

THE EFFECTIVE CROSS SECTION FOR ELASTIC SCATTERING OF SLOW ELECTRONS
BY HYDROGEN ATOMS

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A new version is proposed for the electric conductivity method of measuring the effective cross section for the scattering of electrons with energies $E \sim 1$ eV. This version permits the measured effect to be related reliably to a certain type of atom. It is demonstrated that the more rigorous kinetic theory formulae must be used in the calculations instead of the elementary formula usually applied to electric conductivity. The cross section for the elastic scattering of electrons with energies $E \sim 0.7$ eV by hydrogen atoms is found to be 65 ± 20 atomic units. Possible reasons are suggested for a systematic shift of the value obtained.

I. INTRODUCTION

IN recent years dozens of theoretical papers have been published on the scattering of slow electrons by hydrogen atoms. The results reported in most of these papers are in more or less satisfactory agreement for the energy region above 0.5 eV. Unfortunately this is far from being the case for the published experimental results. We know of only four experimental attempts to measure the cross sections for electron scattering with $E < 10$ eV. The cross sections reported in two of these [1,2] are included in Fig. 1.* The cross sections reported in the other two experiments [3,7] lie out-

side ($q > 100$ a.u.) our graph. Two of the main experimental attempts—the ones by Fite et al [1] and by Bedersen et al [2]—are concerned with the application of the new technique of crossed atom and electron beams. Since their virtues and shortcomings have been thoroughly discussed in [1] and [8], we shall not attempt to evaluate them here. We only emphasize that, as indicated by Fite, [8] the crossed beam technique makes it possible to obtain more or less reliable cross section values only for electrons with energies $E \geq 4$ eV. But as Fig. 1 shows, it is precisely when $E \sim 4$ eV that the discrepancy between the data in [1] and [2] attains its maximum. The sole essential difference in the conditions for these two experiments was in the selection of apertures for the scattered-electron collectors. In the case of [1] the measured current contained electrons scattered at an angle of 45 to 135°, while in [2] the minimum scattering angle accepted by the collector was 7°. Consequently, when these data are used to calculate the total cross section, the accuracy of the assumed angular distribution of the scattered electrons becomes most important.

Generally speaking, the nature of the angular distribution depends on the role played by the polarization of the atom and the contribution by the partial waves with non-zero moment in the pertinent energy region. The sharp disparity in the experimental results (see [1] and [2]) has prompted much discussion of the importance of these effects for the hydrogen atom. [4,5,9-13] However, even the most systematic allowance for polarization, which is to be found in [5], failed to

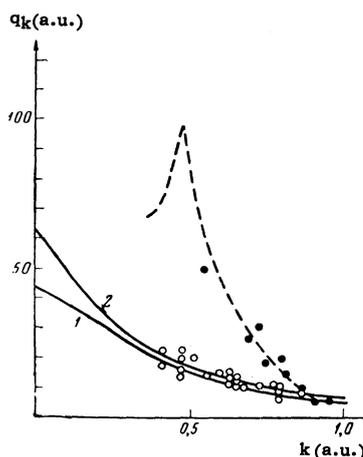


FIG. 1. Elastic scattering cross section; O — Fite's experiment [1]; ● — Bedersen's data [2]; broken curve — Bedersen's data as cited in [4]; curve 1 — theoretical calculation from [5]; curve 2 — theoretical calculation from [6]. $k = (2mE)^{1/2} \hbar^{-1}$.

*Bedersen's data have not been published in full.

yield any important increase in the cross section for $E > 0.5$ eV in comparison with predictions in which polarization was completely ignored.^[6] The solid curves in Fig. 1 represent the cross sections as calculated in ^[5] (curve 1) and ^[6] (curve 2). Both curves are in quite satisfactory agreement with Fite's measurements.^[1] Apparently, however, these measurements are more reliable than Bedersen's.^[2]

In the other two experimental attempts^[3,7] the electric conductivity method was used to measure the scattering cross sections for electrons whose mean energy was ~ 1 eV. The data obtained here are larger by almost one order of magnitude than the theoretical values (see Fig. 1), so that the two methods are in contradiction. It is worth commenting that the experimental technique for the electric conductivity method has been rather well worked out and, unlike the crossed-beam method, involves no hidden traps. Therefore, the strange discrepancy in the cross sections may mean only that some vital factor was lost sight of when the data of ^[3,7] were being processed. In this article we have attempted to resolve this problem. It appears to us that the main reason for such a large value of the cross section is that the expression used in ^[3,7] for the electric conductivity of a partially ionized plasma was too imprecise. Here we correct this defect. Moreover, we propose a new version of the electric conductivity method to permit a more reliable determination of the cross section for the scattering of slow electrons by atoms.

II. ELECTRIC CONDUCTIVITY OF A PARTIALLY IONIZED PLASMA

The calculations in ^[3,7] were made using the standard formula for electric conductivity,

$$\sigma = 407N_e/T^{1/2}(N_i q_i + \Sigma N_a q_a), \quad (1)$$

where N_e , N_i , and N_a are the concentrations of electrons, ions (singly charged), and neutral atoms (or molecules); q_a and q_i are the cross sections for electron scattering by neutral particles and ions. The summation is over all the plasma components. However, this is not a rigorous formula, since it was obtained by solving an approximate equation for the mean electron velocity in which the collisions of electrons with gas particles are treated as collisions of billiard balls, i.e., with cross sections independent of velocities, and in which electron-electron interactions are completely neglected.

If there is to be a more rigorous calculation of the electric conductivity of a plasma, σ , then, of course, the Boltzmann kinetic equation must be solved, i.e., the velocity distribution function must be found for the electrons. The total current can then be expressed by an integral over the asymmetrical part of the distribution function; on the other hand, in electrodynamics the total current is, of course, expressed by the electric conductivity and dielectric constant of the medium. Further, equating these two expressions yields the required formula for σ . Ginzburg and Gurevich^[14] have solved the Boltzmann equation (with specific allowance for electron-electron collisions) and obtained for the case of a constant electric field

$$\sigma = e^2 N_e K_\sigma(P) / m \nu_{eff}, \quad (2)$$

where ν_{eff} is the so-called effective frequency of electron collisions with neutral particles and ions, with

$$\nu_{eff} = \nu_{eff a} + \nu_{eff i},$$

and where $K_\sigma(P)$ is a function of the ratio

$$P = \nu_{eff i} / \nu_{eff a},$$

and has a complicated analytic form. $K_\sigma(P) = 1.13$ when $P = 0$, and when $P \rightarrow \infty$, $K_\sigma(P)$ asymptotically tends to the value 1.95 (see ^[15]). The effective collision frequency is expressed in terms of the transport cross section $q_t(v)$ (a momentum transfer cross section), averaged over all velocities

$$\nu_{eff} = \frac{V\sqrt{2}}{3\sqrt{\pi}} \left(\frac{m}{kT}\right)^{1/2} N \int_0^\infty q_t(v) v^5 \exp\left(-\frac{mv^2}{2kT}\right) dv, \quad (3)$$

where

$$q_t(v) = 2\pi \int_0^\pi q(v, \theta) (1 - \cos \theta) \sin \theta d\theta, \quad (4)$$

and $q(v, \theta)$ is the differential cross section for elastic scattering of electrons.

Thus, the relationship in (2) is not so readily interpreted as the one in (1). Nevertheless, in a purely formal way Eq. (2) can be written in a form analogous to (1) on the basis of the circumstance that under the conditions of any experiment $K_\sigma(P)$ will be a slowly varying dimensionless function on the order of 1. To this purpose we use the usual relation

$$\nu_{eff} = N\bar{v}\langle Q \rangle \quad (5)$$

to introduce the conventional velocity averaged cross sections $\langle Q \rangle$ which act as "effective" cross sections in determining the electric conductivity.

Henceforth we shall refer to them as electric conductivity cross sections. Equating (3) and (5), we obtain

$$\langle Q \rangle = \frac{1}{6} \left(\frac{m}{kT} \right)^3 \int_0^{\infty} q_t(v) v^5 \exp \left(-\frac{mv^2}{2kT} \right) dv. \quad (6)$$

From here on the electric conductivity cross sections can be easily calculated for atoms or molecules, provided that one knows, either from experiment or calculations, the differential electron cross sections for elastic scattering $q(v, \theta)$ or that the transport cross sections $q_t(v)$ is known from quantum-mechanical calculations. To calculate the electric conductivity cross section for the ions one can use the Rutherford formula for $g(v, \theta)$. If the lower limit in (4) is selected so as to allow for Debye screening of the ionic field, we finally obtain

$$\langle Q_i \rangle = 20.2 \cdot 10^{-6} T^{-2} \lg(221T/N_e^{1/3}). \quad (7)^*$$

This cross section is about twice as large as the one calculated by the Gvozdover formula and over three times as large as the corresponding cross section found in [3,7]. Finally, for the electric conductivity of the plasma we obtain

$$\sigma = 407 N_e K_\sigma(P) / T^{1/2} [N_i \langle Q_i \rangle + \Sigma N_a \langle Q_a \rangle]. \quad (8)$$

Formula (8) is applicable to an equilibrium plasma with any degree of ionization (not more than once) in a constant electric field. It differs from the elementary formula (1) by the appearance of the $K_\sigma(P)$ term and the use of certain conventional electric conductivity cross sections $\langle Q \rangle$ instead of elastic scattering cross sections q . The validity of (8) can be checked by the following three tests: (a) application of (7) and (8) to a completely ionized plasma yields an expression that, after substitution of the numerical values for all the constants, coincides to within 3–5% with the well-known Spitzer formula; [16] b) application of (6)–(8) to the case where the cross sections do not depend on velocities leads to a reproduction of the elementary formula (1) to within 5–10%, in which for Q_i one takes the total cross section, which is about 1.5 times the value calculated by the Gvozdover formula; (c) application of (6)–(8) to a real partially ionized plasma as characterized in [17] gave thoroughly satisfactory results for a wide range of charged particle concentrations.

III. DETERMINATION OF THE $\langle Q_H \rangle$ CROSS SECTION

The state of any real quasi-stationary plasma is a function of its coordinates. Therefore, the

* $\lg = \log_{10}$.

electric conductivity also depends on the coordinates, and when its value is calculated by (8), local values for all the variables that enter into the formula must be used. In practice the most common situation is that of a plasma column with axial symmetry. Here, to find the local values for the temperature and the concentrations N_i or N_a one applies the "transverse photograph" technique and solves an Abel integral equation (see [17]). If the $\langle Q \rangle$ cross sections are known for all of the plasma components and if nonlinear plasma phenomena and field scattering can be neglected, then the total current, as calculated by the formula

$$i = 2\pi E \int_0^{\infty} \sigma(r) r dr, \quad (9)$$

should agree with the actual current strength. When the plasma state is constant, the value for the cross section of electron scattering by hydrogen atoms q_H is adjusted to yield agreement (see [3,7]). However, in this form the electric conductivity method has a serious drawback in that it does not per se permit its results to be treated as unambiguous. Since plasma conductivity is due to the collective action of all the collisions ($\Sigma N \langle Q \rangle$), accuracy in determining any single cross section depends very strongly upon the correctness (completely unchecked in [3,7]) of the assumptions as to the composition of the plasma and the magnitudes of the other cross sections. To overcome this drawback the experiment must be performed for several hydrogen concentrations N_H . In particular, when $N_H = 0$, the correctness of the cross sections for all the other plasma components can be checked. Argon can be taken as the principal gas, since at temperatures of $\sim 10^4$ °K the equilibrium constants for ionization are very close for hydrogen and argon, and a variation in the relative hydrogen concentration should not have much effect on the plasma state. Moreover, the elastic scattering cross section for argon is well known. Figure 2, a shows the dependence of the electric conductivity cross section for argon $\langle Q_{Ar} \rangle$ on temperature, the cross section here having been calculated by formula (6). For the sake of comparison the

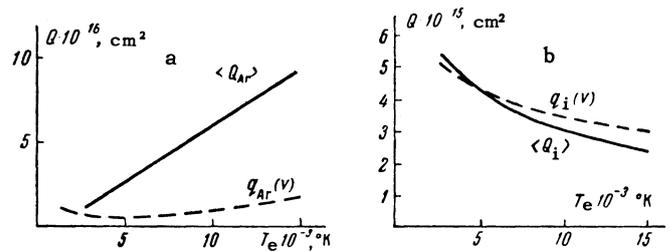


FIG. 2. Variation in $\langle Q_{Ar} \rangle$ (a) and $\langle Q_H \rangle$ (b) with temperature.

transport cross section $q_{Ar}(v)$ was calculated from the data in [18,19] and included in this same graph (with $v = \bar{v} = \sqrt{8kT/\pi m}$). The great difference in the values of these cross sections is due to the non-monotonic behavior of $q_{Ar}(v)$ (Ramsauer effect). It is interesting to note that the $\langle Q_H \rangle$ cross section, by way of contrast, scarcely differs from $q_H(v)$ over the entire temperature range of interest. Figure 2, b shows the dependence on T of the hydrogen electric conductivity cross section $\langle Q_H \rangle$, which was calculated from the data given in [6]. In the same graph $q_H(v)$ is indicated by a broken line (again with $v = \bar{v} = \sqrt{8kT/\pi m}$). Since in the energy range of interest the transport cross section for hydrogen atoms coincides to within 10% with the elastic scattering cross section, we can conclude that the $\langle Q_H \rangle$ cross section as measured by the electric conductivity method coincides, to within the experimental error, with the elastic scattering cross section for electrons with an energy $E = m\bar{v}^2/2 = 4kT/\pi$. This deduction applies, of course, only if the theoretical calculations presently in use represent accurately the dependence of $q_H(v)$ on electron energy.

A dc arc running through a mixture of hydrogen and argon under atmospheric pressure was used in the present measurements. The current was kept constant at 50 A; at this strength the volt-ampere characteristic is almost horizontal. The argon was 99.5% pure, with 0.3% nitrogen and 0.2% oxygen. The hydrogen was added to the argon by means of a calibrated capillary system, and the proportion of hydrogen (on an atomic gas scale) was varied between the limits of 0.35 to 35.3%, i.e., two orders of magnitude. A definite percentage of plasma "contamination" was caused by sublimation and combustion of the carbon electrodes. The carbon content was estimated at 0.5% maximum by measuring the rate at which the electrodes were consumed.

When the sum in Eq. (8), $\sum N_a \langle Q_a \rangle$, was being calculated, in addition to collisions with atoms of Ar, H, N, O, and C, collisions with molecules of N_2 , O_2 , CN, and CO were taken into account, but the role played by all the components except Ar, H, and the ions proved (within the experimental error) to be negligible.

Experiments were conducted for seven different hydrogen concentrations within the limits indicated above. In each case the strength of the electric field was measured, and at the same time a DFS-4 diffraction spectrograph (with 6.9 \AA/mm dispersion) took "transverse photographs" of the

discharge column in the 4861 \AA region. From these photographs spectral line contours for H_β for any radius in the arc column were obtained. From these one obtained the radial distribution for the charged particle concentration. A "Ural" computer performed all the necessary calculations. In addition, an ISP-51 prismatic spectrograph photographed the "transverse" spectrum, including the H_α , H_β , and H_γ Balmer lines. As was demonstrated by Kolesnikov and Sobolev, [20] the excited hydrogen level populations reach equilibrium for current strengths $i \geq 10 \text{ A}$; hence these spectrograms yield an independent measure of the plasma temperature (from the relative line intensities), and in addition provide a check on the radial distribution of the hydrogen atom concentration [from the absolute line intensities $J(r)$]. The $T(r)$ distribution, as measured by the intensity of the hydrogen lines and calculated by the Saha formula from measured values for $N_e(r)$, agreed to within 4%. The hydrogen atom concentrations $N_H(r)$ found from the absolute line intensities were 30–40% greater than the concentrations predicted from the initial composition of the gas. Most likely this discrepancy was due to the low degree of accuracy with which the absolute intensities were measured, and therefore we based all our calculations on data for the known initial composition of the gas.

For details of the experimental layout, the technique of "transverse photography," determination of $N_e(r)$, etc we refer to [17,20].

The $\langle Q_H \rangle$ cross section can be considered constant within our experimental errors in the temperature range 6 to $9 \times 10^3 \text{ K}$. Consequently it can be found by the trial-and-error method. This is done by substituting a variable parameter Q for $\langle Q_H \rangle$ in Eq. (8) and plotting an $i = i(Q)$ dependence for each concentration N_H . All the curves should intersect at one point at which $Q = \langle Q_H \rangle$. Such a graph is shown in Fig. 3, where by way of illustration $i = i(Q)$ curves are shown for three N_H values: 35.3%, 1.8%, and 0%. It can be seen that the curves do in fact intersect almost at one point. The strength of the current as calculated by Eq. (9) when $N_H = 0$ is very close to the actual strength. This proves that when $N_H \neq 0$, we actually do measure the contribution by collisions with hydrogen. Thus, from Fig. 3 we find

$$\langle Q_H \rangle = 57 \cdot 10^{-16} \text{ cm}^2 = 65 \text{ atomic units}$$

As we have already noted, the cross section for the elastic scattering of electrons by hydro-

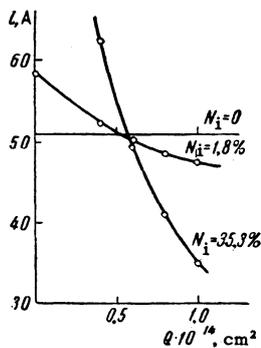


FIG. 3. $i = i(Q)$ curves for different hydrogen concentrations.

gen atoms will closely approximate this value for an electron energy $E \approx 0.7$ eV.

IV. DISCUSSION OF THE RESULTS

1. Comparison with results reported elsewhere.

If the curves found in [1,2] are extrapolated into the electron energy region where $E \sim 0.7$ eV, the cross sections obtained do not differ much from the value found by us (see the table). It is hardly worthwhile to give detailed consideration to the degree to which these data coincide or fail to coincide, because extrapolation into the low energy region involves much that is arbitrary. But it may be stated most definitely that the electric conductivity method generally gives a cross section equivalent in magnitude to that obtained by the crossed beam method.

We have also collected together in the table all the cross sections for electron scattering by hydrogen atoms that have been calculated by theoreticians for the past two or three years. Without bothering here to go into superfluous critical analysis of these results, we can state one rather interesting fact: regardless of the methods of calculation and the assumptions made, for electron energies $E \approx 0.7$ eV, there is extraordinarily good agreement among all the references. The

maximum deviation from the mean value (about 30 atomic units) does not exceed 10–15%, although when $E = 0$, the deviation is much greater. Thus, the cross section found by us (65 a.u.) is about twice as large as the theoretical one but, generally speaking, does not exceed the threshold cross section value. In this connection it is necessary to consider not only the accidental errors in our experiments, but also the possibilities of a systematic shift.

2. Accidental errors. We shall not comment on errors directly attributable to photographic photometry, as they are comparatively slight. The accuracy of the electric conductivity method mainly depends on the precision, difficult to estimate mathematically, with which the radial distribution $N_i(r)$ is found. The following causes of error are the most important ones: (a) random disturbances of symmetry and of space-time stability in the plasma column during exposure; (b) scattered light distortion of the “tails” of the $J(r)$ distributions; (c) the low degree of accuracy with which N_i is determined from the contour of the H_β line ($\sim 10\%$ [see [17]]).

We ran a constant check (by the usual means) on the stability and symmetry of the arc discharge. The introduction of various degrees of trimming of the “tails” of the $J(r)$ and $N_i(r)$ distributions permits the contribution by the second source to be estimated. Finally, an idea of the combined action of all the mentioned effects may be had from the reproducibility of the T and N_i values and from the deviation of the calculated current strength from the nominal one. A careful analysis of our experimental data indicated that the accidental error in $\langle Q_H \rangle$ does not exceed 20–30%. In other words, our $\langle Q_H \rangle$ value differs from the theoretical one by more than the accidental errors involved in the experiment.

Cross sections (in atomic units) for elastic scattering of electrons by hydrogen atoms at two electron energies

E = 0	E = 0.7 eV	Method	Reference
—	65 ± 20	Electric conductivity	This article
—	30–40 *	Electric conductivity	[1]
—	55–65 *	Crossed beams	[2]
—	147 **	Crossed beams	[3]
—	254 **	Electric conductivity	[7]
63	33.8	Electric conductivity	[6]
—	29.2	Variational	[9]
85.5	36.5	Hartree-Fock	[10]
49.8	27.0	Hartree-Fock	[11]
84.1	34.5	Variational	[12]
55	31.0	Variational	[21]
43.3	30.0	Polarized orbital	[5]

*Extrapolation of experimental data.

**E ≈ 1 eV.

3. Possibilities of a systematic shift. We shall now consider three groups of factors that, in our opinion, could cause a systematic displacement of the measured cross section. Since these factors are all involved in problems that have scarcely been investigated, their pertinence to the conditions of our experiments remain altogether hypothetical. But for this very reason they cannot be ignored.

In the first category we include the accuracy of the kinetic theory approximation used in the calculations of the electric conductivity; in the second we include the physical assumptions made in these calculations; and finally, in the third we place certain elementary processes that might turn out to be competitive with the elastic collisions. We thought it expedient to evaluate each group of factors in each instance at least qualitatively, on the basis of the available experimental data.

A. The kinetic theory for electric conductivity^[14] is applicable only to those plasmas where

$$600 T \gg N_1^{1/2}. \quad (10)$$

Since in our case $T \sim 10^4$ °K and $N_1 \sim 10^{16}$ cm⁻³ on the discharge axis, inequality (10) is fulfilled, however with hardly anything to spare. At first glance this may indicate that the value of $\langle Q_i \rangle$ is very sensitive to the fulfillment of (10). In^[14] where ν_{eff} is calculated, terms on the order of $1/\ln(mv^2e^{-2}D)$ are discarded, although when $T \sim 10^4$ °K and $N_1 \sim 10^{16}$ cm⁻³, they represent $\sim 30\%$ of the dominant term. Therefore, it is necessary to evaluate the discarded terms more accurately. True, the fact that the current strength as calculated by (9) coincides with the actual strength when $N_H = 0$ gives definite grounds for assuming the discarded terms to be very small. The results obtained by Kitaev et al (see^[17]) are an even more convincing affirmation of this assumption.

The theory makes no allowance for energy losses due to transfer and other mechanisms, though such losses are inherent in bounded, thermally open plasma. We suggest that these effects have more importance for the heating peculiarities of the plasma than for the form in which its electric conductivity is expressed, and all the more so because the criterion of homogeneity (see p. 216 in^[14]) is excellently fulfilled under high pressure.

B. In calculating the strength of the current by formula (9) we allow at least three assumptions that are not quite so unconditional as one might like. First, we neglect the nonlinear phe-

nomena in the plasma, although the field intensity in our case is near the critical value and hence according to^[14], nonlinear phenomena cannot be ruled out. However, an analysis of the data from numerous investigations of various arc discharges indicates that criterion (0.1) in^[14] can be considered too restrictive for a thermally open plasma. Second, we assume that the electrons have a Maxwell velocity distribution. Deviations begin to be noticeable for sufficiently high energies i.e., for values of v such that they can actually be left out of the integration in (6). But if we are correct in our surmise that inelastic collisions play an essential role when $E \sim 1$ eV (see below), their influence on the form of the distribution at low velocities should be given more careful consideration. Third, we neglect field scattering in the plasma. This would not appear to cause large errors, either, since the integrand in Eq. (9) has a distinct maximum when the values for r are so small that the electric conductivity of the plasma no longer decreases very much.

At this point yet another possibility of a systematic shift should be indicated, improbable though it may seem. As mentioned above, the N_H concentration calculated from measured absolute values for the intensities of the spectral lines proved to be 30–40% greater than the concentration predicted from the initial composition of the gas in which allowance is made for dissociation and ionization in the discharge column. The $\langle Q_H \rangle$ cross section calculated with this value used for N_H is in good agreement with the theoretical one. However, we know of no processes that could cause so significant an increase in the concentration of hydrogen atoms in the column. Therefore, we thought we had no right to rely on these measurements and in our calculations used for N_H a value based on the initial composition of the gas.

C. The conductivity for a hydrogen plasma is ordinarily calculated with elastic $e-H$ collisions in mind. Collisions such as $e-H^-$ and $e+H \rightarrow e+H^*$ at a temperature of $\sim 10^4$ °K and a pressure of ~ 1 atm are unimportant for electric conductivity. Here let us mention two more processes whose roles are still not clear.

a. $e-H^*$ collisions. As is known, inelastic collisions that cause transitions among excited levels have very large cross sections, and the maxima of these cross sections lie in a region of very low energies ($E_{\text{max}} \sim \Delta E$). Recently the cross sections for transitions in the hydrogen atom were calcu-

lated in a Born approximation.^[22] As was demonstrated, they increase with exceptional rapidity with an increase in the principal quantum number n of the lower excited state. It is easy to show that with the increase in the cross sections found in^[22] inelastic collisions with hydrogen atoms in a state with $n \sim 6-7$ would have become quite capable of competing with the elastic collisions. Here we shall not attempt to determine how applicable the Born approximation is to the present case. We shall only observe that the value for $\langle Q_H \rangle$ obtained by us is too small for there to be any question of a decisive role by inelastic collisions.

b. $H^+ + e + e \rightarrow H^* + e$ collisions. A recently published commentary by Bates^[23] mentions a very large cross section for this process. However, consideration of this subject will have to await the appearance of a more detailed article.

Thus, so far we cannot confidently indicate the reason why the cross section obtained by us is larger than the theoretical one. However, the agreement of the actual current strength with that predicted by (9) when $N_H = 0$, as well as the data reported by Kitaev et al,^[17] supports the suggestion that this excess is specific only for hydrogen.

When the electric conductivity of a partially ionized plasma is calculated by Eqs. (6) to (8), it follows, of course, that the cross section found by us, viz., 65 ± 20 a.u., should be used, not the theoretical value. The modification that we have proposed in the electric conductivity method can be used to find cross sections for many atoms in the energy region from 0.3 to ~ 1.5 eV.

In conclusion, we deem it our pleasant duty to express our gratitude to A. V. Gurevich, L. A. Vaĭnshteĭn, and Prof. N. N. Sobolev for going over this article and offering a number of valuable comments.

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