4. CORRELATION OF PHOTOCONDUCTIVITY WITH EDGE LUMINESCENCE

Some CdS crystals show the so-called edge luminescence[17] while others do not. This edge luminescence is a light green luminescence under ultraviolet irradiation which shows up only when the crystal is cooled to liquid nitrogen temperature. Since the primary process in both photoconductivity and luminescence is the generation of an electron hole pair, it was thought that there might be some correlation between these two phenomena. For that reason a few observations were made on this edge luminescence. First it was established that all crystals which showed edge luminescence under ultraviolet light also show this under x-ray irradiation, and vice versa. This means that the property of a crystal being luminescent or not is a volume effect, not a surface effect.

Next the edge luminescence scintillations caused by α particles in these crystals were observed with a photomultiplier tube. These scintillations have a rise time of about a microsecond, and therefore much longer than the primary photocurrent pulses. The maximum pulse was about 50 000 photons, corresponding to 1% efficiency. In the end, however, no correlation was found between the property of being luminescent and the photoconductive behavior of the crystals.

5. CONCLUSION

The observations on CdS by previous authors were supplemented to demonstrate that a primary photocurrent could be observed in insulating crystals. No correlation was found between this primary photocurrent and the presence of edge luminescence in these crystals.

ACKNOWLEDGMENTS

I want to thank J. M. Stanley of the Signal Corps Engineering Laboratories and W. W. Piper of this Laboratory for supplying me with samples of CdS crystals.

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[17] Lambe, Klick, and Dexter, Phys. Rev. 103, 1705 (1956), and references.

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Temperature Dependence of Ion Mobilities in Helium, Neon, and Argon

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Measurements have been made of the temperature variation of the atomic and molecular ion mobilities in the parent gases, helium, neon, and argon over the range 77–300°K. The experimental values for the atomic ion mobilities are compared with calculations based on Holstein's theory. The results for neon and argon are in good agreement with the values calculated from the theory. This is in contrast to the case of helium where the experimental results lie consistently below the theoretical values. The molecular ion mobilities are compared with the temperature variation predicted by the Langevin and Hassé-Cook theories. The experimental results in neon and argon lie intermediate between the predictions of the two theories in agreement with expectations; however, the helium data cannot be reconciled with either of these theories.

RECENTLY many of the apparent discrepancies among the various ion mobility measurements have been removed as a result of more precise measuring techniques and proper identification of the ions under study.[1–4] By using a mobility tube in which measurements with small applied drift fields are possible we have been able to measure the mobilities of ions moving with near-thermal (300°K) energies.[3] The experimental values have been compared with the recently developed theory for atomic ions moving in their parent gases[5] and good agreement has been found at 300°K.

If one wishes to make a more detailed comparison with theory by studying the energy dependence of the ionic mobilities, it is preferable to vary the temperature of the gas in which the ions drift rather than to increase the drift field to change the ion energy. This situation results from the fact that ionic drift velocities, unlike those of electrons, are very difficult to calculate when the ions depart from thermal equilibrium with the gas under the action of an applied electric field.[6] Thus, to facilitate comparison with theory we have confined our measurements to drifts in small electric fields and have varied the ion's energy by varying the temperature of the gas in which they move.

I. METHOD OF MEASUREMENT

The mobility tube used in these studies has been described in detail previously.[3] The tube, which is shown schematically in Fig. 1, consists of a shielded

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[1] J. A. Hornbeck, Phys. Rev. 83, 374 (1951).

[2] R. N. Varney, Phys. Rev. 88, 362 (1952).

[3] M. A. Biondi and L. M. Chanin, Phys. Rev. 94, 910 (1954).

[4] A. M. Tyndall, *The Mobility of Positive Ions in Gases* (Cambridge University Press, New York, 1938).

[5] T. D. Holstein, J. Chem. Phys. 56, 832 (1952).

[6] See, for example, G. Wannier, Bell System Tech. J. 32, 170 (1953), and Phys. Rev. 83, 281 (1951).

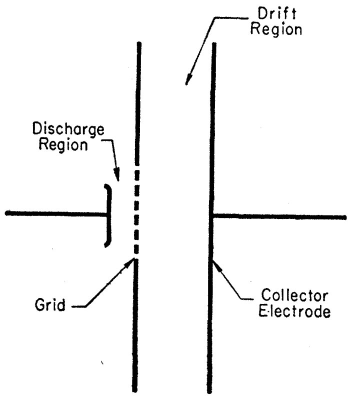

FIG. 1. Schematic arrangement of the electrodes in the mobility tube.

discharge region in which a short duration pulse of ions is generated, a grid which admits the ions to the drift space, and a collector electrode to which the ions drift under the action of an applied electric field. The motion of the ions in the drift region induces a current in an external resistor. The voltage signal across this resistor is amplified and displayed on a synchronized oscilloscope.

In order to study the variation of ion mobility with temperature, the whole mobility tube is immersed in a refrigerating bath either at 77°K (liquid nitrogen) or at 195°K (dry ice). The refrigerants are contained in a styrofoam box which surrounds the tube. At the initial cool-down, several hours are permitted to elapse before measurements are made to assure that the electrodes and gas in the tube are in thermal equilibrium at the refrigerant temperature.

The gas samples employed in these studies were Airco Reagent Grade. An ultrahigh-vacuum gas-handling system[7] was used which attained pressures $<10^{-8}$ mm Hg and rates of rise of contamination pressure $<10^{-9}$ mm Hg/min. Thus, the handling system did not add significant contamination to the gas samples as received from the supplier. Previously, in the studies carried out at 300°K, a heavily sputtered magnesium electrode arc was used in our gas-handling system to remove impurities from the argon gas samples.[3] The use of this device did not affect the measured values of the ionic mobilities. More recently we have used a cataphoresis tube[8] to purify the argon. Measurements made in this manner are identical to those made previously.

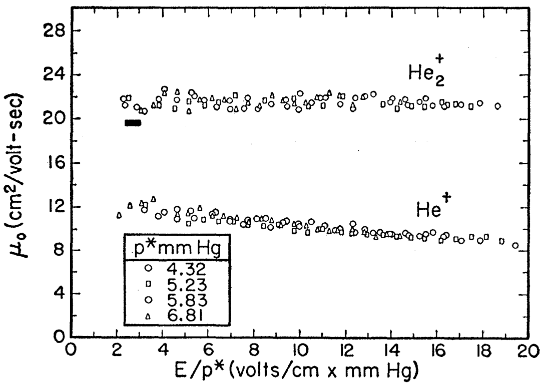

FIG. 2. Mobilities of He^+ and He_2^+ in helium at 195°K. Tyndall and Pearce's measurements are indicated by the short heavy bar. A pressure $p^*=1$ mm Hg refers to a gas density of 3.22×10^{16} atoms/cc.

II. EXPERIMENTAL RESULTS

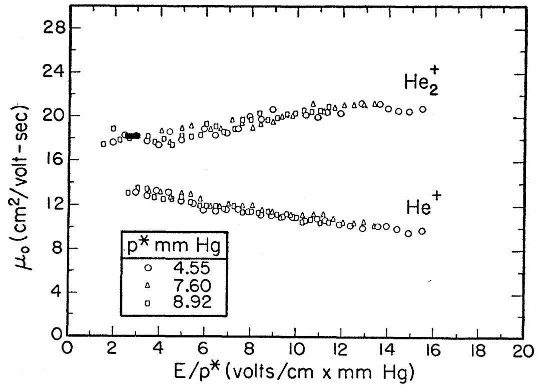

FIG. 3. Mobilities of He^+ and He_2^+ in helium at 77°K. Tyndall and Pearce's measurements are indicated by the short heavy bar.

The measured values of mobility, μ_0, *versus* the electric field to normalized pressure ratio, E/p^*, are shown in Figs. 2–7. The mobility μ_0 refers to a standard gas density of 2.69×10^{19} atoms/cc, in keeping with previous usage, while the pressures at various temperatures are normalized to constant density, i.e., $p^*=1$ mm Hg is equivalent to a gas density of 3.22×10^{16} atoms/cc. The measurements for helium, neon, and argon at 300°K are given in a previous paper.[3] Figures 2 and 3 show the measured values of the mobility of He^+ and He_2^+ in helium at 195°K and 77°K, respectively. It will be seen that the extrapolated zero-field value, $\mu_0(0)$, of the atomic ion increases from its 300°K value of 10.8 to 12.1 at 195°K and 13.5 at 77°K. These extrapolations were made on the assumption that the atomic ion mobility obeys an equation of the form[9]

$$\mu_0(0)/\mu_0(E/p)=(1+aE/p)^{\frac{1}{2}}, \qquad (1)$$

where a is a constant. This empirical form of mobility variation has the desired property that at low E/p, when the ion energy is controlled by the thermal motion of the gas atoms, the mobility becomes independent

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[7] D. Alpert, J. Appl. Phys. **24**, 860 (1953); M. A. Biondi, Rev. Sci. Instr. **24**, 989 (1953).

[8] R. Riesz and G. H. Dieke, J. Appl. Phys. **25**, 196 (1954).

[9] L. S. Frost, Phys. Rev. **105**, 354 (1957). Frost verified the validity of Eq. (1) over an extended range of E/p at 300°K by use of our data (reference 3) and that of Hornbeck (reference 1).

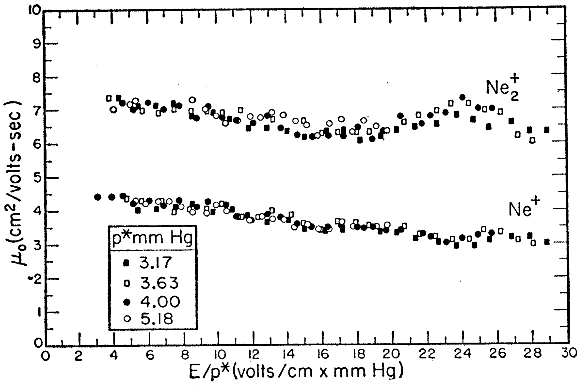

FIG. 4. Mobilities of Ne^+ and Ne_2^+ in neon at 195°K.

of E/p. The extrapolated molecular ion mobility at zero field increases from its 300°K value of 20.3 to 21.7 at 195°K but then decreases to 18.0 at 77°K.

Figures 4 and 5 show the measurements in neon at 195°K and 77°K. Combining these results with the earlier measurements,[3] we find that the extrapolated values of $\mu_0(0)$ at 300°K, 195°K, and 77°K for Ne^+ are 4.2, 4.5, and 5.2, respectively, and for Ne_2^+ are 6.5, 7.3, and 6.7, respectively.

Figures 6 and 7 refer to argon at 195°K and 77°K respectively. The values of $\mu_0(0)$ at 300°, 195°, and 77°K are 1.6, 1.95, and 2.2 for A^+ and 2.7, 2.9, and 2.7 for A_2^+. These values are compared with theoretical predictions in Sec. V.

III. ATOMIC ION THEORY

For ions of near-thermal energy the mobility, μ, is related to the momentum transfer cross section, Q_m, by[10]

$$\mu=\frac{3\sqrt{\pi}}{8}\frac{e}{(mkT)^{\frac{1}{2}}N\langle Q_m\rangle},\qquad(2)$$

where e is the ionic charge, m the common mass of the ion and the atom, T and N are gas temperature and density, respectively, and $\langle Q_m\rangle$ is the momentum transfer cross section averaged over the ion energy distribution.

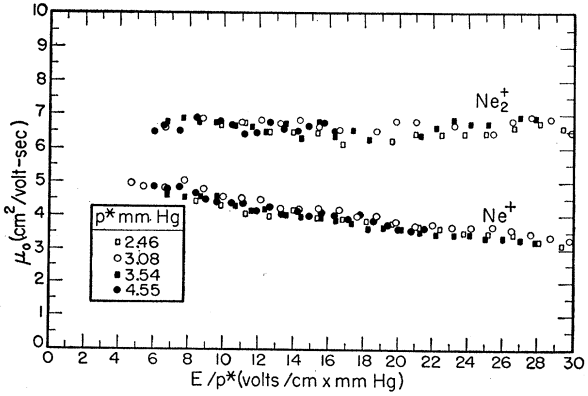

FIG. 5. Mobilities of Ne^+ and Ne_2^+ in neon at 77°K.

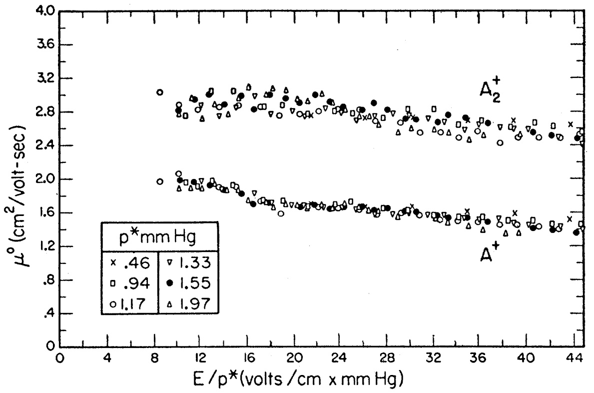

FIG. 6. Mobilities of A^+ and A_2^+ in argon at 195°K.

The theoretical calculation of the mobility of an atomic ion in its parent gas was given for the case He^+ in helium by Massey and Mohr.[11] Subsequently, Holstein[5] developed a generalized method applicable to any system, X^+ in X, for which the atomic wave functions are known. In these cases the momentum transfer cross section is largely determined by the process of charge transfer, i.e.,

$$He^+ + He \rightarrow He + He^+.$$

Holstein showed that the probability of charge transfer oscillates rapidly between 0 and 1 for distances of closest approach between ion and atom, r, ranging from zero to some critical radius, $r_{\frac{1}{2}}$, and then dies off rapidly to zero with further increase of radius.[12] Thus, the charge transfer domain may be thought of as a sphere of radius r_c (slightly larger than $r_{\frac{1}{2}}$) surrounding the atom. Inside r_c the probability of charge transfer is equal to $\frac{1}{2}$, and outside of r_c it is zero.

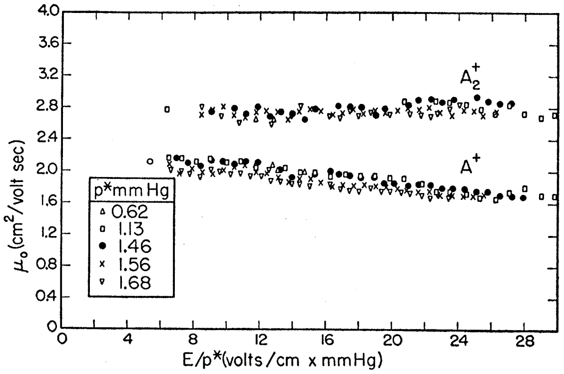

FIG. 7. Mobilities of A^+ and A_2^+ in argon at 77°K.

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[10] H. S. W. Massey, Repts. Progr. Phys. **12**, 248 (1949).

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

[12] We have changed the notation somewhat from that used in Holstein's paper to permit explicit inclusion of polarization effects in the final result.

If an ion approaches an atom, it will be deflected toward the atom as a result of the dipole moment it induces in the atom. If the distance of closest approach is greater than r_c, then only the actual deflection of the ion leads to scattering. If the ion penetrates the charge transfer sphere, then half of the time it emerges as a neutral atom and the other half remains an ion. As a result, when viewed in the center-of-mass system, these scattering events are always symmetrical about the plane perpendicular to the line of motion between ion and atom.[5] In this case the momentum transfer cross section resulting from charge transfer is simply

$$Q_m = \pi b_c^2, \tag{3}$$

when b_c is the critical impact parameter for charge transfer and is related to the critical charge-transfer radius, r_c, by

$$(b_c/r_c)^2 = 1 + (\phi_c/E), \tag{4}$$

where E is the initial kinetic energy of relative motion between ion and atom and ϕ_c is the potential energy at r_c which results from the polarization attraction, i.e.,

$$\phi_c = e^2 p / 2 r_c^4, \tag{5}$$

p being the static polarizability of the gas atom.[13] The method of calculating r_c is given in the Appendix.

At ion energies considerably less than room temperature the polarization attraction is dominant in determining the momentum transfer cross section. In this case one can quickly obtain an approximate value for Q_m by noting that at a given energy there exists a distance of closest approach between ion and atom, r_s, inside which spiralling orbits occur rather than simple deflections.[14] This distance, r_s, defines an impact parameter, b_s [through Eq. (4)], inside which, for small changes in b, the scattering angle takes on all possible values. Thus, if we neglect for the moment the contribution to Q_m of deflections for $b > b_s$, one finds that

$$Q_m(\text{spir.}) = \pi b_s^2. \tag{6}$$

One calculates r_s, the critical spiralling radius, by setting the radial kinetic energy equal to zero in the equations of motion. One then finds that

$$Q_m(\text{spir.}) = e\pi (2p/E)^{\frac{1}{2}}. \tag{7}$$

As one goes to lower ion energies the spiralling radius, r_s, exceeds the critical charge-transfer radius, r_c, and consequently the momentum transfer cross section is determined by polarization attraction alone. The exact theory of Langevin[14] shows that in the polarization limit, orbit deflections for $b > b_s$ lead to an increase of the momentum transfer cross section given by Eq. (7) by 10%. When these effects are all taken into account, one obtains for the calculated momentum transfer cross section as a function of energy the results given in Fig. 11 (see Appendix).

In order to calculate the ionic mobilities we have approximated Q_m *versus* E by a four-term power series and averaged over the Maxwellian energy distribution of the ions. The resultant mobilities for the atomic ions of helium, neon, and argon as a function of temperature are

$$1/\mu_0(\text{He}^+) = 2.96\times10^{-3}T^{\frac{1}{2}} + 3.11\times10^{-2} + 2.11\times10^{-2}T^{-1} + 6.66T^{-2},$$

$$1/\mu_0(\text{Ne}^+) = 8.69\times10^{-3}T^{\frac{1}{2}} + 9.16\times10^{-2} + 0.20T^{-1} + 59.7T^{-2},$$

$$1/\mu_0(\text{A}^+) = 2.08\times10^{-2}T^{\frac{1}{2}} + 0.24 + 1.33T^{-1} + 1.43\times10^{2}T^{-2},$$

valid over the temperature range 50 to 1200°K. These results are compared with the measured values in Sec. V.

IV. MOLECULAR ION THEORY

The calculation of the molecular ion mobilities is made simpler by the absence of charge transfer as a significant process and made more complicated by the fact that the ion is diatomic and therefore not accurately representable by a point charge or even a spherically symmetric body. Geltman[15] has attempted a rigorous calculation for the case He_2^+ in helium but has obtained rather poor agreement with experiment. The other applicable theories are the "classical" treatments of Langevin[14] and Hassé and Cook.[16]

The Langevin theory assumes that the ions are smooth elastic spheres moving in a gas consisting of elastic spheres, the atoms being polarizable in the field of the ions. The interactions between the ions and gas atoms therefore consist of a polarization attraction and a hard sphere repulsion. The velocity distributions of the ions and atoms are considered to be Maxwellian and are determined by the gas temperature. From this theory the mobility of an ion is given by

$$\mu = \frac{A(\lambda)}{[N(\epsilon-1)]^{\frac{1}{2}}}\left(1+\frac{m_a}{m_i}\right)^{\frac{1}{2}}, \tag{8}$$

where $\lambda = (kT\sigma^4/C)^{\frac{1}{2}}$, $C = pe^2/2$, σ is the sum of radii of ion and atom, m_a and m_i are the masses of the gas atom and ion, respectively, and ϵ is the dielectric constant. Values of $A(\lambda)$ have been tabulated by Hassé.[17]

Hassé and Cook have arrived at a different expression for the mobility assuming that the force between ion and atom has the form

$$F = \frac{\gamma}{r^5} - \frac{\beta}{r^9},$$

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[13] Landolt-Börnstein, *Atom und Molekular Physik, Part 1, Atome und Ionen* (Springer-Verlag, Berlin, 1950).

[14] P. Langevin, Ann. Chem. Phys. **5**, 245 (1905).

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

[16] H. R. Hassé and W. R. Cook, Phil. Mag. **12**, 554 (1931).

[17] H. R. Hassé, Phil. Mag. **1**, 39 (1926).

TABLE I. Comparison of experimental and theoretical values of atomic and molecular ion mobilities (in cm²/volt-sec).

		Atomic ion			Molecular ion					
		Expt.		Theory	Expt.			Theory		
Gas	Temp °K	Present	Beaty	Holstein	Present	Beaty	Tyndall Pearce	Langevin	Hassé Cook	Geltman
He	300	10.8	...	12.16	20.3	...	20.6	21.3	35.1	22.7
	195	12.1	...	13.75	21.7	...	20.6	21.5	36.2	22.0
	77	13.5	...	17.11	18.0	...	18.7	21.1	31.2	20.7
Ne	300	4.2	...	4.12	6.5	...	...	6.82	10.97	...
	195	4.5	...	4.64	7.3	...	...	6.92	11.6	...
	77	5.2	...	5.54	6.7	...	...	6.86	10.3	...
A	300	1.6	1.38	1.65	2.7	1.8	...	2.35	3.79	...
	195	1.95	...	1.85	2.9	...	...	2.42	4.02	...
	77	2.2	1.88	2.16	2.7	1.8	...	2.41	3.77	...

where γ is the usual polarization force constant and β is the repulsive force constant. The Langevin and Hassé-Cook theories differ therefore only in the form of the assumed repulsion. The mobility based on the Hassé-Cook theory is given by

$$\mu=\frac{3e(1+\eta)}{16\pi^{\frac{1}{2}}(2kT\beta)^{\frac{1}{4}}(m_r)^{\frac{1}{2}}NI(S)}, \tag{9}$$

where $S^2=2kT\beta/\gamma^2$, m_r is the reduced mass of the ion and gas atom, and η is a small constant. Tabulated values of $I(S)$ are given in the paper of Hassé and Cook. These theories require the determination of two parameters—the attractive and the repulsive force constants. The attractive force constant was taken from published values of the static dielectric constants.[13] The repulsive force constant was determined by assuming that the maximum theoretical mobility coincides with the observed experimental maximum. The comparisons of these theories with experimental results for the molecular ion mobilities are given in Figs. 8–10 and are discussed in the following section.

V. DISCUSSION

(a) Atomic Ions

The experimentally determined values of the mobilities of thermal energy ions are compared with available theoretical values in Table I. The experimental results for the atomic ion mobilities are compared with calculations made using Holstein's theory. Good agreement is found for neon and argon, the agreement being well within the errors of theory and experiment. For helium, the agreement is less satisfactory, the experimental values at 300° and 195°K lying approximately 10% below the theoretical results, and approximately 20% below at 77°K. At the present time it is not clear why one obtains less satisfactory agreement in helium, particularly since the theory requires the outer atomic shell to be an *s* shell, a condition fulfilled by helium but not by neon and argon whose outer shells are *p* shells. It seems quite unlikely that the wave functions for helium are in error by the amount indicated. The increasing discrepancy between experiment and theory with decreasing temperatures suggests that some interaction which becomes significant at lower temperatures has not been included in the theory.

The experimental data may be shown to be internally consistent in two ways. For example, in the thermal energy range the ion energy distribution is controlled by the gas temperature. As E/p is increased, the ions gain more energy from the field until at sufficiently high E/p the ion energy distribution will be controlled by the applied electric field. Hence, at sufficiently high E/p one should expect the mobilities to be independent of the gas temperature. The atomic ion data of the present experiment fulfills this condition as can be seen by reference to Figs. 2–7. At sufficiently high E/p the plots of μ *versus* E/p at 77°K merge with those at 195°K and at 300°K.

An additional check on the self-consistency of the data is provided by comparison of the variation of mobility with E/p and with temperature. For example at 77°K (Fig. 3) as E/p is increased, the atomic ion mobility decreases; hence one would expect the atomic ion mobility at higher temperatures to be less than that at 77°K. This is confirmed in Fig. 8. Similar comparisons of the atomic ion data in neon and argon can be made.

Recent experimental results obtained by Beaty[18] on the temperature variation of A^+ in A is given for comparison in Table I. The agreement is seen to be rather poor, his extrapolated results lying approximately 15% below the present results and the theoretical values. It should be noted that the conditions under which these measurements were made differ considerably from those of the present work. Beaty's results in the lower E/p range were taken at gas pressures high (~25 mm) compared to the present experiment. In addition, the results reported here extend to considerably lower values of E/p than Beaty was able to obtain, thereby minimizing uncertainties in the extrapolation down to the thermal energy range. It is interesting to note that the ratio of the atomic ion mobility at 77°K to the

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[18] E. C. Beaty, Phys. Rev. **104**, 17 (1956).

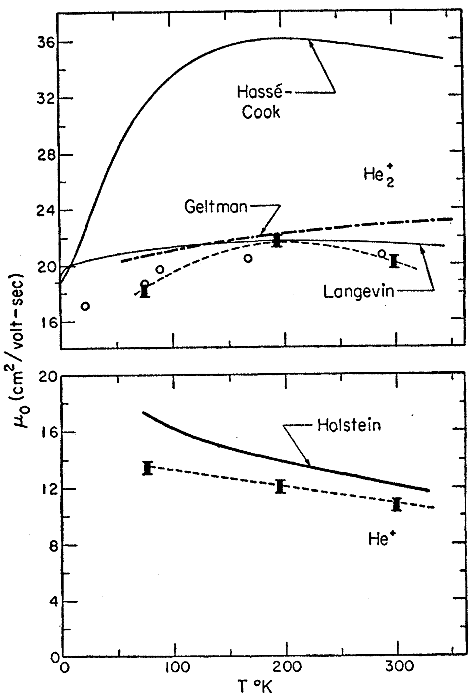

FIG. 8. Comparison of the measurements in helium as a function of temperature with available theories. The I symbols refer to the present measurements; the open circles refer to the measurements of Tyndall and Pearce.

mobility at 300°K is almost the same in both experiments.

(b) Molecular Ions

The experimental and theoretical values of the molecular ion mobilities are compared in Table I and in Figs. 8–10. The significance of the type of assumed repulsive force in the Langevin and Hassé-Cook theories is clearly demonstrated by these curves. The Langevin theory allows the mobility to increase approximately 15% over its value for a pure polarization interaction ($T=0$ limit); the Hassé-Cook theory allows approximately a 90% increase. For the case of He_2^+ it is clear that the experimental results cannot be reconciled with either of the two theoretical curves. At 77°K the mobility of He_2^+ is already below the minimum value of the mobility calculated from the theories (pure polarization interaction). For the case of neon and argon it may be seen that the results lie intermediate between the extreme cases represented by the two theories; in addition, the extrapolated mobility at 0°K agrees well with the polarization limit. It would therefore seem reasonable that the true temperature variation lies somewhere between that described by the two theories. Since the hard-sphere repulsive field used by Langevin is too hard and the inverse ninth power field of Hassé-Cook is too soft, it is felt that a theory which included a more realistic type of repulsive field (e.g., an exponentially varying short range repulsion) would give results in better agreement with experiment. However, the mathematical difficulties involved in such a theory are formidable.

As in the case of the atomic ions, examination of the *μ versus E/p* data for the molecular ions reveals that at sufficiently high *E/p* the ion mobility curves at all temperatures merge together in agreement with expectations. In addition the mobility data as a function of *E/p* are reasonably consistent with the mobility data as a function of temperature.

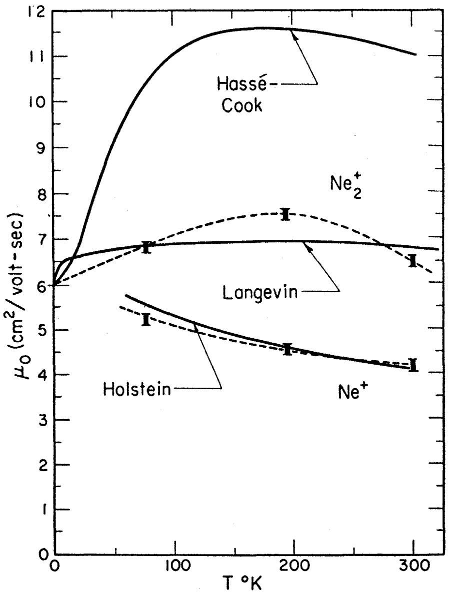

FIG. 9. Comparison of the measured Ne^+ and Ne_2^+ ion mobilities with theory.

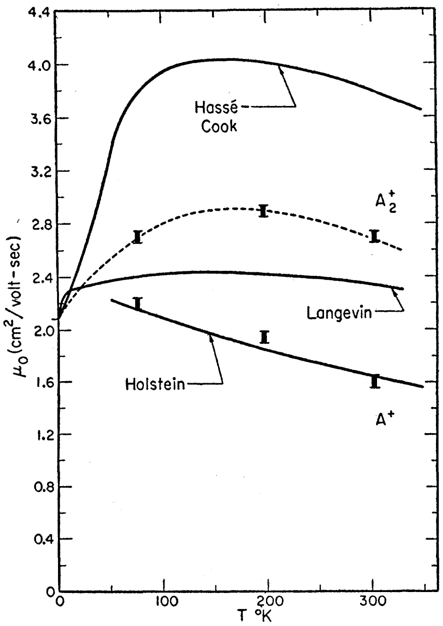

FIG. 10. Comparison of the measured A^+ and A_2^+ mobilities with theory.

The theoretical results of Geltman for He_2^+ in helium are shown in Fig. 8. The agreement of experiment with theory is rather unsatisfactory. He has also compared the experimental results of Tyndall and Pearce[19] (which agree with the present results) with Langevin's theory which has been modified to include the possibility of ionic clustering, and has obtained reasonable agreement between experiment and theory. Although there is little direct evidence to support the clustering hypothesis in simple gases and existing clustering theories are open to criticism, alternative explanations of the discrepancy between theory and experiment do not seem significantly better. From Fig. 8 it is clear that the extrapolated mobility at 0°K lies considerably below the polarization limit of the Langevin and Hassé-Cook theories. The values could be brought into agreement by a 35% increase in the dielectric constant, and in fact this would remove the discrepancy in the case of He^+; however, it is unlikely that the published dielectric constant values are in error by this amount.

Beaty's recent results for A_2^+ are given in Table I. As can be seen, the agreement with the present results is quite poor. Beaty's results were obtained at gas pressures high compared to those of the present work. At room temperature his extrapolated value for A_2^+ is 1.8 cm²/volt-sec compared to the present value of 2.7. The gas samples used in both experiments were Airco Reagent Grade, with impurities present to not more than 1 part in 10^5. The observed discrepancies are therefore probably not due to impurities. Preliminary studies at room temperature and low E/p of the dependence of the mobility of "A_2^+" on gas pressure have shown that at low pressures ($\sim$1 mm Hg) the present value is obtained. At higher pressure ($\gtrsim$5 mm Hg) two "molecular" ions are observed, one with a mobility of 2.7, in agreement with our low-pressure value, and another, 1.9, in agreement with Beaty's value. At still higher pressures the ion of mobility 2.7 is no longer observed. Since Beaty's measurements at the low E/p end of his curve are made at pressures of the order of 20 mm Hg it appears that the discrepancy between the two experiments is removed. A possible explanation for the apparent variation of molecular ion mobility with pressure is that at low pressures A_2^+ is observed while at higher pressures a more complex ion, of lower mobility, is formed. A detailed investigation of this question is in progress; therefore we should like to defer a more complete discussion to a later time.

The authors wish to thank T. Holstein and A. V. Phelps for helpful discussions and suggestions concerning the calculation of the atomic ion mobilities.

APPENDIX. CALCULATION OF THE CHARGE TRANSFER RADIUS

In Sec. III the method of calculating the momentum transfer cross section Q_m (plotted in Fig. 11), from the radius, r_c, of the "charge-transfer sphere" was outlined.

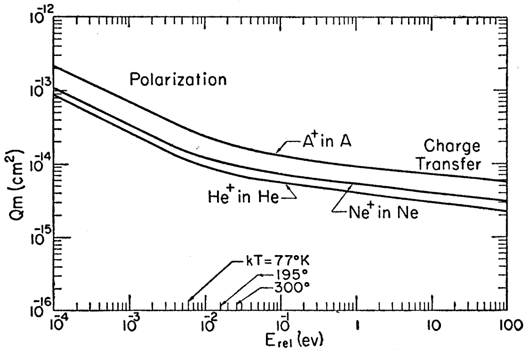

FIG. 11. Calculated variation of the momentum transfer cross section with energy.

The radius r_c was shown[5] to be slightly larger than the radius $r_{\frac{1}{2}}$ inside of which the charge-transfer probability oscillates rapidly between zero and one, being given by

$$r_c = r_{\frac{1}{2}}[1 + 1/(2r_{\frac{1}{2}})]. \tag{10}$$

The values of $r_{\frac{1}{2}}$ are determined by solution of the transcendental equation given in Holstein's paper:

$$\frac{\pi}{4} = \frac{V_1 e^{-\alpha r_{\frac{1}{2}}}}{\hbar v}\left(\frac{2\pi r_{\frac{1}{2}}}{\alpha}\right)^{\frac{1}{2}}, \tag{11}$$

where α and V_1, the interaction constants characteristic of the charge transfer process, have been calculated by Holstein[20] and are given in Table II. $\hbar$ is Planck's constant divided by 2π and v is the relative velocity between ion and atom. The details of this calculation are given elsewhere.[21]

TABLE II. Interaction constants for the charge transfer process.[a]

	Helium	Neon	Argon
V_1	$1.67R$	$0.74R$	$1.48R$
α	$1.48/a_0$	$1.31/a_0$	$1.13/a_0$

[a] Atomic units are used; thus $r = Ra_0$, where a_0 is the Bohr radius.

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[19] A. M. Tyndall and A. F. Pearce, Proc. Roy. Soc. (London) **149**, 426 (1935).

[20] T. D. Holstein (private communication).

[21] M. A. Biondi and L. M. Chanin, Westinghouse Research Report 60-94439-7-R3 (unpublished).