PROBABILITY OF IONIZATION OF GAS MOLECULES BY ELECTRON IMPACTS. II CRITIQUE

By K. T. Compton and C. C. Van Voorhis

Abstract

Corrections to results of Hughes and Klein. Three sources of error are found and approximate corrections for them determined. They are (1) an effect of the electric field on the effective area of holes in the grid through which the primary electrons pass, which introduces corrections varying from −18 percent at the lowest voltages to +14 percent at 300 volts; (2)presence of slow secondary electrons and lack of uniform velocity of electrons in the primary electron stream, which necessitate additive corrections ranging from 30 to 50 percent; (3) warming of the gas by the filament, necessitating an additive correction of 12 percent. *Correction to our previous results.* Owing to lack of uniformity of velocities of electrons in the primary electron stream, we must add corrections of 24 percent at 45 volts, 11 percent at 100 volts and 9 percent beyond 125 volts. With these corrections the results from these two sets of experiments are in fair agreement. Curves show the final values for the probability that an ionizing collision will be made in a cm path in the gas at 0.01 mm pressure and 25°C by an electron of any speed up to 400 volts in He, Ne, A, H_2, N_2, Hg, HCl, and also for the probabilities of ionization at an impact in these gases.

Several attempts have been made to measure directly the average ionization per centimeter path by an electron moving with known speed through a gas at definite pressure, leading to calculations of the probability of ionization at a collision as a function of the speed of the electron and the nature of the gas. Of the three recent investigations of this subject, two[1] are in qualitative agreement with each other and with earlier work,[2] while the third[3] presents unique results. The present paper is devoted to an investigation of sources of error inherent in the methods which have been used and to the correction of previous results.

In our earlier paper we pointed out that our values for probability of ionization could hardly be too large, owing to the rather direct method of making the measurements. Since the values reported by Hughes and Klein were much smaller than ours (25 to 40 percent), we constructed and tested an apparatus built to duplicate as nearly as possible the essential features of their apparatus and found inherent

[1] Hughes and Klein, Phys. Rev. **23,** 450 (1924); Compton and Van Voorhis, Phys. Rev. **26,** 436 (1925).

[2] Lenard, Ann. der Physik. **12,** 474 (1903); **15,** 484 (1904); Kossel, Ann. der Physik **37,** 393 (1912); Mayer, Ann. der Physik **45,** 1 (1914).

[3] Jesse, Phys. Rev. **26,** 208 (1925).

in their method two considerable sources of error which, together with a third error mentioned in our preceding paper, explain the low values obtained by them. The filament F, grid G and plate P were similar to the electrodes used by Hughes and Klein, but the collector C was added for reasons which will be apparent. In particular the holes in the grid were made of the same size as those in Hughes and Klein's apparatus.

Hughes and Klein measured the ionization by the positive ion current to P when a field V_1 greater than the accelerating field V_a was applied to prevent the primary electrons from the filament from reaching it. In order to measure the primary current through the grid, they reversed the field V_1 into the direction V_2 and measured the electron current to P. This current increased slowly linearly with V_2

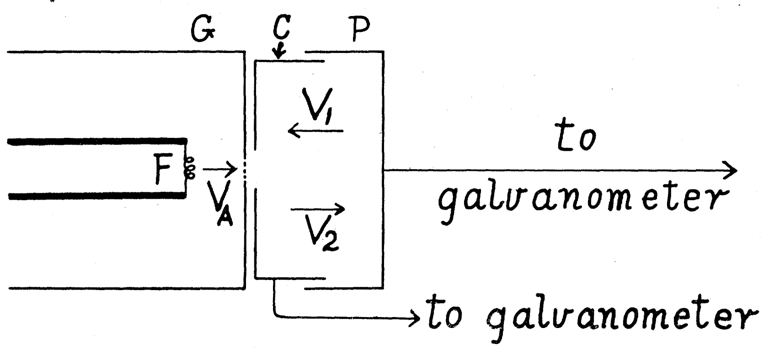

Fig. 1. Apparatus for measuring probability of ionization by the method of Hughes and Klein. The collector C was added to permit measurement of primary electron current.

for values of V_2 greater than V_a, and they assumed that by extrapolating this back to the field V_1 they would find the primary current through the grid for the field V_1.

Now this variation of electron current to P with V_2 is due in part to the action of the field on the *effective open area of the holes in the grid*. In other words, a large field V_2 will pull through the holes some electrons which, with smaller fields, would have struck the grid near these holes. A consideration of the geometry of the electric field near such holes suggested that the relation between current and field V_2 should be nearly linear *only for large values of* V_2 and that linear extrapolation through $V_2=0$ to the oppositely directed V_1 is unjustifiable.

To measure the error introduced by Hughes and Klein's extrapolation method, we measured directly the primary current through the grid, with the field V_1 just so large that no electrons reached P, by measuring the current to C which was kept at the same potential as the grid G. Then with the same fixed value of accelerating field V_a, the current to P was measured for various values of field V_2, as was done by Hughes and Klein. The results are shown in Fig. 2 in which A is the direct measurement whereas B is the value which would have been taken by the extrapolation method of Hughes and Klein. It should be noted that the direct measurement is too small, because some of the primary electrons return again through the hole in C and are not detected. The hole in C had an area of about 10 percent of the whole area of C and we think that 15 percent is probably an upper

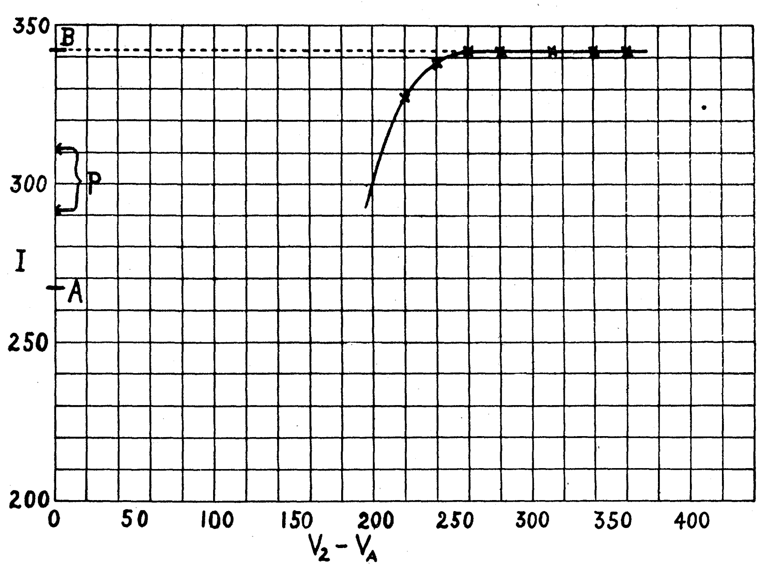

Fig. 2. Effect of retarding or accelerating field on the number of electrons passing through the holes in G. A is the actual primary electron current with sufficient retarding field to prevent electrons from reaching plate. P is this current corrected for loss through the hole in C. B is the current as estimated by Hughes and Klein.

limit to the fraction of the primary electrons which thus escape. Thus the true primary current effective in the ionization experiments should be about that indicated by P instead of B. Similar tests were made at various accelerating fields V_a. The curve I of Fig. 3 indicates the approximate corrections which should be made to Hughes and Klein's results at various voltages to take account of this source of error.

Considerably more serious is an error due to the fact that the primary electron stream, thus measured, contains a large proportion of slow secondary electrons from the grid, which contribute little or nothing to the ionization. The existence of large numbers of slow secondaries in this type of apparatus was demonstrated recently by Lehman and Osgood.[4] We made tests of the distribution of velocities of the electrons passing through the grid, by measuring the current to P for various retarding fields V_1 between 0 and V_a, and repeated this at various values of the accelerating field V_a. Without showing these curves, the following results may be stated as clearly indicated: (1) There is an ineffective group of secondaries amounting to about 15 percent at 50 volts, 22 percent at 98.5 volts, 33 percent at 151 volts, 40 percent at 202 volts and 42 percent at 290 volts. (2) The remaining effective group of electrons at each accelerating voltage is fairly homogeneous,

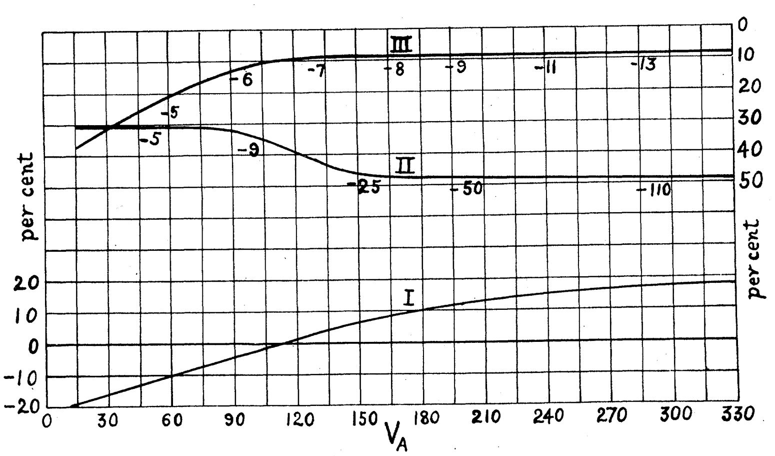

Fig. 3. Curve I gives corerctions to be applied to results of Hughes and Klein on account of the effect of the field on the number of electrons passing through the grid. Curve II gives the corrections to results of Hughes and Klein due to inhomogeneity of the primary electron beam. Curve III gives the correction due to the same cause applicable to the experiments of Compton and Van Voohris.

in that most of them have nearly the energy corresponding to the applied field, but there is always an appreciable group with variously diminished energies.

It is clearly incorrect, therefore to assume, as did Hughes and Klein, that every electron found in the primary beam has energy corresponding to the accelerating field. It is necessary first to subtract the ineffective group of slow secondaries and then to make a step by step correction to take account of the velocity distribution among the remaining electrons which are able to ionize. These corrections to Hughes and Klein's results may be made to at least the right order of magnitude by use of curve II, Fig. 3. The ordinate at any voltage V_a

[4] Lehman and Osgood, Proc. Camb. Phil. Soc. **22**, 731 (1925).

is the percentage of Hughes and Klein's value of probability of ionization at voltage $V_a-\delta$ (where δ is the number marked on the curve) which should be added to their value for voltage V_a in order to give a value of this probability at voltage V_a, which is thus corrected for the neglect of the inhomogeneity in the velocities of electrons in the primary beam.

For example, at $V_a=150$ volts, the correction to Hughes and Klein's probability of ionization, from this cause, is the addition to their value for 150 volts of 46 percent of their value for $150-25$ or 125 volts.

Finally, as we suggested in our previous paper, Hughes and Klein neglected the decrease in gas density in the region of ionization caused

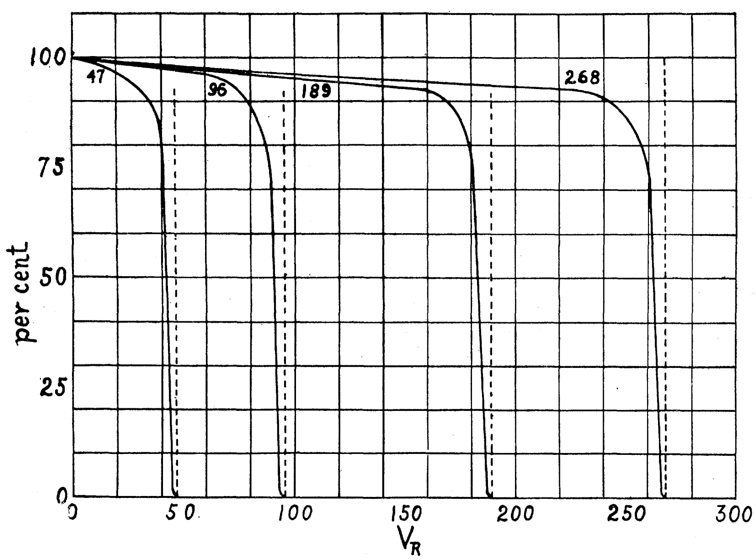

Fig. 4. Curve showing velocity distribution in primary electron beam in experiments of Compton and Van Voorhis.

by the warming of the gas by heat from the filament. In our experiments this amounted to a rise of about 25°C above the temperature of the room. The electrode arrangement of Hughes and Kein would indicate rather greater warming than in our apparatus. As a guess, which is probably fairly accurate, we may take the gas temperature in their experiments to be 60°C, which necessitates an increase of about 12 percent in all their values of probability of ionization.

Thus, to all probabilities reported by Hughes and Klein, should be added three corrections whose values are given approximately as follows: (1) a correction for variation in effective size of grid holes given by Fig. 3, curve I; (2) a correction for secondary electrons and velocity distribution of primary electrons given by curve II; (3) a correction of 12 percent for the warming of the gas by the filament.

Turning now to the values which we previously reported, we may note that the first and third corrections described in the preceding

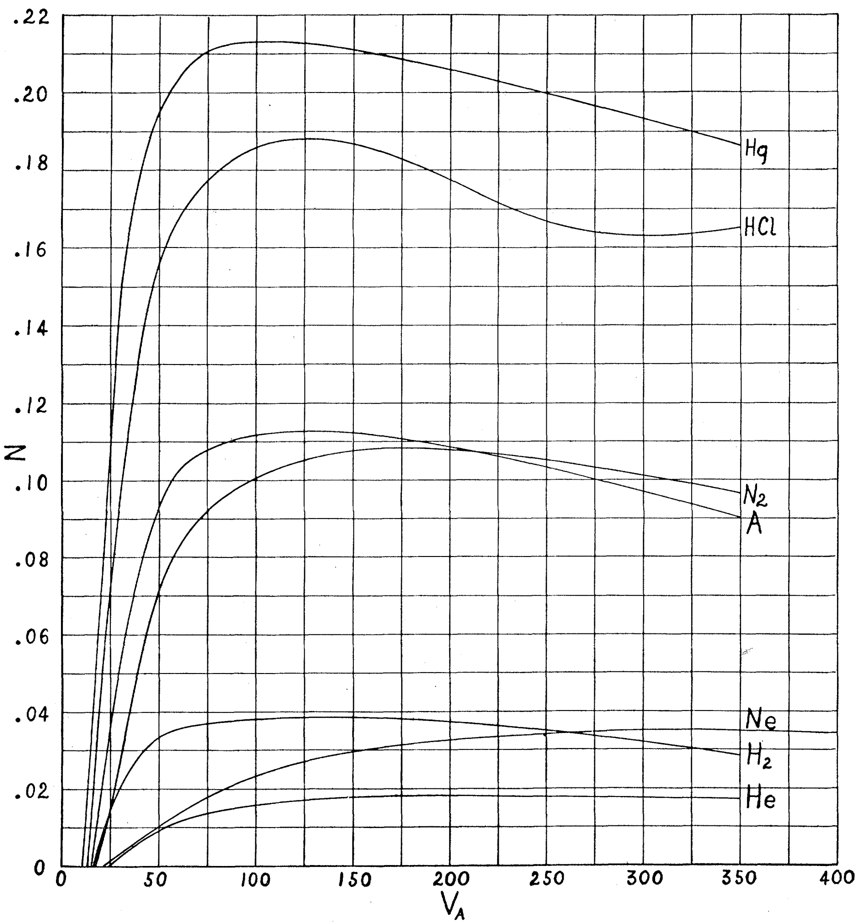

Fig. 5. Curves showing the number N of ionizing collisions made per cm path through gas at 0.01 mm pressure at 25°C.

paragraph do not need to be considered, since they were eliminated or allowed for in our original experiments. We did not, however, sufficiently consider the second source of error,—that due to velocity distribution in the primary electron stream. We have, therefore, measured the velocity distributions for various accelerating fields V_a in our original apparatus, with results shown in Fig. 4. The collecting field V_r held back all secondary electrons, so that we were not subjected to error from the phenomenon described by Lehman and Osgood The lack of homogeneity in our electron stream, however, leads to the necessity of a correction to our previous results of an amount shown in Fig. 3, curve III, which was derived from velocity distribution curves like those in Fig. 4, by the same method employed in obtaining curve II

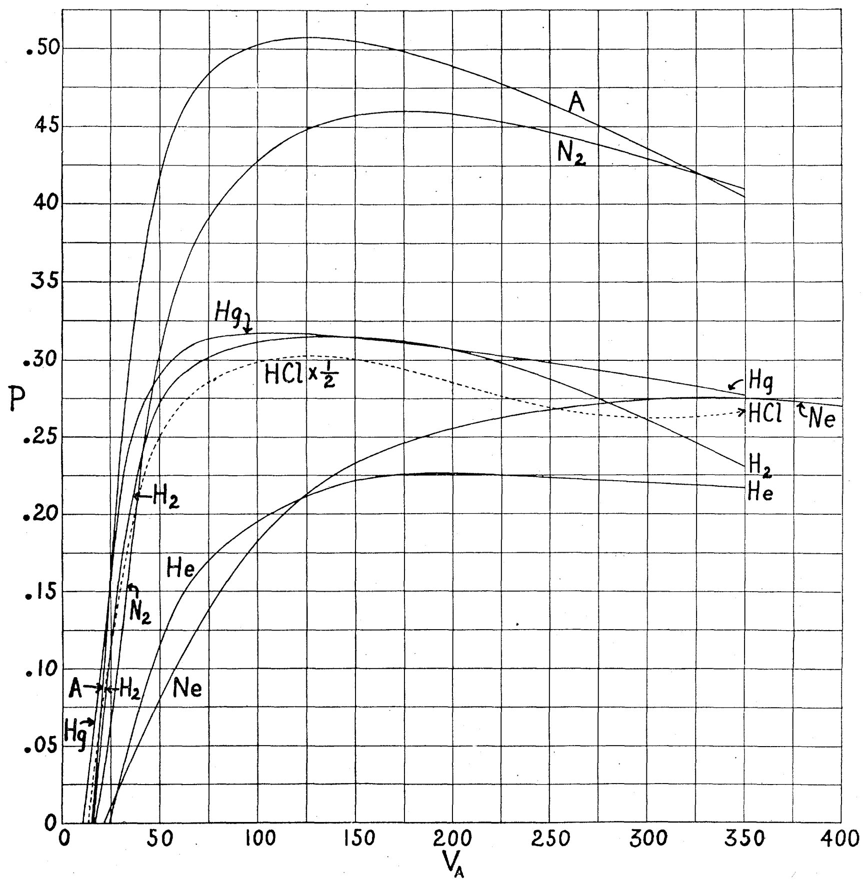

Fig. 6. Curves showing probability of ionization at a collision as a function of the speed of the impacting electron in volts.

for Hughes and Klein's results. Thus, for instance, we must add to our previous value for the ionization by 150 volt electrons, 8.5 percent of our value at 142 volts.

That the values finally arrived at in this way are fairly accurate is indicated by a comparison of our corrected results with the corrected results of Hughes and Klein, as shown in Table I. In view of the magnitude and approximate character of the corrections in the latter case, we believe the agreement is satisfactory.

TABLE I

Comparison of probabilities of ionization from corrected results of Compton and Van Voorhis and of Hughes and Klein.

Va (volts)	Helium C&VV	Helium H&K	Neon C&VV	Neon H&K	Argon C&VV	Argon H&K	Hydrogen C&VV	Hydrogen H&K	Nitrogen C&VV	Nitrogen H&K
50	.115	.109	.083	.080	.430	.434	.259	.262	.310	.333
100	.197	.155	.181	.183	.500	.496	.310	.286	.425	.457
200	.227	.201	.255	.256	.490	.527	.303	.291	.457	.502
300	.219	.175	.274	.244	.436	.473	.259	.230	.430	.422

In Figs. 5 and 6 we give the final corrected values calculated from our experiments. The values of electronic mean free paths used in calculating the probabilities shown in Fig. 6 are, for 1 mm gas pressure at 25°C, He(0.1259), Ne(0.0787), A(0.045), H_2(0.0817), N_2(0.0425), Hg(0.0149), HCl(0.0322) in cm.

Finally we have made some attempts to reconcile with these results the values reported by Jesse.[3] The complicated geometry of the electric fields, the existence of secondary and perhaps tertiary electron emission and the presence of the exposed insulating walls of the glass vessel have all been shown to introduce complicating effects, so that we have not succeeded in showing how his results may be brought into agreement with the others. Jesse cites evidence to show that his second "maximum" is spurious. Neglecting this, his results are in rough agreement with ours, as was shown in our earlier paper.

PALMER PHYSICAL LABORATORY,
PRINCETON, N. J.
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