continuous radiation in each setting), the integral was evaluated by measuring the area under the line connecting the points. In this way the value of f was found to be 3.2. Wulf and Deming[4] predicted a total oscillator strength of 3.27 for these two transitions. They do not consider their value to be accurate because the calculations were made on the basis of dispersion measurements down to only 1900A.

[4] O. R. Wulf and L. S. Deming, Terrestrial Magnetism and Atm. Elec. **43**, 284 (1938).

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Professor W. B. Pietenpol and Professor W. A. Rense and to Barbara Todd and Donald Erb for their help and encouragement in this research.

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Mobilities of Atomic and Molecular Ions in the Noble Gases*

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A method is described for measuring the mobilities of ions of near-thermal energy. A pulse of ions is generated in a discharge region and passes through a grid into a drift region where a uniform electric field causes the ions to move to a collector electrode. The mobilities are determined from measurements of the transit time of the ions in crossing the drift space. The experimental mobility values for thermal energy ions moving in their parent gases at 300°K and a gas density of 2.69×10^{19} atoms/cc are $\mu_0=10.5$ cm²/volt-sec (He^+), 20.3 (He_2^+), 4.0 (Ne^+), 6.5 (Ne_2^+), 1.60 (A^+), 2.65 (A_2^+), 0.90 (Kr^+), 1.21 (Kr_2^+), 0.58 (Xe^+), and 0.79 (Xe_2^+). These values are in good agreement with available theoretical results. Our measurements join smoothly at higher ion energies with the measurements made by Hornbeck and by Varney except in the case of A_2^+. In addition, our results indicate that earlier measurements at near-thermal energy by Tyndall and collaborators refer to the molecular ions in helium and neon, and to the atomic ions in krypton and xenon.

I. INTRODUCTION

THE mobilities of ions in gases have been the subject of numerous investigations during the last fifty years. The continuing interest in this topic arises from improvements in both the experimental and theoretical situations. Prior to 1930, impurities in the gas samples used led to conflicting results concerning the experimentally determined values of the mobilities.[1] Theoretical calculations of that period followed classical treatments based on ion-atom interactions of electrostatic origins.[2]

During the 1930's, major advances were made in both the experimental and theoretical investigations. Improvements in gas handling techniques and the development of new methods for measuring ionic mobilities[3] resulted in reliable, reproducible data. It was then found that, in cases other than ions moving in their parent gas, good agreement was often obtained between experiment and theory. The inclusion in the theory of charge exchange as part of the ion-atom interaction permitted the accurate calculation of the mobility of a positive ion in its parent gas for the particular case of He^+ in helium.[4] Unfortunately, in this one case in which the new theory could be tested, the measured mobility was roughly twice the theoretical value. As a result it was concluded that the theoretical treatment had overestimated the effect of the charge exchange interaction on the ionic mobility.

The next significant changes in our understanding of ionic mobilities occurred during the post-war period. The recently developed electronic timing and microwave techniques were used in new types of apparatus for studying the behavior of ions in gases. The data obtained from these experiments[5,6] gave a mobility for He^+ in helium which agreed with the theoretical value, but therefore disagreed with the previous measurements. It had been suggested by Meyerott[7] that the earlier measurements applied to the molecular helium ion, He_2^+, moving in helium. The existence of stable diatomic ions of noble gases, e.g. He_2^+, had been experi-

* This research has been supported in part by the U. S. Office of Naval Research.

[1] A detailed account of the history of ion mobility studies is given by L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939), Chap. I.

[2] P. Langevin, Ann. chim. phys. **5**, 245 (1905); H. R. Hasse and W. R. Cook, Phil. Mag. **12**, 554 (1931).

[3] A. M. Tyndall and C. F. Powell, Proc. Roy. Soc. (London) **A134**, 125 (1931) and A. M. Tyndall, *The Mobility of Positive Ions in Gases* (Cambridge University Press, Cambridge, 1938).

[4] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. (London) **A144**, 188 (1934).

[5] M. A. Biondi and S. C. Brown, Phys. Rev. **75**, 1700 (1949); **76**, 302 (1949); A. V. Phelps and S. C. Brown, Phys. Rev. **86**, 102 (1952).

[6] J. A. Hornbeck, Phys. Rev. **83**, 374 (1951); **84**, 615 (1951).

[7] R. Meyerott, Phys. **70**, 671 (1946).

mentally demonstrated[8] in the late 1930's. Hornbeck[6] and Phelps and Brown[5] were able to observe two ions in their experiments. By using a mass spectrometer to identify simultaneously the ions whose mobility they were measuring, Phelps and Brown were able to demonstrate conclusively that the measured mobility of He^+ agreed with the theoretical value. Earlier, Hornbeck had reached this conclusion, basing his ion identification on less direct evidence, and also had found that the mobility of the second ion (He_2^+) agreed with the experimental value of Tyndall and Powell.[3]

The most recent change in the theoretical treatments occurred when Holstein,[9] devised a general method for calculating the mobility of an ion in its parent gas. The theory was used to calculate the mobility of thermal energy He^+, Ne^+, and A^+ ions moving in their parent gases. These values were found to agree quite well with extrapolations of Hornbeck's measurements which applied to ions having greater than thermal energies. The present experiment was devised to extend mobility measurements to the thermal energy range in order to obtain an accurate comparison with theory.

II. PRINCIPLE OF THE EXPERIMENT

The mobility of an ion is defined as the ratio of the drift velocity it acquires to the electric field in which it moves, that is,

$$\mu = v/E, \tag{1}$$

where μ is the mobility, v the drift velocity, and E the applied electric field. Experimental methods for determining ion mobilities are usually based on measurements of the time required for the ion to move a known distance in an applied electric field.

In the present experiment, ions generated in a discharge region (see Fig. 1) are admitted through a grid into a constant field drift region and move through the gas until they strike the collector electrode. The motion of the ions in the drift space induces a current in the external circuit. The decrease in current which occurs when the ions arrive at the collector serves to indicate the transit time of the ions. The mobility may be determined from the relation

$$\mu = d/Et_t, \tag{2}$$

where d is the separation between the grid and collector electrode, and t_t is the transit time of the ions in crossing the drift region.

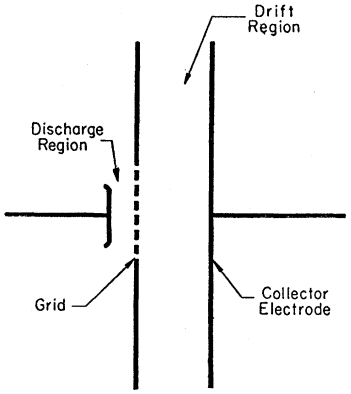

FIG. 1. Schematic arrangement of the electrodes in the mobility tube.

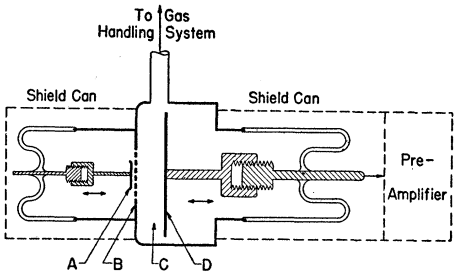

FIG. 2. Simplified drawing of the mobility tube. The discharge electrode (A) and the collector electrode (D) may be moved by means of a fine screw thread and a magnetic armature (not shown).

The generation of ions in a region outside of the drift space permits the use of small enough applied fields in the drift region so that the ions are essentially in thermal equilibrium with the gas. This technique represents an improvement over Hornbeck's method[6] in which the ions were generated by an electron avalanche in the drift space. The latter method of ion generation necessitates a *minimum* drift field which is strong enough to ionize the gas.

III. APPARATUS

The mobility tube is constructed of glass and Kovar. A simplified drawing of the tube is shown in Fig. 2. The discharge region, in which the ions are generated, is at the left. The discharge is created by the application of a short ($\sim$0.5-μsec), high-voltage pulse to electrode A. The spacing between this electrode and the grid B can be varied by means of a magnetic armature (not shown) to obtain optimum discharge conditions for various gas fillings and pressures. Some of the ions formed in the discharge move through the grid B into the drift region C. A negative dc voltage is applied to the collector electrode D, which produces the electric field in which the ions move across the drift space. The spacing between the collector electrode and the grid electrode can be changed by means of a second magnetic armature (not shown).

The collector electrode is connected to the drift voltage supply through a resistor. The induced current caused by the motion of ions in the drift space produces a voltage signal across this resistor which is approximately 10^{-4} volt in amplitude. Since a pulse of $\sim$1000 v is used to create the ions in the discharge region, it is clear that excellent shielding is required between the discharge and drift regions. The present tube achieves

[8] D. Tuxon, Z. Physik **103**, 463 (1936); F. L. Arnot and M. B. M'Ewen, Proc. Roy. Soc. (London) **A166**, 543 (1938); **A171**, 106 (1939).

[9] T. Holstein, J. Phys. Chem. **56**, 832 (1952), and Phys. Rev. (to be published).

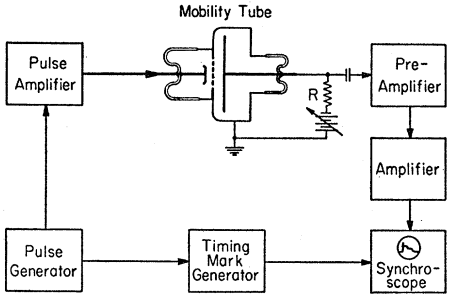

FIG. 3. Simplified block diagram of the electronic equipment used in measuring ionic mobilities.

the required degree of shielding by the use of external shield cans (the dashed lines surrounding the tube in Fig. 2) which screw onto the exterior of the metal mobility tube. The only internal coupling between the discharge and drift regions occurs through the slots in the grid which separates the two regions. The grid consists of a series of slots 0.008 in. wide, spaced 0.024 in. apart. It is found in practice that the leakage pulse from the discharge region results in negligible pickup in the collector circuit.

A simplified block diagram of the electronic equipment is given in Fig. 3. A Hewlett-Packard Model 212A Pulse Generator is used as the master timing generator. A 0.5-μsec pulse from this generator is fed to the pulse amplifier which generates a high-voltage positive pulse. This pulse is fed to the discharge electrode of the mobility tube. The electric field produced by this pulse ionizes the gas and causes the positive ions to move toward the grid. In order to create a sharply defined ion pulse in the drift region, the discharge electrode is made slightly negative ($\sim$10 v) immediately following the pulse. This sets up a retarding field which prevents ions formed in the discharge region from diffusing through the grid after the end of the pulse.

The motion of the ions in the drift space induces a current in the external circuit which is given by the relation

$$i(t)=N(t)ev/d, \tag{3}$$

where $i(t)$ is the instantaneous induced current, $N(t)$ is the number of ions moving in the drift space at the time t, e is the charge of the ions, v is their drift velocity, and d is the plate separation. If ions of more than one type are present, the resultant current is simply the sum of the contributions from each type of ion. This current is amplified by a cathode follower preamplifier which is contained in the collector electrode's shield can. The signal is further amplified by means of two Hewlett-Packard Model 450A Amplifiers and the amplifier of the Tektronix Model 511A Synchroscope. The resulting signal is fed to the y axis of the synchroscope, whose sweep is triggered by the pulse generator. The output of the timing mark generator produces intensified timing marks on the sweep trace. In order to improve the signal-to-noise ratio of the highly amplified signal, suitable filters are used at various points in the amplifiers to reduce the amplifier band width as much as is consistent with accurate reproduction of the mobility current waveform.

The gas samples used in these studies are introduced to the mobility tube by means of an ultrahigh vacuum gas handling system.[10,11] Following bakeout at 420°C for 15 hours, the system attains an ultimate vacuum of $<10^{-8}$ mm Hg and a rate of rise of contamination pressure of $<10^{-9}$ mm Hg/min. The gas samples used in these studies are Airco reagent grade gases. In all cases the source of impurities in the mobility measurements originates in the gas flasks themselves. Except in the case of argon, no further attempt has been made at purification of the Airco samples.

IV. EXPERIMENTAL MEASUREMENTS

According to Eq. (3), the instantaneous current induced in the external circuit depends on the number of ions in the drift space. Suppose that at time $t=0$ we suddenly introduce a sheet of N ions into the drift region immediately adjacent to the grid. If we neglect for the moment the effects of diffusion, all of these N ions will drift toward the collector under the action of the applied field. The current therefore shows an abrupt increase from zero to a constant value at $t=0$. At the time $t=t_t$ (the transit time required for the ions to cross the drift space) the ions all strike the collector electrode. The current will therefore abruptly drop to zero.[12] This idealized situation is illustrated by the solid curve of Fig. 4(a). In the actual experiment, diffusion

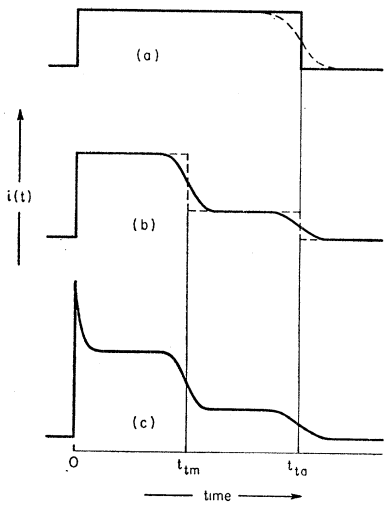

FIG. 4. Theoretical current wave forms for the mobility tube. The symbols t_{tm} and t_{ta} refer to the transit times of the molecular and the atomic ions, respectively. In part (c) the injected pulse contains roughly twice as many ions as in part (b).

[10] D. Alpert, J. Appl. Phys. **24**, 860 (1953).
[11] M. A. Biondi, Rev. Sci. Instr. **24**, 989 (1953).
[12] We have omitted the effect of electron ejection from the collector by the ions. In our low E/p experiments such effects are negligible, although electron ejection is observed at high E/p.

causes the sharply defined sheet of ions introduced into the drift region at $t=0$ to spread out as the ions drift toward the collector. As a result, the ions do not all strike the collector at $t=t_t$ but arrive at times distributed about t_t. The resultant current is illustrated by the dashed line in Fig. 4(a).

If ions of different mobility or charge are simultaneously present in the injected pulse, the current consists of components whose magnitudes are proportional to the product (Nev) for each ion. For example, in the case of atomic and molecular helium ions in helium, the mobility of He_2^+ is approximately twice that of He^+. If equal numbers of atomic and molecular ions move across the drift region, the resultant current pattern is as shown in Fig. 4(b).

Finally, we must consider the effect of "back" diffusion on the current wave form. The sharply defined ion pulse is injected through the grid into the drift region. As the ion pulse drifts away from the grid electrode toward the collector, the pulse simultaneously broadens as the result of diffusion. Some of the ions which diffuse back toward the grid strike the metallic grid surface and are neutralized. The result is that the number of ions in the drift space diminishes until the ion pulse has moved away from the grid electrode. The effect of this "back" diffusion is illustrated in Fig. 4(c).

An example of the observed current *vs* time wave forms is shown in Fig. 5. The width of the oscilloscope trace results from the noise in the amplified signal. A large amplifier gain is required to permit measurements at sufficiently low ion concentrations to avoid space charge effects. Unless the ion density is small, the applied drift field is distorted and the measurements are subject to unknown error. In addition, the ion pulse itself is broadened by mutual repulsion of the ions, leading to a less sharp indication of the transit time. The observed current wave form closely approximates the theoretically predicted shape[13] when the effects of diffusion and the finite ion pulse width are considered.

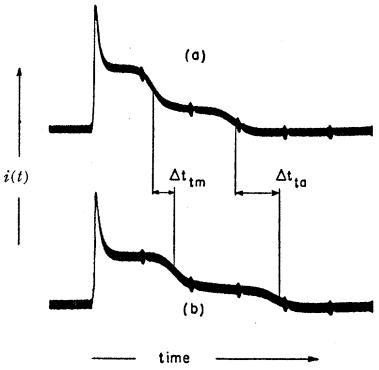

FIG. 5. Photographs of the current *vs* time wave forms for two drift distances; (a) 1.17 cm, (b) 1.54 cm. The helium pressure is 4.35 mm Hg and $E/p=5.2$ v/cm-mm Hg. The dots on the traces are 10-μsec markers.

[13] A detailed analysis of the current wave form has been carried out by I. B. Bernstein, Westinghouse Research Report R-94411-9-N (unpublished). The effect on the wave form of the conversion of atomic ions to molecular ions has not been discussed since such conversion is negligible at the pressures used in the present studies.

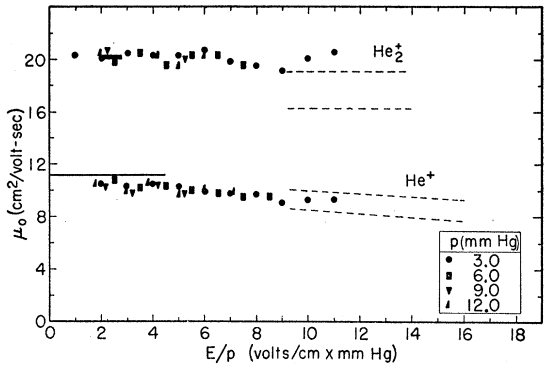

FIG. 6. Mobilities of He^+ and He_2^+ in helium. The present measurements are indicated by the symbols, Hornbeck's data by the dashed lines (mean square deviation shown), and Tyndall and Powell's measurements by the short heavy bar. The theoretical value of Massey and Mohr is shown by the solid line which is extended over the range of E/p such that $El<kT/e$.

The preceding discussion has suggested that the mobilities are determined from the transit time of the ions from the grid to the collector. Since the ions injected through the grid from the discharge region have greater than thermal energy, their motion during the first part of their transit is not characteristic of the equilibrium drift motion. In order to avoid errors due to injection velocities, measurements are actually made of the difference in transit time Δt_t, for two different drift distances. In Fig. 5(a) the grid-collector drift distance is 1.17 cm, while in Fig. 5(b) it is 1.54 cm. The differences in transit time for the molecular and the atomic ions are indicated in the figure. The ionic mobility is then calculated from the relation

$$\mu=\Delta d/E\Delta t_t, \tag{4}$$

where Δd is the difference in the drift distance.

V. RESULTS

The mobilities of atomic and molecular ions have been measured for the noble gases. It is customary to express the mobility in terms of an extrapolated value at atmospheric pressure. In the present paper, we follow Hornbeck's convention[6] and define μ_0 as the ionic mobility at a temperature of 300°K and a gas density of 2.69×10^{19} atoms/cc (equivalent to 760 mm Hg at 0°C). The results of the present measurements are shown in Figs. 6–10. We plot the mobility μ_0 *vs* the ratio of the drift field to the gas pressure E/p, which is a measure of the energy the ions gain from the field.

The results for helium are shown in Fig. 6. Our experimental data are indicated by the various symbols. The experimental values of Hornbeck[6] are indicated by the dashed lines, which show the mean square deviation

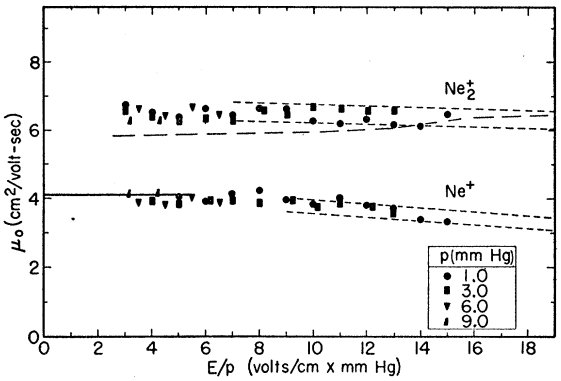

FIG. 7. Mobilities of Ne^+ and Ne_2^+ in neon. The present measurements are indicated by the symbols, Hornbeck's by the short dashed lines, Tyndall's by the long dashed line, and Holstein's theoretical value by the solid line.

in his data. The heavy line at the upper left of the figure represents Tyndall and Powell's measurements.[3] It will be seen that the various measurements agree within experimental error when proper identification is made of the ions under study.

Our measurements for He^+ agree quite well with the theoretical value of Massey and Mohr,[4] indicated by the solid line, which applies to ions which are in thermal equilibrium with the gas. In order to plot the theoretical value over the applicable range of the experimental variable E/p, we have made the assumption that the ions remain essentially in thermal equilibrium with the gas so long as

$$El \ll kT/e, \tag{5}$$

where l is the ionic mean free path, T the gas temperature, and e the ionic charge. Wannier[14] has shown that in the case of constant mean free time between collisions the average energy $\bar{u}$ of the ions is simply

$$\bar{u} = Mv^2 + \tfrac{3}{2}kT, \tag{6}$$

where M is the mass and v the drift velocity of the ions.

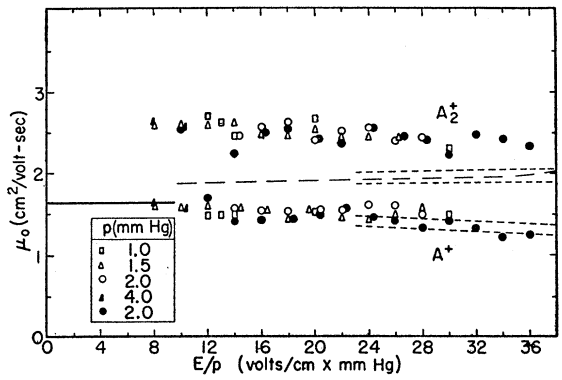

FIG. 8. Mobilities of A^+ and A_2^+ in argon. The solid circles refer to measurements made after running a magnesium clean-up arc for 24 hours. The coding of the various lines is the same as in Fig. 7.

[14] G. Wannier, Phys. Rev. **83**, 281 (1951).

In the present case the ionic mean free path, rather than the time between collisions, is nearly constant and hence Wannier's theory is only qualitatively applicable. At $E/p=1.5$, the lowest value for which experimental measurements are obtained, Eq. (6) indicates that the energy acquired from the drift field is less than ten percent of thermal energy. Thus, according to the criteria either of Eq. (5) or (6), we are sufficiently near thermal equilibrium to permit direct comparison between theory and experiment.

The measurements obtained with neon are shown in Fig. 7. Here again our measured values merge smoothly with Hornbeck's data at higher E/p. In addition, as in the case of helium, it is to be noted that the measurements of Tyndall's group apply to the molecular ion rather than to the atomic ion. Our measurements for Ne^+ are in excellent agreement with the results of Holstein's[9] theory.

The results obtained in argon (Fig. 8) disagree in part with previous measurements. Our data for the atomic ion merge smoothly at higher E/p with Hornbeck's results and are in excellent agreement with

TABLE I. Mobilities of thermal energy ions of the noble gases at 300°K and a gas density of 2.69×10^{19} atoms/cc.

	Atomic ion		Molecular ion	
	Exp.	Theory	Exp.	Theory
Helium	10.5	11.1[a]	20.3	22.7[d]
Neon	4.0	4.2[b]	6.5	···
Argon	1.60	1.62[b]	2.65	···
Krypton	0.90	1.0[c]	1.21	···
Xenon	0.58	0.66[c]	0.79	···

[a] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. (London) **A144**, 188 (1934).
[b] T. Holstein, J. Phys. Chem. **56**, 832 (1952).
[c] I. B. Bernstein (private communication).
[d] S. Geltman, Phys. Rev. **90**, 808 (1953).

theory[9] in the thermal range. However, our measurements of the faster ion, which we have indicated as A_2^+, are in disagreement with Hornbeck's and Tyndall's results. (Furthermore, it should be noted that the agreement between Hornbeck and Tyndall disappears at higher E/p, their results diverging[6] at $E/p>40$.)

The discrepancies among the various measurements probably may be attributed to impurities in the argon samples used by the different investigators. Mass spectrometric and chemical analysis of the Airco gas samples which we used indicate the presence of small amounts of nitrogen ($<1:10^4$) in our argon. It has previously been shown[15] that the heavy sputtering of magnesium electrodes from an arc run in argon removes impurities which affect the microwave breakdown potential of argon. Since breakdown measurements are very sensitive to impurities such as nitrogen, we conclude that sputtered magnesium effectively removes these impurities. Consequently, we have used a magnesium electrode arc in our gas handling system. The

[15] Krasik, Alpert, and McCoubrey, Phys. Rev. **76**, 722 (1949).

open symbols of Fig. 8 indicate the data obtained without running the clean-up arc. The solid circles were obtained after the arc had been run for 24 hours, with resultant heavy sputtering of magnesium. The lack of change in the measured mobilities indicates either that the faster ion is indeed A_2^+ or that an impurity is present which is not removed by the magnesium arc. Since nitrogen is the only known impurity present and should be removed by the arc, we feel that our measured mobility is that of A_2^+.

Additional support for this assumption is obtained by considering the mobilities of the various noble gas molecular ions. By substituting the measured thermal mobility values (see Table I) into Langevin's mobility equation[2,16] together with the measured polarizabilities of the various noble gas atoms, it is possible to compute the range of the "hard sphere" repulsion[17] between the systems He_2^+ and He, Ne_2^+ and Ne, etc. The results are summarized in Table II. If one plots the hard sphere repulsion radii calculated from our data against the mass number of the ions, one obtains a smooth curve. The repulsion range obtained from

TABLE II. Range of the hard sphere repulsion between the molecular ion and its parent gas atom.[a]

	Range (A)
Helium	2.7
Neon	3.3
Argon	4.3; [6][b]
Krypton	5.4
Xenon	5.8

[a] See reference 17.
[b] Value obtained from Hornbeck's (see reference 6) and Tyndall's (see reference 3) measurements.

Hornbeck's and Tyndall's data on argon lies 50 percent above this curve. This result supports the assumption that our measurements apply to the molecular argon ion A_2^+, rather than to some impurity ion.

The data obtained for krypton and xenon are shown in Figs. 9 and 10. It is interesting to note that in these gases, where molecular ions are more difficult to form,[18] Tyndall's group[19] actually succeeded in measuring the mobility of the *atomic* ion. Their data are indicated by the long dashes and are in good agreement with our results and the measurements at higher E/p of Varney[20] (short dashed lines). In the case of the molecular ions, Kr_2^+ and Xe_2^+, our results agree with Varney's measurements within the combined experimental errors.

[16] H. R. Hasse, Phil. Mag. **1**, 139 (1926).
[17] S. Geltman, Westinghouse Research Memo 60-94411-9-19 (unpublished). The authors are indebted for permission to use his results in Table II.
[18] J. A. Hornbeck and J. P. Molnar, Phys. Rev. **84**, 621 (1951).
[19] A. M. Tyndall and R. J. Munson, Proc. Roy. Soc. (London) **A177**, 187 (1940).
[20] R. N. Varney, Phys. Rev. **88**, 362 (1952).

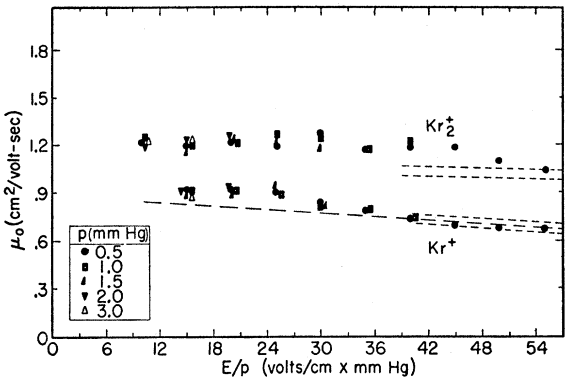

FIG. 9. Mobilities of Kr^+ and Kr_2^+ in krypton. The short dashed lines refer to the measurements of Varney and the long dashed line to those of Tyndall and Munson.

VI. DISCUSSION

The experimentally determined values of the mobilities of thermal energy ions are compared with the theoretical values in Table I. The measured values are believed accurate to ±5 percent. The theory for the ions He^+, Ne^+, and A^+, for which precise calculations have been carried out,[4,9] should involve less than a ten percent uncertainty in the calculated mobilities. The differences between the experimental and the theoretical values (<6 percent) lie well within these limits.

The calculations for Kr^+ and Xe^+ are seriously hampered by the fact that the Hartree-Fock wave functions are not known. Using a Fermi-Thomas core to calculate the wave function of the outermost electron, Bernstein[21] has made an approximate calculation of the Kr^+ and Xe^+ mobilities following the general method of Holstein.[9] The discrepancy between theory and experiment (<13 percent) is smaller than the uncertainties introduced by the imperfect knowledge of the wave functions of krypton and xenon.

The mobilities of the various atomic ions in their parent gases are especially interesting since, at room temperature, the dominant interaction between ion and

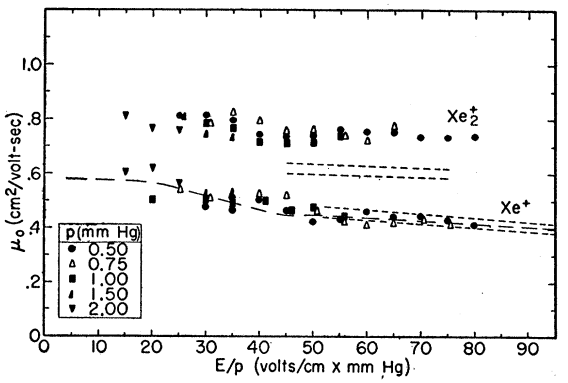

FIG. 10. Mobilities of Xe^+ and Xe_2^+ in xenon. The coding of the lines is the same as in Fig. 9.

[21] I. B. Bernstein (private communication).

atom is the resonance interaction of charge transfer. Polarization of the parent gas atoms by the ions is of only secondary importance in the scattering process, since the charge transfer between atom and ion takes place even during "distant" collisions which would normally lead to very little deflection of the particles. The very good agreement between theory and experiment is therefore an indication of the success of the quantum calculations of the resonance transfer process.

In the case of the molecular ions, only the mobility of He_2^+ has been calculated.[22] Here the resonance charge transfer process is absent, and polarization effects are of importance. The theoretical treatment is complicated, however, by the fact that the calculation of the wave function for the *mo'ecu'ar* ion is not rigorous and that the interaction between the ion and the atom during a collision depends on the orientation of the molecular ion. The uncertainties in the calculations are probably sufficient to account for the discrepancy (11 percent) between theory and experiment.

In Sec. V, it was pointed out that if one treats the molecular ion–gas atom system as a point charge interacting with a polarizable hard sphere, one can estimate the range of the "hard sphere" repulsion between ion and atom from the measured mobility values. The results of such calculations are summarized in Table II. In view of the relative insensitivity of the repulsion range to the value of the mobility, the five percent uncertainty in the measured mobility may lead to a ten percent uncertainty in the calculated range of repulsion. These molecular ion-neutral atom repulsion ranges are all approximately 30 percent larger than the corresponding atom-atom repulsion ranges estimated from viscosity data.

The present experimental techniques provide a simple method for measuring the mobilities of ions at thermal energy. The thermal energy range is especially useful for comparison with theoretical calculations since the treatment of ion distribution functions in nonthermal equilibrium cases is exceedingly difficult[14] and cannot, in general, be carried out for the various collision cross section energy dependences of interest. At the present time, the mobility measurements are being extended to studies of ions in gases other than their parent gases, e.g., Ne^+ in helium, and to the determination of temperature dependences of the various ion mobilities.

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[22] S. Geltman, Phys. Rev. **90**, 808 (1953).