetic field, to produce a sufficient energy loss for accurate measurement. It follows that the experiment has an enhanced chance of success if the energy spread of the beam from the accelerator is minimized, and the resolving power of the energy analyzer maximized in order to permit an accurate measurement of an energy loss $\pi\epsilon_0$ as small as possible. The feasibility of a determination of ϵ_0 may be discussed as follows. In the stopping cell, the intensity attenuation on admitting gas in the presence of the magnetic field will be $s\exp(-\pi\sigma_{10})$ where s is a factor less than unity due to the loss through small-angle scattering. From previous experience in measuring stopping powers in gases, we could be reasonably sure that $s=0.1$ is a value almost certain to be exceeded. The fractional losses in cells 1 and 3 are $F_{1\infty}$ and $F_{0\infty}$, respectively.

Thus, the attenuation produced by a pressure corresponding to π atoms per cm^2 in cell No. 2 must be expected to be

$$N/N_0 \sim sF_{0\infty}F_{1\infty}\exp(-\pi\sigma_{01}). \tag{5}$$

N_0 is the beam current received by the detector with minimum pressure ("gas out") in all the three cells and no magnetic field on the second one.

Let $(E_p-E_p')_{\min}$ be the smallest energy decrement, in eV, which can be measured to the desired accuracy (say 5%); then

$$\pi\epsilon_0=(E_p-E_p')_{\min}$$

and

$$N/N_0 \sim sF_{0\infty}F_{1\infty}\exp[-(E_p-E_p')_{\min}\sigma_{01}/\epsilon_0]. \tag{6}$$

For a 50-keV hydrogen beam in hydrogen gas, $F_{0\infty}=0.525$ and $F_{1\infty}=0.475$. For a feasibility calculation, ϵ_0 may be assumed to be half the total stopping power ($\frac{1}{2}\epsilon=3.2\times10^{-15}$ eV cm^2/atom), and σ_{01} is 7.9×10^{-17} cm^2. By stabilizing the accelerator, filtering out the ripple left from the rectifying circuit, etc., we succeeded in minimizing the acceptable (E_p-E_p') to about 1% of the energy or 500 eV at 50 keV. The beam, then, according to (6) must be expected to attenuate by a factor of 10^{-7}. Whether this is tolerable depends on the beam current which can be passed through the seven small apertures (1 mm diam), of which the first and the seventh are 110 cm apart. It was estimated that 10^{-10} A could be transmitted with vacuum throughout the system, and thus that the detectable beam current in the ϵ_0 experiment would be not less than 10^{-17} A, or 3750 particles per minute. Thus, with a detector such as an electron multiplier tube, placed in the vacuum and counting with 100% efficiency, the final proton beam in the ϵ_0 experiment should be detectable. Observed counting rates were of this order.

APPARATUS

The essentials of the apparatus are as indicated in Fig. 2. There are no foils in the path of the beam. Differences in gas pressures in the cells and the traverse tubes are maintained by specially shaped apertures and differential pumping. Preliminary tests had developed a standard aperture consisting of a tubular canal cut through a brass plate of 1-cm thickness. The entrance aperture is 0.091 cm in diam, and this diameter is maintained for a depth of 0.0125 cm, at which the diameter is expanded to 0.126 cm. The diameter then progressively increases in a diverging cone, reaching 0.147

cm at the exit. Tests showed that our 4-in. diffusion pumps, even with their speed slowed down by liquid nitrogen traps and unavoidable bends in 5-cm diam vacuum piping, could maintain a pressure differential of 80 to 1 over such an aperture.

The two equilibrator and stripper cells were of identical construction with path lengths in the gas of 10 cm. They were kept during the experiment at roughly $6\,\mu$ pressure of H_2. The stopping cell was 54.2 cm long. The required energy decrements were attained by hydrogen pressures from 30 to $80\,\mu$. The cylindrical electrostatic energy analyzer (CYESA) which was used to measure the energies of the protons emerging from the stripper cell had previously been described and calibrated.[6] It was used with 0.05-cm (w) slits, and since the mean radius R is 15 cm, the energy resolution ($w/2R$) is approximately 1 in 600. Repeated tests with various magnetic field intensities of the order of 1500 G showed that ϵ_0 measurements were independent of field intensity. The field, applied over the 54.2 cm of path, was normally at approximately 1600 G, sufficient to impress a radius of curvature of $\sim$20 cm on the protonic constituent of the beam.

It was necessary to use five diffusion pumps, four oil, and one mercury, in maintaining the pressure differentials caused by the admission of hydrogen gas into the three cells. Each one of these pumps was separately trapped with liquid nitrogen, and the same applies to the McLeod gauge used to read the pressure in the stopping cell. Alphatron vacuum gauges[7] were used for rapid and approximate adjustment of pressures, but the final values used in calculating results were always McLeod gauge readings. The region in which the magnetic field for proton rejection was created was 2.54 cm parallel to the lines of force, and 18×52 cm in cross section at right angles to them. A current of 1.2 A through each of the four coils produced approximately 1600 G.

Electron multiplier tubes made in this Institute by Allen[8] were well suited to the extreme differences in detector currents characteristic of this experiment. Used as a particle counter, they were rugged and dependable; for measurements of the ordinary stopping power, and of the "gas-out" beam in the ϵ_0 experiment, where $10^{-10}-10^{-11}$ A were available, the signal was taken directly from the first dynode of the counter, without amplification, and measured on a vibrating reed electrometer.

EXPERIMENTAL PROCEDURES AND SOURCES OF ERROR

The most serious difficulty of the experiment was in obtaining any beam at all through the 7 defining apertures. The beam drift tubes and the stopping cells were, after adjustment, rigidly mounted in slotted steel frames. In the lining up process a bright light source was placed at one end of the train of openings and they were set, in turn, for maximum transmission. The type of vacuum coupling used between tubes, and some flexible sections, permitted the small adjustments which were necessary. Finally, the transmitted beam was maximized by trial through the positioning of small permanent magnets outside the drift tubes through which the beam passed before entering the first of the defining apertures.

Two ion accelerators were used for different energy regions; a Cockcroft-Walton accelerator for voltages above 100 kV and a small, two-section accelerating tube with a stabilized (0.1%) high-voltage dc power supply was used in the 30–60 kV region. It was assumed that deuterons could be substituted for protons of equal velocity,[9] and since the accelerators gave larger beam intensities at higher energies, many of the low-energy points were taken with deuteron beams. In every case a sorting magnet was used to select by deviation the proton or deuteron component and direct it through the train of gas cells.

For the initial adjustments of a run, all cells were at first at high vacuum (5×10^{-6} mm Hg). The electrodes in the CYESA were connected together and to an electrometer, thus, at this stage, using the CYESA as a Faraday-cell beam detector. After maximizing the transmitted beam, H_2 gas was admitted into the equilibrator cell (No. 1) until charge equilibration was approximately attained, as revealed by a pressure independent, but diminished current collected in the CYESA. The magnetic field on the stopping cell was then switched on, the effect being to reduce the current detected in the CYESA nearly to zero, since only particles which had traversed the evacuated stopping cell as neutrals could reach it. At this point gas was admitted to the stripper cell (No. 3) until the current collected in CYESA rose to a pressure-independent maximum. No further changes in the pressures in cells No. 1 and 3 were made during a run.

The deflecting potentials were connected to the CYESA, its defining slits adjusted, and the proton beam constituent incident on it was deflected into the Allen counter used as a Faraday cell, as previously stated.

The determination of ϵ_0 then began by taking the energy profile of the beam with "gas out" of the stopping cell. Fig. 3 shows a double run in which ϵ and ϵ_0 were determined in successive experiments, with the same beam energy and gas pressure in the stopping cell, so that the reduced stopping power characteristic of ϵ_0 is seen by inspection. Actually, this double run was not one to which great reliability was assigned. A higher gas pressure could have been used as is seen by the low attenuation indicated in the ϵ_0 run.

[6] S. K. Allison, S. P. Frankel, T. A. Hall, J. H. Montague, A. H. Morrish, and S. D. Warshaw, Rev. Sci. Instr. **20**, 735 (1949).
[7] NRS Equipment Corporation, Newton, Massachusetts.
[8] J. S. Allen, Phys. Rev. **55**, 336 (1939); **55**, 966 (1939). See also L. del Rosario, *ibid.* **74**, 304 (1948).
[9] For an experimental test see J. A. Phillips, Phys. Rev. **90**, 532 (1953).

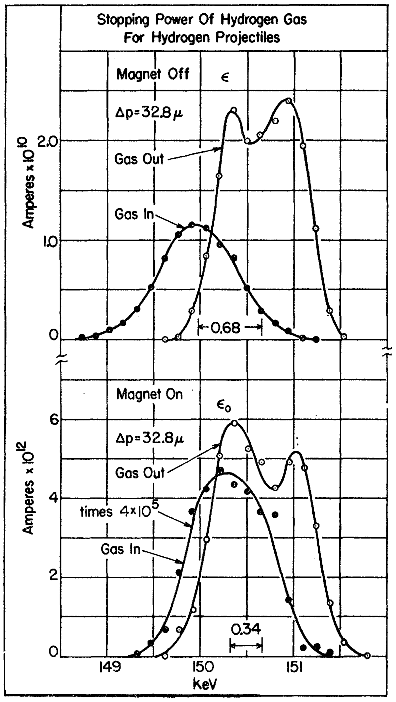

FIG. 3. Energy shifts caused by total (ϵ) and atomic partial stopping powers (ϵ_0). The two-peaked "gas-out" energy profile is inherent in the ion source used.

After running the "gas-out" profile, the Allen counter connections were re-arranged for single-particle counting and the counter connected to a scaling circuit. Because of the exponential attenuation of the beam, under these circumstances, with increasing pressure, it was found expedient to use the counting rate as the pressure gauge. Gas was admitted until the counting rate had fallen to approximately 50 counts/sec. The pressure was taken on a McLeod gauge and the energy profile redetermined. (Left-hand lower curve, Fig. 3.)

A two-way valve permitted the McLeod gauge connection to be shifted to the beam traverse tubes between cell No. 2 and cells No. 1 and 3, so that the small rise in pressure in these compartments could be corrected for. A potentiometer-type circuit opposed the emf of a cell against a small fraction of the accelerator voltage and exhibited any lack of balance on a sensitive galvanometer, allowing the observer to note any drift (to 1 in 10^4).

There are several important sources of error in the ϵ_0 measurement, some due to imperfect technology, and some inherent in the basic idea of the experiment. In the former class are the following. A very small leak in the stopping cell, or even outgassing from its walls, could significantly contaminate the few microns of hydrogen in it with heavier gases which, per atom, have three to four times the stopping effect of hydrogen. The pumping speed on the stopping cell was very low through its two 0.09-cm apertures, and in addition such apertures selectively pass hydrogen in preference to air or H_2O. The effect can be minimized by waiting several minutes after admitting hydrogen for equilibrium to be established in the stopping cell and then taking the "gas-out" reading after the only change in the system has been to shut off the flow of hydrogen. In "shutting off" or "opening" the gas needle valves no actual mechanical motions were made; after they had been adjusted to the flow desired, "shutting off" consisted in exhausting the gas from the high-pressure side with a mechanical pump. Another source of error not completely under control was the variability in the energy profile of the "gas-out" beam as indicated by the upper right-hand curve of Fig. 3. It has already been noted by other observers[10,11] that at high resolution an energy analysis of the accelerated beam from a radio frequency ion source will often reveal a two-peaked profile. We have observed such a structure, but it is variable, and we have not completely understood how it is formed. In general, the "gas-in" energy-degraded and straggled curves did not show this structure and thus the problem of deciding the significant energy decrement between profiles of different shape was not unambiguously solved. In general, we took the shift between the axes of symmetry of the curves as judged by the steep side slopes rather than the irregular tops, and rejected runs in which the asymmetry was, in our judgment, too pronounced.

A correction inherent in the basic idea of the experiment is due to the fact that the sweeping out of protons cannot be 100% effective over the entire path in the stopping cell. There is a small portion of the path, near the exit aperture of the cell, along which a proton, if formed, is not bent out of the exit aperture by the imposed field. The extent of this region is easily seen to be $(\rho d)^{\frac{1}{2}}$, where ρ is the radius of curvature of the proton's path and d the diameter of the exit hole. Neglecting the possibility of subsequent capture in the cell, this particle in addition to the energy loss in stripping will experience an enhanced stopping power ϵ_1 and emerge with too low a kinetic energy, thus making the observed stopping power higher than the true ϵ_0 and necessitating a correction. The length $(\rho d)^{\frac{1}{2}}$ was between 1 and 3 cm compared to the total length 54.2 cm and a mean free path λ_{01}, approximately 6 cm. Calculation of the correction indicated that the true ϵ_0 values were less than $1-2\%$ lower than those obtained from the uncorrected data. No such correction was made.

Since reliable data already exist on the conventional, or total stopping power of H_2 gas throughout the energy range of our experiments, our purpose in measuring ϵ was not to produce new data but to detect systematic errors, if they exist in our method. A new source of error appears here, namely, that it is impracticable to remove the large electromagnet each time an ϵ measurement is

[10] R. Hölz and H. Löb, Z. Naturforsch. **13a**, 602 (1958).
[11] G. Forst, Z. Physik **159**, 7 (1960).

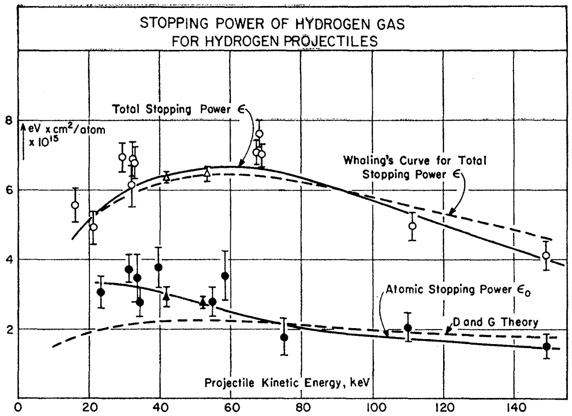

FIG. 4. The upper, solid, curve is the best curve through our total stopping power determinations. The upper dashed curve is that of Reynolds *et al.* for the total stopping power, based on measurements with smaller errors. The lower dashed curve is the theoretical ϵ_0 of Dalgarno and Griffing for H^0 in H^0 gas.

desired, and a very slight residual magnetic field partially removes protons from the highly collimated beam, producing an apparent ϵ somewhat too low. A magnetic field of 1.3 G will prevent a 50-keV proton, formed just inside our stopping cell, from leaving through its exit, and thus will begin to decrease the measured stopping power from its true total value. Although a sensitive gaussmeter was used in bringing the magnetic field to low values, the best procedure is to use the proton component issuing from the equilibrator cell, and, with "gas out" of the stopping cell, vary the magnetizing current through positive and negative ranges very close to zero until an enhanced signal indicates that protons are leaving through the exit aperture. An additional check is to verify that the "gas-out" and "gas-in" beams are of the same order of magnitude, not differing in intensity by 10^7 as in the ϵ_0 experiment.

To make our ϵ measurements as similar as possible to the ϵ_0 determinations, we sacrificed accuracy by using the low pressures and small energy decrements necessitated by the ϵ_0 measurements. Our ϵ measurements are shown in Fig. 4, and within their rather large estimated uncertainty show good agreement with the accepted values.[12] (Upper dashed curve.)

RESULTS

The experimental points which survived certain criteria of reliability are shown in Fig. 4. The results of a few runs were rejected because of instability of the primary energy as revealed by drifts in the "gas-out" energy during the run, by too great an asymmetry of the energy profile, or by the occurrence of sparks. Determinations of ϵ were rejected if the intensity attenuation with "gas in" was too high, indicating a residual magnetic field. A few ϵ_0 determinations were rejected because of too low an attenuation, indicating that a sufficiently high magnetic field had not been established.

Certain points in the region of 40–50 keV kinetic energy are triangles instead of circles. These were taken by Huberman for the purpose of measuring the energy loss in charge changing collisions.[13]

Also shown in Fig. 4 are the best smooth (solid) curves through our data. These are the basis for the experimental results collected in Table I. The lower dashed curve is constructed from theoretical predictions of Dalgarno and Griffing[14] (DG) from which ϵ_0 for a hydrogen beam traversing atomic hydrogen gas can be deduced. The calculations on which the DG predictions are based were largely those of Bates and Dalgarno[15] and Bates and Griffing.[16]

DISCUSSION OF RESULTS

It may first be noted that the stopping power due to hard collisions[17] is two orders of magnitude lower than the stopping powers measured here. The largest contribution from this source would arise from the experiment in which 15-keV protons were simulated by using 30-keV deuterons in H_2 gas. The hard-collision stopping power calculated here is 5.8×10^{-17} eV cm²/atom which is only 1.4% of the measured value. The interpretation of the data therefore lies in considering collisions in which the significant momentum transfers are to electrons only.

There are no theoretical predictions which apply exactly to the case studied by us, namely, the passage of H^0 through H_2 gas.

The case of H^0 projectiles through a gas of hydrogen atoms has, however, been explored, and may be compared with our experiments. Dalgarno and Griffing[14] have collected the results of calculations made by them and others, including Bates, and broken down the total

TABLE I. Results from smooth curve through data; ϵ_0 and ϵ in units of 10^{-15} eV cm²/atom.

Kinetic energy (keV)	ϵ_0 (exp)	ϵ_0 (theor) D and G	ϵ (exp)	ϵ Whaling
20	3.3±0.5	1,80	5.15±0.6	5.15±0.18
40	3.0	2.20	6.40	6.20
60	2.5	2.25	6.68	6.45
80	2.0	2.15	6.40	6.25
100	1.8	2.00	5.70	5.80
120	1.7	1.86	5.00	5.35
140	1.5	1.80	4.30	4.86
150	1.4±0.35	1.75	3.95±0.5	4.60±0.16

[12] W. Whaling, *Handbuch der Physik* (Springer-Verlag, Berlin, 1958) Vol. 34. Data by H. K. Reynolds, D. N. F. Dunbar, W. A. Wenzel, and W. Whaling, Phys. Rev. **92**, 742 (1953); J. A. Phillips, reference 9.

[13] M. Huberman, following paper [Phys. Rev. **127**, 799 (1962)].
[14] A. Dalgarno and G. W. Griffing, Proc. Roy. Soc. (London) **A232**, 423 (1955).
[15] D. R. Bates and A. Dalgarno, Proc. Phys. Soc. (London) **A65**, 919 (1952).
[16] D. R. Bates and G. W. Griffing, Proc. Phys. Soc. (London) **A66**, 961 (1953); **67**, 663 (1954); and **68**, 90 (1955).
[17] N. Bohr, Phys. Rev. **59**, 270 (1941).

TABLE II. Theoretical estimate of ϵ_0.

Dalgarno and Griffing's classification of inelastic events in H^0, H^0 collisions	Contributions to ϵ_0 as measured by the present methods.	Numerical values for 56.2 keV (10^{-15} eV cm^2/atom)
single ionization	1/2, since ionization of the projectile will be rejected	$1/2\times3.33$
double ionization	zero, because charge change is involved	...
single excitation	full amount	0.113
double excitation	full amount	0.161
simultaneous excitation and ionization	1/2, as above	$1/2\times0.603$
capture excitation	zero, since charge is changed	...
Total $\epsilon_0=2.24\times10^{-15}$ eV cm^2/atom		
ϵ_0 (obs) $=(2.6\pm0.4)\times10^{-15}$ eV cm^2/atom		

stopping power into contributions from the negative hydrogen ions, hydrogen atoms, and protons which make up the beam. Their calculations are made using wave functions characteristic of unperturbed, stationary, hydrogen atoms in the matrix elements which determine the probability of a given transition as a result of the collision. Subsequent to their calculation, Bates[18] has investigated the effect of allowing for distortion of the unperturbed wavefunctions caused by the proximity of centers of force during the collision. In the collision $H(1s)(H^+,H^+)H(2s)$, in the kinetic energy region below 100 keV (laboratory system), large errors may be made by neglecting such distortions, and the effect of the neglect is that too high a cross section is calculated.

[18] D. R. Bates, Proc. Phys. Soc. (London) **73**, 227 (1959).

Nevertheless, we shall compare our results with the calculations under the Born approximation and in the absence of distortions. Another feature of the H^0H^0 collisions calculated by them is the identity of projectile and target. Thus, the cross section for single ionization calculated theoretically for $H^0(H^0,H^+)H^0$ gives twice the contribution to the stopping power that we would observe if our method were applied to atomic hydrogen gas, since in the calculation either the projectile or the target might be the one ionized; we would reject the former case.

Table II shows a regrouping of the various inelastic events in H^0H^0 collisions which suits our experimental conditions rather than the theoretical calculations. All events in addition to those just mentioned which change the charge of the projectile are excluded.

The theoretical values of ϵ_0 in column 3 of Table I are constructed in this way, and are shown in the lower dashed curve of Fig. 4. The agreement between theory (on H^0,H^0) and experiment (on H^0,H_2) is surprisingly close from 50 to 150 keV. As we proceed from 50 keV to lower energies, the experimental values rise slightly, which is a qualitatively different behavior from that of the theoretical values, which decrease with decreasing energy.

ACKNOWLEDGMENTS

It is a pleasure to thank J. Erwood and L. Palmer for their work in maintenance and rearrangement of the equipment. The construction of the small accelerator was largely the work of J. Erwood. M. Huberman assisted us in taking data and in several of the calculations.