the triplet spin state they are of opposite sign.) This demonstrates very vividly that the long-range polarization potential has a proportionately larger effect on the higher partial waves. The results are in accord with the argument of Bransden *et al.*,[19] that the dipole polarizability make the $l>0$ phase shifts approach zero as k^2 (as $k\rightarrow 0$) rather than k^{2l+1} as predicted by the Born approximation with no r^{-4} potential present. The (relatively) large d-wave shifts, although they do not indicate any resonance in the total cross-section curve, do give considerable structure to the differential cross section even for as low an energy as 3 ev (see Figs. 2, 3, and 4).

(After this work was done, measurements of the angular distribution were completed at General Atomic Division of General Dynamics by Gilbody, Stebbings, and Fite.[23] We are indebted to them for advance communication of their results. Both the shape and absolute values of their angular distributions seem to be in satisfactory agreement with our differential cross-section curves. A more detailed analysis of this experiment and the ability to estimate the error in the absolute value may allow one to distinguish between the polarized orbital results and other calculations.)

[23] H. B. Gilbody, R. F. Stebbings, and W. L. Fite, following paper [Phys. Rev. 121, 794 (1961)].

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Collisions of Electrons with Hydrogen Atoms. VI. Angular Distribution in Elastic Scattering*

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The angular distribution of electrons scattered elastically by hydrogen atoms has been determined for electron energies below 10 ev. The elastically scattered electrons arising from the interaction of crossed electron and modulated hydrogen-atom beams were examined over an angular range extending from 30° to 120°. The results are discussed with reference to other recent experimental and theoretical developments.

I. INTRODUCTION

The elastic scattering of electrons by atoms and molecules has been of widespread interest for many years, particularly in the fields of astrophysics and gaseous electronics. Following the development of quantum mechanics in the mid-1920's, it was natural that the elastic scattering of electrons by atomic hydrogen should become the subject of many theoretical investigations. The wave functions of the target atom are completely and exactly known, so that calculated cross sections should be somewhat more accurate than in more complex scattering problems. A review of the theoretical work on this problem, however, reveals a considerable variation in results, depending on the scattering approximations used in the calculations. Clearly, it was desirable to carry out experiments on elastic scattering by atomic hydrogen to determine which of the calculations were superior.

The chemical instability of the hydrogen atom made experimentation in this area difficult, but by 1955 the development of modulated-beam techniques and crossed-beam experiments permitted the first experimental studies to be made. In these experiments a beam of atomic hydrogen, produced either by thermal dissociation in a tungsten furnace or in a high-frequency gas discharge tube, was crossed with a beam of electrons, and the electrons scattered by the beam were detected. These electrons gave rise to a signal which occurred at the beam modulation frequency and in a specified phase, while electrons scattered by the background gas gave rise to a dc signal plus noise at the modulation frequency.

The first experiment, to measure the cross section for scattering of electrons at angles greater than about 7°, was carried out by Bederson, Malamud, and Hammer[1] (BMH). The results of their experiments were surprising, in that they exceeded all of the theoretical predictions.

This immediately refocused attention on the elastic-scattering problem, and a fundamental question arose in regard to the scattering theory. This question concerned the role of the partial cross sections higher than the s-wave cross section. At low energies the quantization of angular momentum dictates that partial cross sections for $l>0$ be rather small, and most of the theoretical work prior to 1958 had been carried out for s-wave contributions only. It was conceivable that higher partial cross sections were significant—that forward scattering could be more prominent than had been

* This research was supported by a joint General Atomic-Texas Atomic Energy Research Foundation program on controlled thermonuclear reactions.

[1] B. Bederson, H. Malamud, and J. Hammer, Bull. Am. Phys. Soc. 2, 122 (1957). See also New York University Technical Report No. 2, 1958 (unpublished).

believed by the theoreticians and that the BMH results reflected the presence of strong forward scattering. Another alternative was that all scattering approximations, even for s-wave components, led to serious errors. The third alternative was, of course, that systematic errors in the BMH experiment had led them to incorrect results.

In order to clarify the situation somewhat, the elastic scattering of electrons into a right circular cone whose axis was normal to the initial electron direction was examined by Brackmann, Fite, and Neynaber[2] (BFN). In the treatment of the data, in order to relate observed cross sections to total cross sections, they assumed only s- and p-wave scattering contributions. Then the total elastic-scattering cross sections for the hydrogen atom fell in the general neighborhood of the theoretical predictions, although the data were not sufficiently good to select the "best" of the calculations which had been done up to that time, and which themselves considered no higher partial wave contributions than $l=1$.

Temkin[3] pointed out that both the BMH and BFN experiments might be correct. One can select a d-wave contribution which, when used with the s- and p-wave phase shifts of Bransden, Dalgarno, John, and Seaton,[4] will give a total cross section approximating the results of BMH and which will destructively interfere with the s-wave component to yield the 90° values of the BFN experiment. In the BFN experiment the strong forward scattering associated with a d-wave contribution would of course be completely missed.

In order to learn the extent to which d-wave and higher partial wave contributions influenced the total scattering, it was desirable to determine the entire angular distribution of the elastically scattered electrons.

The present paper summarizes the results of measurements of the angular distribution of electrons elastically scattered by atomic hydrogen in the energy range from 3.8 to 10 ev.

II. EXPERIMENTAL APPROACH

Atomic hydrogen was produced by the dissociation of hydrogen in a high-temperature tungsten furnace (Fig. 1). The beam then flowed through a differentially pumped chamber, where it was modulated at 100 cps by a mechanical chopping wheel, and any charged components which may have been present were removed by electrostatic deflection plates before the beam entered a high-vacuum chamber, where the experiment was performed.

The slow-electron gun used a standard oxide-coated cathode and cylindrical focusing elements, and exposed portions of the gun assembly were surrounded by a screening can in order to prevent any stray electrons from escaping. All metal surfaces in the vicinity of the slow electrons were gold-plated, and heating was provided to reduce the formation of surface films and preclude contact potentials. Care was taken with the positioning of current leads in the region of the slow-electron stream to avoid effects arising from the associated magnetic fields, and magnetic materials were avoided in the construction of the whole assembly.

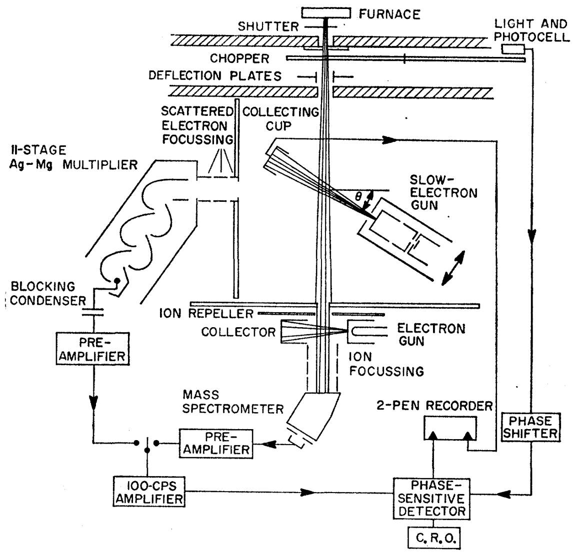

FIG. 1. Schematic diagram of the apparatus for investigating the angular distribution of electrons elastically scattered from atomic hydrogen. The slow-electron gun is rotated in plane at right angles to plane of drawing and normal to the atom beam.

In order to investigate the scattered-electron signal at different scattering angles, it was considered more convenient in the present experiment to rotate the gun assembly rather than the more complex scattered electron detector system. The atom beam passed through a circular aperture at the center of a large disk and in a direction normal to it, while the gun was placed on the disk so that the electrons moved parallel to it and thus intersected the beam at right angles. The scattering volume was determined by the cross section of the atom beam, which was 9 mm in diameter. With this arrangement the scattering volume was constant for all the scattering angles investigated.

The scattered electrons passed through a circular aperture in a plate which was normally grounded, and were focused by three cylindrical focusing elements onto the first dynode of an eleven-stage, silver-magnesium electron multiplier with a measured gain of approximately 5×10^4. This aperture subtended an angle of about 10° at the scattering center, though the effective solid angle may have been modified by the focusing characteristics of the lens system.

The ac signal from the multiplier passed into a preamplifier via a high-quality dc blocking condenser, which was necessary because the final collector of the multiplier was at the high-potential end of the dynode

[2] R. T. Brackmann, W. L. Fite, and R. H. Neynaber, Phys. Rev. **112**, 1157 (1958).
[3] A. Temkin, Phys. Rev. **116**, 358 (1959).
[4] B. H. Bransden, A. Dalgarno, T. L. John, and M. J. Seaton, Proc. Phys. Soc. (London) **71**, 877 (1958).

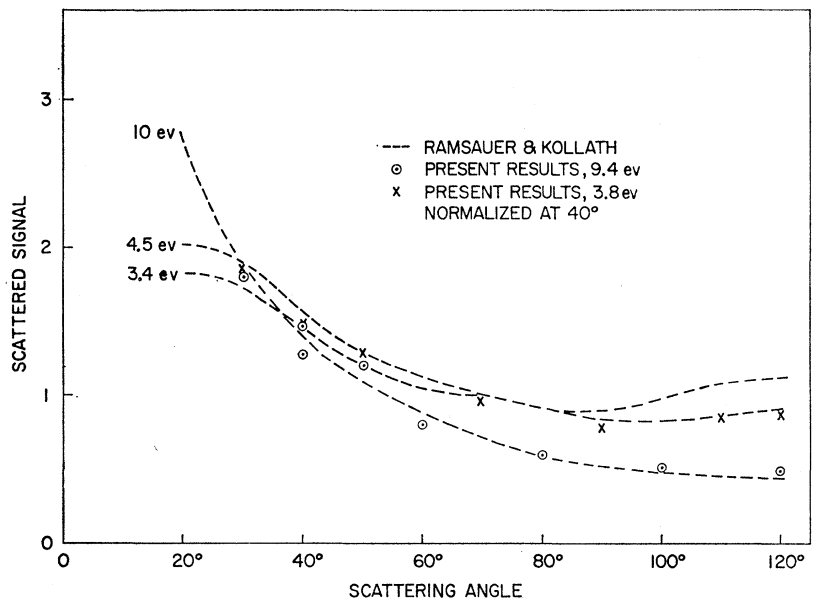

FIG. 2. Angular distribution of electrons scattered elastically by molecular hydrogen, compared with the results of Ramsauer and Kollath.

voltage-dividing chain. After further amplification by a band-pass amplifier, the signal was applied to a phase-sensitive detector whose reference signal was derived from a photocell and light at the chopper wheel. The rectified output of the detector was monitored for correct phasing on an oscilloscope before integration and display on a pen recorder. The details of the circuitry have been discussed in an earlier paper.[5]

The electron current was monitored by a small collecting cup placed in front of the gun. This cup rotated with the gun, so that the scattered current could be observed at different angles while the dc current to the collecting cup was maintained at a constant value, usually about 0.5 μamp. This system enabled the focusing characteristics of the gun to be checked. The current to the cup relative to the stray current to the large plate behind it was a useful indication of the extent to which good focusing could be maintained at the lower energies. The cup current was always over 90% of the total, down to the lowest energy used (3.8 ev). At lower energies good focusing conditions for reasonable gun currents became more difficult to achieve, and the stray 60-cps magnetic field from the furnace began to affect the slow-electron trajectories in spite of the screening of the steel-walled vacuum chamber. For these reasons measurements at energies below 3.8 ev were not made.

The electron energy was determined by a retarding potential analysis of the cup current. The energy spread at half maximum in the retarding potential characteristic was about 0.4 ev for energies below 10 ev.

The major problem encountered in this experiment was the high shot-noise background. At large scattering angles the shot noise was associated with the dc electrons scattered by the background gas. At smaller angles, the principal noise source was the current of imperfectly focused electrons from the gun that entered the detecting system directly. At angles of less than 30° the noise level was so high that reliable data could not be obtained.

A problem of no less importance arose from the fact that it was impossible to distinguish between electrons that were scattered from hydrogen atoms and those scattered from any impurity atoms which might have been present in the beam. In certain cases it would be possible for comparatively small amounts of impurities to have a large effect on the observed scattering distribution. To ascertain that atomic hydrogen was indeed the primary constituent of the beam, a mass spectrometer was incorporated into the system. A second electron gun was used to ionize the beam after it had traversed the scattering region, and the beam composition could be analyzed by comparing the peak heights corresponding to the various ions formed. Molecular hydrogen was the only significant impurity, and the dissociation fraction could be determined from the ratio of the peak heights of H^+ to H_2^+, the cross section for ionization being known in each case; the dissociation fraction was typically 90%. Details of this technique have been described previously.[6]

Preliminary experiments were made with molecular hydrogen, and the angular distributions obtained were in good agreement with those of Ramsauer and Kollath[7] (see Fig. 2). The symmetry of the angular distribution with respect to the zero position was also satisfactory,

[5] Wade L. Fite and R. T. Brackmann, Phys. Rev. **112**, 1141 (1958).

[6] W. L. Fite and R. T. Brackmann, Phys. Rev. **112**, 1151 (1958).

[7] C. Ramsauer and R. Kollath, Ann. Physik **12**, 529 (1932).

which indicated that the influence of stray magnetic fields was small.

It was possible to determine the ratio of the atomic to the molecular scattering cross sections, Q_A/Q_M, at a particular gun angle by comparing the scattered signal $S(T)$ from a highly dissociated beam corresponding to a furnace temperature T, with the signal S_r obtained from the same total flow of gas with the furnace at room temperature. Under these conditions it was previously shown[2] that

$$\frac{Q_A}{Q_M}=\frac{1}{(2D)^{\frac{1}{2}}}\left[\frac{S(T)}{S_r}\left(\frac{T}{T_r}\right)^{\frac{1}{2}}+D-1\right],$$

where D is the dissociation fraction. Q_A/Q_M was determined for a fixed gun angle of 90°, and it is interesting to note that the values obtained are in fair agreement with those of BFN (see Table I), though it should be remembered that the angular acceptance of the scattered electron detectors was different in each case.

III. RESULTS

Figure 3 shows the angular distribution obtained with atomic hydrogen for the four energies 9.4 ev, 7.1 ev, 5.7 ev, and 3.8 ev. The absolute cross section per unit solid angle was determined by normalizing the measured ratios of Q_A/Q_M to the Ramsauer and Kollath absolute molecular scattering data at 90°. The values given are the most probable ones on the basis of several runs, while the error in determining the absolute value of the cross section may be $\pm 20\%$.

It is interesting to examine the extent to which the experimental results are consistent with recent theoretical treatments of the scattering problem in which different approximations are used.

Bransden, Dalgarno, John, and Seaton[4] carried out a variational calculation that took account of both s- and p-wave scattering. In their adopted values, full allowance was made for electron exchange, and the effect of various polarization potentials on the value of the p-wave shifts was calculated using the polarization potential given by the adiabatic theory. Contributions to the total by higher-order partial waves were shown, on the basis of the Born approximation, to be small.

McEachran and Frazer[8] and more recently John[9] used a numerical method to include d-wave scattering in the calculation, and, although full allowance was

TABLE I. Values of Q_A/Q_M at various energies.

	9.4 ev	7.1 ev	5.7 ev	3.8 ev
Present results, $\pm 20\%$	0.83	0.72	0.94	1.4
BFN results	0.9	0.88	0.95	1.1

[8] R. P. McEachran and P. A. Frazer, Can. J. Phys. **38**, 317 (1960).

[9] T. L. John (private communication).

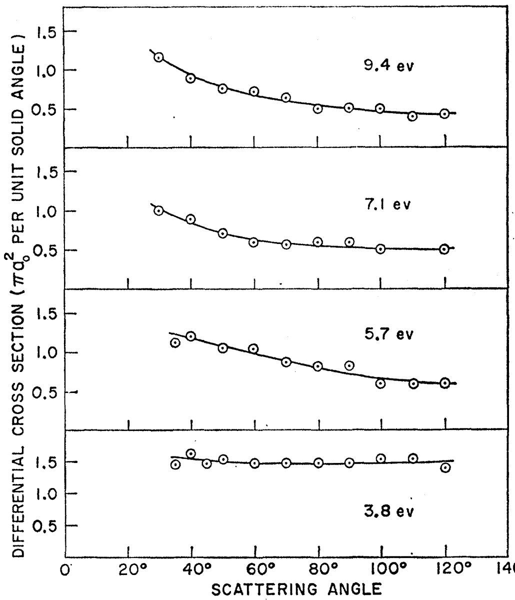

FIG. 3. Angular distribution of electrons scattered elastically by atomic hydrogen at various energies.

made for electron exchange, distortion of the atom by the scattered electron was neglected. Up to energies of 13.6 ev the inclusion of the d-wave partial scattering cross section would affect the total cross section by 1% at the most.

Geltman[10] used a variational method in which a trial function of nonseparable form was employed to allow for the virtual excitation of $2s$ and $3s$ states, and he also obtained very small values for the d-wave phase shifts.

In view of these small theoretical estimates of the d-wave scattering contribution, it was considered instructive to examine the present angular-distribution data assuming only s- and p-wave scattering to be significant.

The differential cross section is given in terms of the phase shifts by

$$I(\theta)=\frac{1}{4k^2}\left|\sum_{l=0}^{\infty}(2l+1)(e^{2i\eta_l}-1)P_l\cos\theta\right|.$$

Neglecting terms higher than $l=1$, we have

$$I(\theta)=\frac{1}{k^2}[\sin^2\eta_0+3[\sin^2\eta_0+\sin^2\eta_1-\sin^2(\eta_1-\eta_0)]\cos^2\theta+9\sin^2\eta_1\cos^2\theta],$$

which can be expressed in the form

$$I(\theta)=A+B\cos\theta+C\cos^2\theta.$$

It was possible to normalize this quadratic to the observed distribution at three points so that the co-

[10] S. Geltman, Phys. Rev. **119**, 1283 (1960).

TABLE II. Values of q_1/q_0 at various energies.

	3.8 ev	5.7 ev	7.1 ev	9.4 ev
Present results, ±20%	...	0.14	0.25	0.35
BDJS[a] with adiabatic polarization potential	0.4	0.5	0.6	0.7
John	0.09	0.19	0.23	0.28
McEachran and Frazer	0.09	0.19	0.23	0.28
Geltman	0.19	0.25	0.31	0.35

[a] See reference 4.

efficients A, B, and C could be determined. Remembering that the lth partial cross section is given by

$$q_l=\frac{4\pi}{k^2}(2l+1)\sin^2\eta_l,$$

the ratio q_1/q_0 could be obtained. This was done for the three energies 9.4 ev, 7.1 ev, and 5.7 ev, and the values are compared with several theoretical estimates in Table II.

Although the present experimental results can be explained in terms of s- and p-wave scattering only, we cannot rule out the possibility that there is an appreciable d-wave contribution. Indeed, Temkin and Lamkin,[11] using the method of polarized orbitals, have recently determined values of the d-wave shifts which, although far too small to support the results of BMH, are much larger than those given by either the exchange or the Born approximation. However, the manner in which the partial waves combine in this calculation gives resulting cross-section values which are also in fair agreement with the ones obtained in the present experiment.

In conclusion, we may say that the results do not show the strong forward peaking which would be required to substantiate the BMH results, whereas they are consistent with theory in that there are no unexpectedly large contributions from higher partial scattering cross sections. Unfortunately, the experimental uncertainties do not permit very precise comparisons with theory, so that it is not yet possible to resolve the small differences which result from different theoretical approaches.

We are indebted to a large number of theoretical physicists with whom we have discussed this problem, particularly our colleagues E. Gerjuoy and N. A. Krall, as well as A. Temkin, S. Geltman, and K. Smith.

[11] A.Temkin and J. C. Lamkin, preceding paper [Phys. Rev. **121**, 788 (1960)].

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Drift Velocities of Slow Electrons in Helium, Neon, Argon, Hydrogen, and Nitrogen*

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(Received August 29, 1960)

The drift velocities of electrons in helium, neon, argon, hydrogen, and nitrogen have been measured for E/p values between 10^{-4} and 10 volt/cm-mm Hg at temperatures between 77°K and 373°K. The data were obtained from measurements of electron transit time in an improved version of the double-shutter tube developed by Bradbury and Nielsen. By applying sufficiently small voltage pulses to the control grids, it was possible to eliminate end effects present in previous experiments. Values of the momentum transfer cross sections for electrons with energies between about 0.003 and 0.05 ev are obtained which are consistent with the measured drift velocities for thermal electrons in helium, argon, hydrogen, and nitrogen. The derived momentum transfer cross section for electrons in helium is found to be independent of electron energy and equal to 5.3×10^{-16} cm². The momentum transfer cross sections for argon, hydrogen, and nitrogen vary with electron energy.

I. INTRODUCTION

THIS paper reports measurements of drift velocities of electrons in helium, neon, argon, hydrogen, and nitrogen for low E/p values using an improved technique. The immediate purpose of this study was to obtain information about elastic collision cross sections from the measurement of electron drift velocities at very low E/p. The data were obtained with the drift tube which is an improved version of the one developed by Bradbury and Nielsen.[1] In a previous report[2] results were presented for helium in which certain end corrections appeared to be necessary at very low E/p. In Sec. II in this paper a technique is described in which end effects appear to be eliminated and greater accuracy is obtained. Measurements of electron drift velocities in argon, neon, helium, hydro-

* This work was supported by the Advanced Research Projects Agency, the Office of Naval Research, and the Air Research and Development Command.

[1] N. E. Bradbury and R. A. Nielsen, Phys. Rev. **49**, 388 (1936).
[2] A. V. Phelps, J. L. Pack, and L. S. Frost, Phys. Rev. **117**, 470 (1960).