THE IONIZATION OF ATOMS BY ELECTRON IMPACT

By Ernest O. Lawrence*

Abstract

A method of high precision for the measurement of critical potentials. Precision in critical potential measurements in the past has been seriously limited by the lack of homogeneity in velocities of the electrons. This source of error has been eliminated by separating out magnetically electrons of definite velocities. The electron beams used in the present experiments were not characterized by great homogeneity in velocities but by *sharp upper limits* to their velocity distributions. Critical potentials were measured as the differences between two retarding potentials—the smallest retarding potential preventing the entrance of the electrons into the Faraday cylinder type of ionization chamber and the largest retarding potential for which the effect under investigation is observed—thereby eliminating errors due to contact electromotive forces.

Critical potentials in mercury vapor. The following critical potentials associated with ionization of mercury vapor have been observed: 10.40, 10.60, 11.29, 11.70 and 12.06 volts, respectively. The first is identified with simple ionization of the mercury atom while the ultraionization potentials are regarded as most probably due to simultaneous ionization and removal of another electron to a higher energy level in the atom. It is also suggested that the new critical potentials may be identified with band spectra data.

Ionization probabilities. Analysis of the data indicates very strikingly that each type of inelastic impact involving ionization has a *maximum* probability of production when the impacting electron has just enough energy to carry through the process, the law governing the probability being of the form,

$$P(e) = P_{e_0}\epsilon^{-10(e-e_0)/e_0}$$

where e_0 is the associated critical potential and e is the energy of the impacting electron. The constants P_{e_0} for the several types of impacts are as follows:

e_0	10.40	10.60	11.29	11.70
Pe_0	0.25	1.0	1.4	1.15

A correspondence principle.—The above law governing the probability of ionization by electrons is identical with the corresponding probability law governing the photo-electric ionization of caesium vapor observed by Mohler, Foote and Chenault. This fact has led to the following generalization: Light quanta and electrons obey the same general laws in processes involving ionization of atoms and molecules. In particular, the probability of atomic ionization of a certain type by a light quantum is the same function of its energy—excepting for constants—as the probability of the corresponding electron inelastic impact. The generalization correlates the author's results on the photo-electric ionization of potassium vapor, the mentioned results in caesium vapor, the observations of recent investigators on ionization probabilities by low velocity electrons and the results recorded in this paper. Furthermore, since ionization by high velocity electrons is, in the main, a process that is described on the basis of classical laws—conservation of energy and momentum—the general

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correspondence here suggested indicates that there is a similar ionization process by light quanta of great energy. *The Compton Effect bears out this implication.*

The ratio e/h. Assuming the first critical potential to be associated with the series limit frequency ν by the relation $Ve=h\nu$, the ratio e/h is determined to be 7.28×10^{16} with a probable error of 0.2 percent. In conjunction with the Bohr theory of the Rydberg constant and known spectroscopic data this leads to values for e and h individually in agreement with the accepted values.

Introduction

THERE is evidence[1] that rapidly distilling potassium vapor is in a diatomic molecular form having an ionization potential of 4.7 volts, that is, 0.4 volt greater than the atomic value observed in the vapor when in equilibrium. During the course of some experiments designed to test this point it became clear that the methods[2] usually employed in critical potential measurements were *not* able to yield results of sufficient precision. The factors which have mitigated against precision are well recognized but it may not be amiss to emphasize the most troublesome source of errors, namely, the initial distribution of velocities of the electrons from the thermionic cathode. This distribution of velocities prevents sharp "breaks" in critical potential curves and, indeed, the positions of the apparent breaks are dependent on the sensitivity of the measuring devices. This latter condition has in many cases been disregarded, perhaps because of its rather deceptive nature, although it is clear that an apparent curve break involving a Maxwellian velocity distribution may be shifted more than 0.5 volt when the scale of plotting is altered by a factor of 10.

Accordingly, a new method and technique has been developed which, as well as making possible highly accurate critical potential determinations, has produced important information on probabilities of ionization by low velocity electrons.

The Method and Experimental Arrangement

The method centers on separating out electrons of definite velocities from a thermionic source by means of a suitable series of diaphragms and magnetic field. In the original plan of the apparatus the design was such that it was thought possible to produce a beam of electrons all moving within 1 percent of a mean velocity and of a magnitude suitable for critical potential work. The initial experiments showed, however, that space charge phenomena prevented the attainment of this objective and

[1] Lawrence, Phil. Mag. **1**, 345 (1925).

[2] A complete resumé of critical potential methods and results is contained in a bulletin of the National Research Council on "Critical Potentials," by K. T. Compton and F. L. Mohler.

the desired degree of precision was realized by producing a beam having a wider band of velocities with a *sharp upper limit.* These velocities were readily altered to any set of values simply by the superposition of additional accelerating voltages.

Figs. 1 and 2 depict the arrangement of the apparatus. Electrons are accelerated from an oxide coated filament F of special design to a grid G and after retardation pass through the first slit of the analyzing chamber AC. A portion of the entering electron stream is deflected through the circle of slits by the magnetic field, emerging into a Faraday cylinder type of ionization chamber I where they are absorbed. An insulated wire A and grid B were used to detect resulting ionization in the cylinder. The procedure was then to find the distribution of velocities of the electrons entering the Faraday cylinder by retarding potential measurements and the ionization therein as a function of its potential. It is clear that a critical potential is determined as the difference between the minimum retarding voltage that must be applied to the chamber to prevent the entrance of electrons and the maximum retarding voltage for which there is observed the phenomenon under investigation. The components of the arrangement are discussed below.

Thermionic source. One of the major difficulties centered around obtaining currents through the slits of the analyzing chamber large enough to produce measurable ionization. An ordinary filament source although capable of giving a copious supply of electrons is not alone effective because with low accelerating voltages the mutual repulsions of the electrons prohibit large currents through the narrow slits. The difficulty was overcome by inserting a grid G between the filament and first slit. The electrons were accelerated through this grid by potentials of the order of 200 volts and subsequently retarded to the low value desired when passing through the first slit. Because of the presence of vapor in the region, the electrons when traveling with the higher velocities produced a large number of positive ions. The presence of such a positive ion sheath in the neighborhood of the filament and slit permitted sufficiently large currents to pass into the analyzing chamber. Since the same vapor density existed in the analyzing chamber and the velocities of the electrons traversing the slits were in general greater than the ionization potential of the vapor, a positive space charge existed also along the path of the beam. This fact contributed to modify the magnitude of the current favorably and tended to widen the band of velocities emerging from the final slit.

The inserted side-section of the filament (Fig. 1) shows that the magnetic field due to the filament heating current was very small. The filament mounting was of tungsten so that a further distortion of the field due to the presence of magnetic materials was eliminated.

Analyzing chamber. Fig. 1 shows to scale the design of the analyzing chamber with the relative positions and sizes of the diaphragms. The electrons entered the chamber from the thermionic source through a slit .013 cm wide and 1 cm in length and emerged through a .02 cm slit. The unusually large number of diaphragms reduced to a minimum

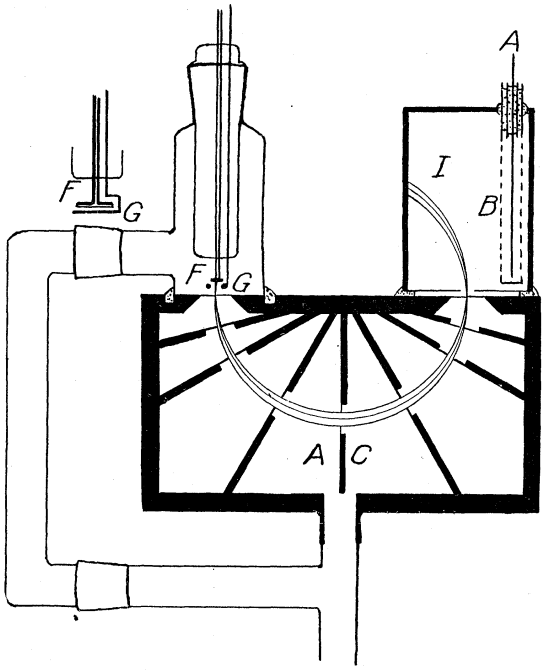

Fig. 1. Diagram of analyzing chamber.

spurious effects arising from reflections of electrons. Electric fields due to contact electromotive forces were eliminated by constructing the entire chamber from a single piece of brass material. The distance between the initial and final slits was 10 cms so that emergent electrons traversed circles of 5 cms radii. The proper widths of intervening slits relative to the first and last were carefully computed and adjusted with an accuracy of at least 0.1 percent. The brass chamber AC was assembled mechanically tight while sealing wax served to make the system vacuum tight. Fig. 1 shows the glass tube containing the thermionic source sealed

on with wax to the analyzing chamber. An arrangement of ground joints in the leads to the diffusion pumps permitted the ready removal of the glass enclosure when alterations were made.

Magnetic system. Fig. 2 indicates the arrangement of the magnetic system. The analyzing chamber was mounted on the axis of a pair of Helmholtz coils so that the slits were on a circle with center on the axis. Immediately above the chamber was mounted an earth inductor which served to show when the combined magnetic field due to the coils and the earth's field was in a direction parallel to this axis. With the expectation that accurate independent estimates of the electron velocities would be made from precise determinations of the deflecting magnetic field, the Helmholtz coils were constructed with greatest care. Machined brass castings formed beds (60 cm diam.) for 182 turns of No. 22 silk and enameled covered wire. The high degree of uniformity of the magnetic field was undoubtedly desirable for obtaining the large electron currents through the circle of narrow slits but the velocities of the emergent electrons were not uniquely dependent on the magnetic field as space charge played an important and variable role.

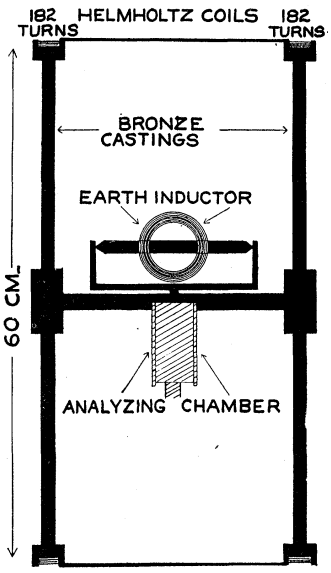

Fig. 2. Arrangement of Helmholtz coils.

Ionization chamber. A Faraday cylinder I 8.9 cm in length, 5.1 cm wide with a slit opening of 1.2 cm by 0.3 cm served as the chamber in which the ionization was measured. Several fine wires crossed the opening so that to all practical purposes the whole interior was at the same potential. The positive ions formed in the chamber were accelerated by a small voltage to a brass grid B which surrounded the brass wire collector A. The portion passing through was drawn to A by a much larger accelerating potential thereby preventing any electrons reaching the wire collector. Clearly this arrangement affected the velocities of the electrons entering the cylinder very little and minimized spurious photoelectric effects.

The electron current to the ionization chamber was measured by an electrometer connected across India ink resistances in the usual manner

while the positive ions were measured by the rate of deflection of a new type of electrometer designed by Professor W. F. G. Swann. This electrometer combined maximum sensitivity with convenient operation, ordinarily being used at a sensitivity of 8000 div. per volt.

Potentiometer. The potential of the ionization chamber relative to the final slit of the analyzing chamber was accurately maintained (exclusive of contact e.m.f.s) at any desired value by a potentiometer arrangement. A Leeds and Northrup potentiometer with Eppley standard cell accurately fixed a current of 1 milliampere flowing through a series of resistances from which potential differences were tapped. The whole system was calibrated by a Wolff potentiometer and a standard cell whose e.m.f. was known with a precision well within requirements. Thus, the applied potentials were known to within approximately 0.05 percent.

Vacuum. Mercury diffusion pumps kept pressures as registered on a McLeod gauge below a measurable value. However, in the present experiments mercury vapor was present throughout the system at a pressure corresponding to room temperature (about 27°C).

Errors

This experimental method presents several possible sources of errors and extended preliminary investigations and precautions have been taken to minimize their magnitude, as the following discussion indicates.

Contact electromotive forces. The most important source of error is concerned with contact electromotive forces of the various metal surfaces. It is important not only because of its magnitude but because of its elusiveness, a deceptive characteristic admirably illustrated in the present research. When the apparatus was first assembled consistent and reproducible results were obtained while later it was found that the experimentally observed values for the various critical potentials were assuming consistently higher values. In the course of a month the values were about 0.2 volt higher than originally and so they persisted in spite of all attempts to find the agency that had caused the change. Clearly, since a critical potential was measured as a *difference* between two potentials applied to the ionization chamber, presumably the effects of contact electromotive forces between the chamber and the slit from which the electrons issued out of the analyzing chamber would be canceled out. However, such an assumption was valid only in case the *inside* surface of the chamber had the same contact e.m.f. as the *external* surface adjacent to the analyzing chamber. This is an interesting point for it involves a fact not generally recognized, viz., that a contact e.m.f. may vary considerably over the surface of a single piece of metal, though

seemingly the metal is quite homogeneous. In view of this fact one readily recognizes that—unless the slit of the ionization chamber is designed properly with respect to the slit of the analyzing chamber—the present method may not eliminate entirely the effects of contact e.m.f.s; for when retarding potentials are applied to prevent the entrance of the electrons into the ionization chamber, the electrons proceed only to a region between the ionization chamber and the analyzing chamber and are in a potential field involving the applied retarding potential and the contact e.m.f. due to the immediately adjacent surfaces, viz., the *outside* surfaces of the analyzing and ionization chambers, while when retarding potentials are applied to merely slow down the electrons when traversing the interior of the ionization chamber the retarding potentials experienced by the electrons are made up of the applied potentials and the contact e.m.f. between the *inside* of the chamber and the final slit of the analyzing chamber. With these considerations in view, the slit of the ionization chamber was widened (the final dimensions are given in a preceding paragraph) and placed very close to the analyzing chamber (about 1 mm) so that the outside surface of the ionization chamber presumably contributed negligible contact e.m.f. fields in the region through which the electron beam passed into the ionization chamber. As a further precaution all metal surfaces were carefully sandpapered to reduce contact e.m.f.s to as nearly uniform values as possible. This done, consistent data were obtained which are regarded as highly probably free of appreciable systematic errors of this sort.

Diffusion of positive ions. There is evidence that there were some positive ions diffusing into the ionization chamber from external regions and it is not known to what extent the phenomenon has affected the observed results. In all cases, electron beams emerging from the analyzing chamber were used having velocities above the ionization potential (this was necessary to get large enough currents) so that there were positive ions present outside the ionization chamber which were drawn into the chamber by the retarding potentials applied in the experiments. Since, however, the results observed were not affected appreciably when the velocity of the electron beam issuing from the analyzing chamber was varied from about 11.0 to 15.0 volts, it is reasonable to conclude that the diffusion of positive ions from the outside did not contribute to the observed effects.

Details of technique. A large number of factors determined the nature of the electron beam and the ionization observed—such as the magnetic field, temperature of filament, various accelerating and retarding potentials, vapor pressure, etc.—and a requirement for trustworthy results

was therefore constancy of all these elements. By maintaining a constant temperature in the room and using adequate individual storage battery sources of current and potential it was possible to keep conditions constant for extended periods. This constancy was always checked by taking data in the order, first an observation of the electron velocity distribution, next observation of the ionization as a function of various retarding potentials and lastly a redetermination of the velocity distribution.

India ink resistances used to measure the electron currents became polarized to a certain extent and possible modification of observations by such a phenomenon was investigated by reversal of the direction of the polarization. In this way it was shown that the observed currents

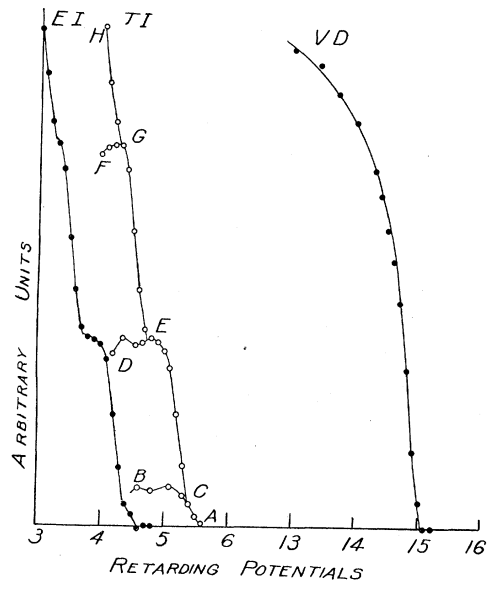

Fig. 3

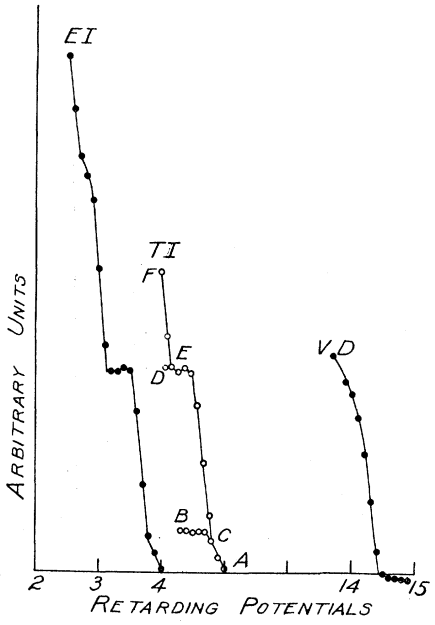

Fig. 4

Fig. 3. The ordinates of *VD* are the electron currents entering the ionization chamber corresponding to retarding potentials represented by the abscissas. (Maximum electron current about 10^{-11} amp.) The ordinates of *EI* record relative values of the ionization as a function of retarding potentials given by the abscissas. Curve *TI* is an ionization curve—abscissas shifted 1 v.—theoretically calculated from the velocity distribution assuming a succession of distinct types of ionization having the critical potentials 10.40, 10.63, 11.32, 11.80 volts respectively, and a probability law presented elsewhere in this paper. The portions *ACB*, *CED*, *DFG*, show the relative contribution of each type of ionization to the resultant ionization *ACEGH*. The agreement of *ACEGH* with the experimentally observed data *EI* is strong evidence in support of the assumed probability law and the assigned critical potentials.

Fig. 4. As in Fig. 3, the following critical potentials are estimated: 10.40, 10.63, 11.33, 11.71 volts, respectively.

were superposed on the polarization, indicating that errors of this origin were absent.

Finally, it was shown that the observed effects were independent of the small fields used to draw the positive ions out of the ionization chamber. This was demonstrated by taking data with potential differences between the grid and ionization chamber ranging from 0.02 to 3 volts.

Experimental Results

Figs. 3, 4, 5, and 6 represent typical results of the present experiments. The curves having black dotted points are the experimentally observed data while the curves drawn through circles are theoretically computed in a manner made clear in a subsequent paragraph.

For example let us consider Fig. 3. Curve *VD* is a plot of the velocity distribution of the electrons emerging from the final slit of the analyzing chamber and entering the ionization chamber, i.e., the ordinates are the observed electron currents into the ionization chamber corresponding to retarding potentials given by the abscissas. Thus, it is seen that the maximum energy of the electrons in this instance is in the neighborhood of 15 volts. The ordinates of curve *EI* represent the relative number of positive ions formed in the ionization chamber corresponding to retarding potentials given by the abscissas. Here it is seen that ionization is first noted when the retarding potential is reduced to approximately 4.6 volts. Thereby, the initial ionization potential is estimated to be 10.4 volts. We see that as the potential retarding the velocities of the ionizing electrons is decreased, the ionization increases gradually to 4.4 volts where it takes on a marked increase in the rate of increase. This change evidently marks another critical potential, that is, the setting in of another type of inelastic impact involving an energy transfer of 10.6 volts. For retarding potentials in the neighborhood of 4 volts the rate of increase of ionization with decrease in retarding potential falls off steadily to 3.7 volts where again the ionization rapidly increases. This

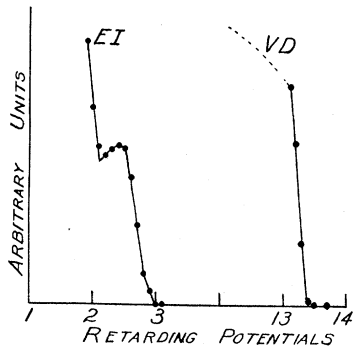

Fig. 5. The small velocity distribution brings out explicitly the decrease with increase in electron energy (over certain ranges) of the probability of inelastic impacts. The following critical potentials are estimated: 10.40, 10.60, 11.29 volts respectively.

step by step increase has been observed to progress for as many as six times, presumably constituting evidence of six distinct types of inelastic impacts of electrons with mercury atoms involving ionization. The curves of Figs. 4, 5 and 6 have a similar description and because of the different velocity distribution in each case they exhibit the information on the ionization of mercury vapor in various forms.

Inspection of these curves reveals at once that the original objective —precise determination of critical potentials—has been attained and further brings to light intensely interesting information of an unexpected sort; for it is seen that the probability of ionization in mercury vapor does not increase quite linearly from zero at the ionization potential

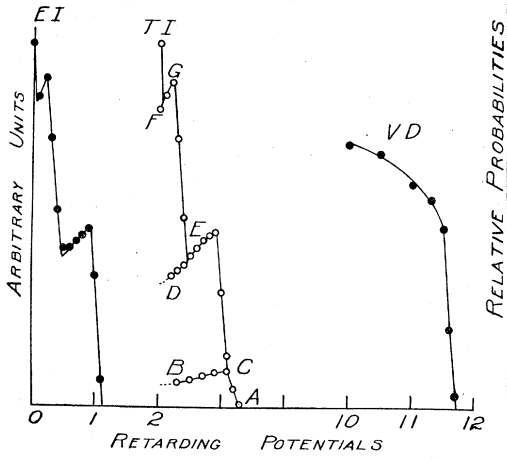

Fig. 6

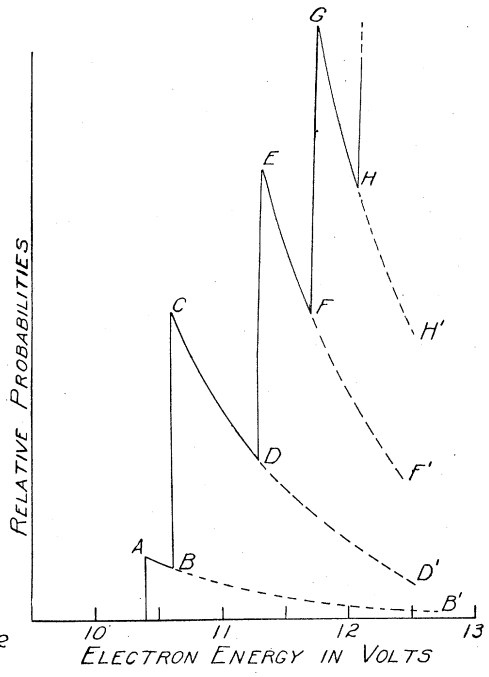

Fig. 7

Fig. 6. The theoretical curve *TI* is computed on the basis of the following critical potentials: 10.40, 10.59, 11.27, 11.63 volts. The absence of observed ionization corresponding to the initial two points of the curve *EI* is not clear but probably is due to momentary fluctuation in experimental conditions. The agreement of the experimental data with *TI* over the major portion of its extent is most striking. The critical potentials recorded are: 10.59, 11.27, 11.63 volts.

Fig. 7. The ordinates record the relative probabilities of ionization of mercury vapor by electrons of energies corresponding to the abscissas. The heavy line *ABCDEF*, etc., represents the resultant ionization probability function while *ABB'* is the probability of 10.40 volt ionization, and the ordinates between *CDD'* and *ABB'* represent the probability of ionization of the 10.60 volt type, etc.

as has been thought to be the case. On the other hand, the data indicate that the *probability of ionization is finite at the ionization potential and decreases with increase in electron energy* to a point where it takes on a sudden increment. There is a further decrease with a second subsequent increment, etc. Detailed investigation of the matter demonstrates that the probability function varies in a manner represented by the heavy continuous line of Fig. 7. We are thereby led to the interesting inference that *there are a succession of distinct types of inelastic impacts above the ionization potential in mercury vapor whose probability of production $P(e)$ varies in each case according to an exponential law, viz.,*

$$P(e) = P_{e_0} \epsilon^{-10(e-e_0)/e_0}$$

where e is the energy of the impacting electron and e_0 is the associated critical potential. Thus, the probability of stimulation of any type of atomic energy transition involving ionization by impacts of slow moving electrons is a maximum when the impacting electron has just enough energy to carry through the process, and the general increase of the probability of ionization from the ionization potential observed by various investigators[3] in the past is evidence merely of a succession of more complicated types of energy transfer than simply the removal of an optical electron from the normal orbit to infinity.

Using this probability law we may compute the forms of the experimental ionization curves from the observed velocity distribution data assuming suitable critical potentials for the various types of atomic transitions. In this way we choose values for the critical potentials which fit the experimental curves not only at the break points but throughout their extent. This permits an unusual accuracy in determination of the critical potentials. On this basis, the circles of the theoretical curves *TI* of the various figures have been computed. The complete agreement with the experimental curves demonstrates the validity of the probability law here suggested as well as the critical potentials assigned. Thus the following critical potentials have been determined:

	10.41	10.62	10.30	
	10.33	10.52	11.20	
	10.40	10.63	11.33	11.71
	10.38	10.58		
	10.40	10.63	11.32	11.80
Average	10.39	10.60	11.29	11.75

The above constitute the most recent determinations and, as indicated under "Errors", are believed to be free of appreciable systematic errors.

[3] Complete references in paper by Compton and Van Voorhis, Phys. Rev. **27**, 724 (1926).

Earlier determinations, although not trustworthy as absolute values, are useful in establishing differences between the various critical potentials and are recorded as follows:

10.40	10.60	11.35	11.70	
10.50	10.67	11.30	11.76	
10.40	10.60	11.29		
	10.59	11.27	11.63	
10.43	10.58	11.22	11.62	
10.62	10.84	11.54		
		11.20	11.60	11.96

Of the first group perhaps the most accurate average value is the second critical potential—10.60 volts. Assuming this value the determinations recorded immediately above may be corrected leading to the following average values:

10.42 10.60(*assumed*) 11.28 11.67 12.03

A general consideration of the whole mass of experimental evidence leads to the following as the most probable values for the critical potentials:

10.40 10.60 11.29 11.70 12.06

The first three values are probably correct to 0.2 percent, the fourth has a probable error of 0.3 percent while the last is of uncertain precision. These probable errors have been assigned from detailed weighting of the experimental technique—a process less arbitrary and having more meaning than a straightforward computation of probable errors in the usual manner.

The region above twelve volts has been examined only very casually and evidence has been obtained of several higher critical potentials which are closer together. At the present time, however, no reliable information of these higher ranges may be given.

The data recorded in Fig. 6 typify results that have been obtained on occasions—especially in the earlier stages of the research—which are like the rest excepting that the first critical potential at 10.4 volts is conspicuously absent. It is seen that its apparent absence may be simply due to a fluctuation in experimental conditions such as to reduce the first one or two points of the ionization curve to the axis. Furthermore, the theoretically computed curve—on the assumption of existence of 10.4 volt ionization—is so well in accord with the experimental curve over the major portion of its length that it supports the conclusion that the 10.4 volt inelastic impact was truly present. In more recent determinations when presumably the most trustworthy results were obtained 10.4 volt ionization has always been present. The conclusion is, therefore, that there is only very meagre evidence of occasional absence of 10.4 volt atomic ionization.

The relative maximum probabilities of the several types of inelastic impacts are approximately as follows:

e_0	10.40	10.60	11.29	11.70
P_{e_0}	0.25	1.0	1.4	1.15

THEORETICAL CONCLUSIONS

A correspondence principle. Perhaps the most interesting result of this research is the fact that the probability of an inelastic impact of a particular type in mercury vapor has a maximum value when the impacting electron has just enough energy to carry through the atomic energy transition, the probability varying according to the law

$$P(e) = P_{e_0}\epsilon^{-10(e-e_0)/e_0}$$

It is remarkable that this law is of the same form as the probability function for the photoelectric ionization of caesium vapor as observed in some very beautiful experiments by Foote, Mohler and Chenault.[4] This correlation suggests the following generalization:

Light quanta and electrons obey the same general laws in processes involving ionization of atoms and molecules. In particular, the probability of atomic ionization of a certain type by a light quantum is the same function of its energy—excepting for constants—as the probability of the corresponding electron inelastic impact.

This generalization brings into accord a rather extended range of experimental facts. Foote, Mohler and Chenault found photo-electric ionization decreasing from the series limit according to the probability law here enunciated and also observed an unaccountably large probability of ionization well below the series limit (at λ2536A). In view of the present experiments and the correspondence principle here suggested, the large effect at λ2536A is interpreted to be direct evidence of a second type of ionization in caesium vapor—corresponding to the 10.6 volt ionization in mercury vapor. Moreover, the author's experiments[1] on photo-electric ionization of potassium vapor are consistent with the present hypothesis and the results obtained in caesium vapor as well as the experiments of Compton and Van Voorhis, Hughes and Klein and others on probabilities of ionization by electron impact. The photo-ionization of potassium vapor was produced by relatively wide bands of wave-lengths (about 100A) and therefore the detailed variation of the probability function was not observed. The general increase of the probability function from a threshold value through a maximum corresponds well to the observed impact ionization probability functions in various

[4] Mohler, Foote and Chenault, Phys. Rev. **27**, 37–50 (1926).

vapors. The fact that the observed photo-electric threshold in potassium vapor was somewhat above the series limit is interpreted to be evidence that probabilities of the ultra-critical potential atomic transitions are so much greater as to mask the initial type of ionization.

The phenomena of the Compton effect[5] harmonizes with the suggested correspondence also. It has been known for a long time that ionization by electrons of great energy is in most cases a process that may be accounted for on the basis of classical laws, i.e., conservation of energy and momentum. Many experiments on ionization by beta rays and the absorption of beta rays in passing through matter support a theory worked out by Bohr[6] on this basis of classical electrodynamics. We would therefore infer from the general correspondence here suggested that for light quanta of great energy—high frequency—there is an ionization process which may be described by the classical laws of conservation of energy and momentum. *The Compton effect verifies this inference.*

Thus we must recognize a general similarity in ionization by light quanta and electrons. Of the many interesting speculative consequences of this correspondence mention should be made of the support of a new sort that it gives to the corpuscular light hypothesis. The analogy suggests that the interaction of radiation quanta and matter can be described by regarding the quanta as corpuscles of energy $h\nu$ momenta $h\nu/c$ and mass $h\nu/c^2$ traveling with the velocity of light c and exerting an inverse square electrical force field—traveling with infinite velocity—from an assigned virtual charge on the corpuscle.

The nature of the ultra-ionization potentials. The nature of the ultra-ionization energy transitions associated with the several observed critical potentials is as yet entirely speculative. Perhaps the most plausible view is that they involve ejection of one electron in the usual manner and simultaneous removal of another optical electron to a higher energy state (though the separations of the critical potentials are only fractions of a volt and are too small to correspond to spark spectra). A further suggestion is that these critical potentials are concerned with mercury molecules and perhaps are to be identified with energy levels associated with band spectra. Finally, it has been suggested* that the magnetic field—about 3 gauss—is concerned with the phenomena. It is possible that the atoms were oriented in several positions and each orientation possessed a distinct probability of excitation, etc. This view is supported by the fact that these critical potentials have not been observed in former

[5] A. H. Compton, Phys. Rev. **21**, 483 (1923).
[6] N. Bohr, Phil. Mag. **30**, 581 (1915).
* I am indebted to Dr. T. H. Johnson for pointing this out.

impact ionization experiments where presumably the magnetic fields present were considerably smaller (i.e., earth's field), though it seems at least the 11.3 critical potential should have evidenced itself.

The ratio e/h. The Bohr theory leads to an evaluation of the Rydberg constant in terms of known spectroscopic data and the two physical constants—the charge on the electron "*e*" and Planck's constant "*h*."[7] It is clear therefore that a measure of the ratio e/h (in conjunction with the Rydberg constant) enables a determination of both e and h. Assuming the smallest ionization potential V observed in these experiments to be associated with the series limit frequency ν according to the relation

$$Ve = 300h\nu$$

we have for the ratio e/h

$$e/h = 7.28 \times 10^{16}$$

which yields values of e and h in agreement with the accepted values[8] within the estimated experimental probable error of 0.2 percent.

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[7] Discussed in Sommerfeld's "Atomic Structure and Spectral Lines."
[8] See Millikan, The Electron; Birge, Phys. Rev. **14**, 361 (1919).